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Wayne Orchiston
Aniket Sule
Mayank Vahia *Editors*

The Growth and Development of Astronomy and Astrophysics in India and the Asia-Pacific Region

ICOA-9, Pune, India, 15-18 November 2016

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Editors

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IX International Conference on Oriental Astronomy
IISER, Pune, November 15-18, 2016
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Preface

It was a pleasure and a privilege to organise the Ninth International Conference on Oriental Astronomy, and we are grateful to Professor Tsuko Nakamura and other members of the ICOA Organising Committee for allowing us to organise an ICOA in India.

The primary purpose behind the meeting was to help Indian researchers meet international scholars and at the same time expose these international scholars to the richness of India's astronomical history. We are happy that more than 100 scholars from India and abroad one way or another participated in ICOA-9.

The history of astronomy is not a very well-studied subject in India. We, therefore, took advantage of the occasion and invited interested young researchers who had limited knowledge of the history of astronomy to a 3-day workshop just prior to the ICOA-9 conference so that they could become familiar with ideas prevalent in the field before they attended the conference. We are happy to report that more than 20 young researchers with various fields of specialisation participated in the workshop. Several distinguished scholars also agreed to come and give lectures at the workshop and present their work at the conference. We believe that this will have an excellent long-term impact on research in this field in India.

We also used the conference as a reason to bring out a book titled *History of Indian Astronomy: A Handbook,* which was edited by K. Ramasubramanian, Aniket Sule and Mayank Vahia and was distributed free of charge to all participants. This 700-page book contains 21 chapters written by 35 different authors and covers the history of Indian astronomy from the early megalithic cultures to the arrival of the telescope in India and the development of the leading nineteenth-century observatories. This book provided international astronomers at the conference with an invaluable overview of Indian astronomy, and it will surely prove to be an excellent resource for any new researcher wishing to enter this field.

Another enjoyable feature of the conference was the hospitality of the Indian Institute of Scientific Education and Research (IISER) in Pune. Due to their excellent infrastructure and cooperation, all conference participants could stay together and discuss topics of mutual interest over breakfast, lunch and dinner. The fact that the IISER was able to organise the conference and accommodation and meals within a single building was a blessing.

The conference itself was a delightful experience. With a relatively small but intensely interested group of participants, the meeting generated a lot of ideas and insights, and the presence of a pool of young participants certainly helped in maintaining an environment for discussion and participation.

Apart from the formal paper sessions, the conference also included a public lecture on the development of radio astronomy in Asia that was jointly presented by Professor Wayne Orchiston and Professor Govind Swarup and an absorbing musical evening by Ms. Rashmi Sule. During the conference, participants also were able to visit the Giant Metrewave Radio Telescope (GMRT) at Khodad.

There also was a post-conference field trip to Aurangabad, which is close to the meteorite impact crater lake at Lonar and the magnificently sculpted and painted rock art caves of Ajantha and Ellora.

The workshop, conference and field trips would have been impossible without generous support from several funding agencies but particularly the Tata Trust and the Infosys Foundation. The conference also benefitted greatly from academic and financial support supplied by the IISER who hosted us, the Tata Institute of Fundamental Research (Mumbai), the Indian Institute of Technology (Mumbai), the Indian Institute of Technology (Gandhi Nagar), Deccan College (Pune), the Inter-University Centre for Astronomy and Astrophysics (Pune) and the National Centre for Radioastrophysics (also in Pune).

Several people played crucial roles in the success of this conference. Professor Narlikar's support and encouragement and his participation in the entire meeting were a great morale booster for the organisers. Mr. Kishore Menon's efforts in immaculately planning all the details of the conference helped ensure its success. Professor Sunil Mukhi and staff at the IISER played a pivotal role in organising the conference and the pre-conference workshop, and we are indebted to them for their excellent logistical support. We also thank the staff at the National Centre for Radioastrophysics for hosting our visit to the GMRT. Members of the SOC provided crucial guidance in making the conference and workshop programmes academically exciting, while the LOC ensured that the conference was pleasant and enjoyable for all. Finally, we wish to thank all of the delegates for their enthusiastic participation in this memorable conference.

We hope that this book will prove useful to future generations of students and researchers who develop an interest in the exciting field of Asian and circum-Pacific history of astronomy.

Toowoomba, QLD, Australia Wayne Orchiston
Mumbai, India Aniket Sule
Mumbai, India Mayank Vahia

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Participants

Note: Co-authors of ICOA-9 papers who were unable to attend the Conference are indicated by asterisks.

AGARWAL, Pulkit (Singapore)*
ANKUSH, Pathania (India)
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JAMKHEDKAR, Arvind (India)
KANDI, Ranjani L. (India)
KAPOOR, Ramesh (India)
KESARI, Sneh (India)*
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KIM, Sang Hyuk (South Korea)
KOCHHAR, Rajesh (India)
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KULKARNI, Sumeet (India)
KUMAR, Naresh (India)*
LALA, Hitesh (India)
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LEE, Ki Won (South Korea)
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LYU, Yufei (China)
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MATHEW, John (India)
MENON, Kishore (India)
MENON, Srikumar (India)
MIHN, Byeong-Hee (South Korea)
MITRA, Sanjeet (India)
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NAIK, Suhas India)
NAM, Moon-Hyon (South Korea)
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ORCHISTON, Wayne (Thailand)
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RAJORIA, Megha (India)*
RAMASUBRAMANIAN, K. (India)
RAO, Balachandra S. (India)

RATHNASREE, Nandivada (India)
ROBERTSON, Peter (Australia)
RODHIYAH, Al Khansa (Indonesia)
RUBAB, Seemin (India)
RUPA, K. (India)
SADATMOOSAVI, Seyedamir (Iran)
SANDU, Pritpal (India)*
SARKAR, Tamal (India)
SARMA, Nataraj (India)
SATHYANARAYANAN, K. (India)
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SHAO, Jing (China)
SHILEDAR, Rasika (India)
SHYLAJA, B.S. (India)
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SIVANANDAN, D.S. (India)
SÔMA, Mitsuru (Japan)
SOONTHORNTHUM, Boonrucksar (Thailand)*
SRIRAM, M.S. (India)
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SULE, Aniket (India)
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VENUGOPAL, Padmaja (India)
VYAS, Pravesh (India)
WADADEKAR, Yogesh (India)
YADAV, Nisha (India)*
YOUNG, Shuk (South Korea)

A Selection of Conference Photographs

An ICOA-9 group photograph (photograph: Srikumar Menon)

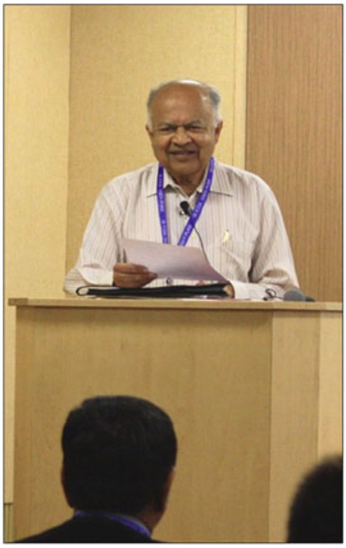
Some distinguished Indian astronomers. In the foreground (left to right) are Dr Ramesh Kapoor, K. Sinha, and Professors Jayant Narlikar, Razaullah Ansari and Govind Swarup (photograph: Srikumar Menon)

Left: Darunee Lingling Orchiston and Wayne Orchiston pose outside the entrance to the very comfortable Guest House of the Indian Institute of Scientific Education and Research (IISER) where delegates stayed during the Conference. Right: A typical meal at the Guest House dining hall (photographs: Darunee Lingling Orchiston)

One of the attractive interior courtyards at the IISER Guest House (photograph: Sitti Attari Khairunnisa)

Dr. Srikumar Menon presenting one of the lectures in the pre-Conference Workshop (photograph: Darunee Lingling Orchiston)

A group photograph taken during the pre-Conference Workshop. The organisers, Professors Mayank Vahia and Aniket Sule, are, respectively, in the back row (second from the right) and sitting (extreme left, in the red shirt) (photograph: Srikumar Menon)

Left: Professor Mayank Vahia (left) opens the Conference, and Professor Rajesh Kochhar asks a question. Right: Professor Jayant Narlikar welcomes delegates to the Conference (photographs: Srikumar Menon)

Part of the audience at the Conference. Third from the left in the front row is Carmen Pérez González from Germany, while first from the left in the third row is Mitsuru Sôma from Japan, both of whom presented papers at the Conference

Part of the audience at the Conference. Those in this photograph who authored or co-authored papers at the Conference include K. Sinha (front row, with the camera), Professor Kiyotaka Tanikawa (in the second row, slightly to the right of K. Sinha), Professor Patrick Das Gupta (in the second row, asking the question), Hani Dalee (in the third row, just to the left of Professor Das Gupta), Dr. Ramesh Kapoor (third row, on the extreme right) and Seyedamir Sadatmoosavi (centre, top, in the red shirt, sitting with his wife)

Part of the audience at the Conference. In the front row (left to right) are: K. Sinha, Professor Rajesh Kochhar, Dr Carmen Pérez González, Dr. Eun Hee Lee and Professor Jayant Narlikar. In the third row on the left is Dr Ramesh Kapoor

Four more distinguished Indian astronomers (left to right): Associate Professor K. Rupa, Dr T.V. Venkateswaran, Professor Balachandra Rao and Professor Padmaja Venugopal

Dr B.S. Shylaja (seated), together with (left to right) Preethi Krishnamurty, Geetha Ganesha, Apasana Neogi, and Ranjana Kandi

Two of India’s most respected historians of astronomy, Professors K. Ramasubramanian (left) and Rajesh Kochhar (right)

Professor Mayank Vahia (left) and Ganesh Halkare (right), who presented a paper on Indian tribal astronomy

Dr. N. Rathnasree (left), Dr. Carmen Pérez González from Germany (centre) and A.K. Rhodhiyah from Indonesia (right) who presented papers on New Delhi’s Jantar Mantar Observatory, Iranian astronomy and Indonesian archaeoastronomy, respectively


Dr. Eun Hee Lee from South Korea (left) and Dr. B.S. Shylaja from India (right), presenting their papers on the Jiuzhi-li Calendar and stars in Indian texts, respectively


Associate Professor K. Rupa (left) and Upasana Neogi (right) who presented papers on Indian lunar occultation observations and Nakshatra junction stars, respectively

Dr. Sang Hyuk Kim from South Korea (left) and Professor Mitsuru Sôma from Japan (right) presenting their papers on the Korean Sun-and-stars Time-determining Instrument and Ptolemy's calculation of the inclination of Mars' orbit, respectively

Dr. Venketeswara Pai (left) and Dr. Ramesh Kapoor (right) presenting their papers on the yogyādi-vākyas numerical tables and the first use of the telescope in India, respectively


Professor D. Narasimha (left) and Professor Razaullah Ansari (right) who presented papers on Varāhamihira's *Pancha Siddhantika* and India's first astrophysicist, Professor K.D. Naegamvālā, respectively


Dr Srikumar Menon (left) and Professor Patrick Das Gupta (right) who presented papers on Indian megalithic astronomy and comets in Vedic literature, respectively


Seyedamir Sadatmoosavi (left) from Iran and Lyu Yufei (right) from China presenting their papers on Iranian astronomy and astrology and on the archaeoastronomy of an ancient Chinese city gate, respectively


On the left is Kishore Menon who worked away relentlessly behind the schemes to make sure that ICOA-9 was a resounding success. On the right is Professor Kyotaka Tanikawa (right) from Japan, who presented a paper on historic Indian solar eclipses

The ICOA-9 Conference featured one Public Lecture, which was presented by Professors Wayne Orchiston (Thailand) and Govind Swarup (India), who are shown in the foreground. Their topic was the early development of radio astronomy in Asia, with emphasis on Australia, China, India, Japan and New Zealand

ICOA-9 was not all astronomy. One evening we attended an enjoyable performance of classical Indian music

Apart from the Conference Banquet, where Dr Srikumar Menon presented the after-dinner speech, we had the ICOA Conference Dinner, which was followed by the traditional ‘sing-along’ (although we also enjoyed story-telling and a flute performance). Here is a selection of photographs, featuring individuals, or pairs or groups of singers (in each case all from the one nation).

During the Conference, we also enjoyed a half-day visit to India's famous Giant Metrewave Radio Telescope (GMRT), the largest low frequency array of this kind in the world. Here is a selection of photographs at one of the radio telescopes, plus a view of part of the scale model of the whole array (photographs: Srikumar Menon).

Contents

About the Editors and Contributors

Editors

Wayne Orchiston was born in Auckland (New Zealand) in 1943 and has B.A. Honours and Ph.D. degrees from the University of Sydney. He formerly worked in optical and radio astronomy in Australia, New Zealand and Thailand. He is now an Adjunct Professor of Astronomy in the Centre for Astrophysics at the University of Southern Queensland in Australia. Wayne has supervised a large pool of graduate students in the history of astronomy. He has wide-ranging research interests and has published on aspects of Australian, Chinese, English, French, German, Georgian, Indian, Indonesian, Iraqi, Italian, Japanese, Korean, New Zealand, South African, Thai, Turkish and US astronomy. His recent books include *Eclipses, Transits, and Comets of the Nineteenth Century: How America's Perception of the Skies Changed* (2015, Springer, co-authored by Stella Cottam); *New Insights from Recent Studies in Historical Astronomy: Following in the Footsteps of F. Richard Stephenson: A Meeting to Honor F. Richard Stephenson on His 70th Birthday* (2015, Springer, coedited by David A. Green and Richard Strom); *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* (2016, Springer); *John Tebbutt: Rebuilding and Strengthening the Foundations of Australian Astronomy* (2017, Springer); and *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (2017, Springer, coedited by Tsuko Nakamura). Wayne has been very active in the IAU for several decades, and was responsible for founding the Transits of Venus and Historic Radio Astronomy Working Groups. In August 2018, he became the President of Commission C3 (History of Astronomy). In 1998, he co-founded the *Journal of Astronomical History and Heritage* and is the current Editor. He also serves as the Editor of Springer's Series on Historical and Cultural Astronomy. In 2013, the IAU recognised his international contributions to astronomy by naming minor planet 48471 "Orchiston" after him.

Aniket Sule is a Faculty Member at the Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research, Mumbai, India, where he also looks after the Indian National Astronomy Olympiad Programme. He is a Visiting Faculty at the Centre for Excellence in Basic Sciences, University of Mumbai, India, since 2012. He earned his Ph.D. in Natural Sciences (Astrophysics) from the University of Potsdam, Germany. He is the Regional Coordinator (Asia-Pacific) for International Olympiad on Astronomy and Astrophysics (IOAA). His research interests include the history of astronomy in India and solar physics.

Mayank Vahia is the dean of School of Mathematical Sciences at the Narsee Monjee Institute of Management Studies. He recently retired a professor at the Tata Institute of Fundamental Research, Mumbai. He completed his Ph.D. at the University of Mumbai in 1984. He began his career with an interest in cosmic rays and was involved in an experiment that was flown on NASA's Space Shuttle Space Lab 3 mission in 1986. After that, he widened his interests and worked on high energy (X-ray and gamma ray) telescopes that were flown on Russian and Indian satellites. For the past 15 years, he has been interested in the origin of astronomy in India and has studied the astronomical aspects from early rock art, megaliths, coins, architecture, ancient texts and the astronomy of some of Indian's oldest tribes. He has published about 250 papers, around 50 of which are in the history of astronomy and history of science. He also spearheaded India's participation in the International Astronomy Olympiad, a programme that he initiated in India and that has guided about 30 students to pursue their studies in science as career.

Contributors

Pulkit Agarwal is an M.Sc. Physics graduate from the National University of Singapore (NUS). His research interests lie in the field of theoretical high energy physics with a current focus on gauge/gravity dualities. He has worked on various small problems, such as the neutrino mass problem, showcasing an interest in physics beyond the standard model on both the smallest and the largest of scales.

Astronomy is a hobby that he has been developing more recently as a Graduate Teaching Assistant at NUS where he helped the department with tutoring undergraduates on the subject.

S. M. Razaullah Ansari, D.Sc. from the University of Tuebingen (Germany), is a retired Professor of Physics of Aligarh Muslim University. In 1970, he established at Aligarh Muslim University (India) the first astronomy and astrophysics research group. Since his retirement in 1992, he has been very actively researching the history of astronomy in Medieval India and its neighbouring Islamic countries.

Ansari has been a Member of the Indian National Commission for History of Science and was nominated as the Leader of the Indian Delegation to the ICHSTM Congress (Manchester 2013). He was elected as President of the Organising Committee of the IUHPS Historical Commissions: for Science and Technology in Islamic Civilization (1993–1997), History of Ancient and Medieval Astronomy (Founding President 2001–2005) and the first Asian President of the IAU Commission for History of Astronomy (1994–1997). His website is <www.razaullahansari.com>.

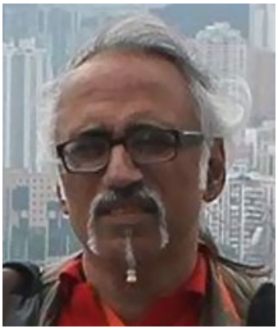
Ramesh Chikara is a Technician at the Nehru Planetarium, Nehru Memorial Museum and Library, New Delhi. Through his hands-on skills, he has contributed to the many outreach activities of the planetarium, like sky watches using telescopes, construction of material for educational activities and the calibration of the Jantar Mantar Observatory instruments.

Hani Dalee has an M.Sc. in Astrophysics from Jordan but works as an Astronomy Research Associate at Hamad Bin Khalifa University in Doha, Qatar. He is a Founding Member in the Jordanian Astronomical Society (JAS) and the Arab Union for Astronomy and Space Sciences (AUASS). His main research interest is in the origin of the names of the stars.

Patrick Das Gupta did his Ph.D. at the Tata Institute of Fundamental Research in Mumbai. Soon after submitting his Ph.D. thesis in 1988, he joined Inter-University Centre for Astronomy and Astrophysics in Pune as a Post-doctoral Fellow. During 1989–1990, he had short stints at the University of Wales, Cardiff (UK), as a Senior Research Fellow to learn about gravitational wave data analysis techniques, as well as at the Observatoire de Paris, Meudon, to have an exposure to gravitational radiation from the Hulse-Taylor binary pulsar. He joined the Department of Physics and Astrophysics at the University of Delhi in 1993 and has been a full Professor there since 2004.

Patrick's current research interests include studies relating to confirmation of the Hawking area theorem from the observed gravitational waves from binary black holes; proposing a unified model for gamma ray bursts and fast radio bursts; modelling dark energy, torsion and Chern-Simons gravity using a dynamical four-form; and the mechanisms to generate supermassive black holes from Bose-Einstein condensation of bosonic dark matter.

Suzanne Débarbat's career took place entirely at the *Observatoire de Paris*, from 1953. From 1955, she was *Assistant*, *Aide-astronome*, *Astronome Adjoint* and *Astronome Titulaire*, *Astronome Titulaire Honoraire*. She has a *Docteur d'Etat* and from 1985 to 1992 was Director of a research group (*Systèmes de Référence Spatio-temporels*/CNRS) and from 1987 to 1992 of the D*épartement d'Astronomie Fondamentale* of the *Observatoire de Paris*, nowadays *Systèmes de Référence Temps-Espace* (SYRTE) with which she has been affiliated since 1997. Among other organisations, Suzanne is a Member of the International Astronomical Union (Commission 41 (History of Astronomy): President 1991–1994), the Bureau des Longitudes (President 2004–2005) and the Académie Internationale d'Histoire des Sciences. She has published extensively, including conference proceedings and books on aspects of French astronomy.

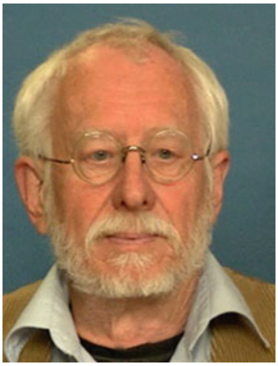


Chander Bhushan Devgun, an Engineer by profession, is a Senior Amateur Astronomer with skills in telescope-making and astrophotography, which he has showcased in various contexts. He was the President of the NGO Space India Ltd. which has a widespread presence in the country for its astronomy outreach work in schools.

Geetha Kydala Ganesha holds a B.Sc. (Physics, Chemistry and Mathematics) from Bangalore University and has been working in the field of history of astronomy from the past 10 years. During 2010–2012, she worked under Dr. B.S. Shylaja, the then-Director of the Jawaharlal Nehru Planetarium in Bengaluru, as a Project Assistant/Coresearcher on a project titled "Stone Inscriptions as Sources of Astronomically Significant Records" and funded by the Indian National Science Academy in New Delhi. Geetha has co-authored several research papers and, in 2016, co-authored the book *History of the Sky on Stones* with Dr. Shylaja. Since the end of the stone inscription project in 2012, Geetha has continued as an independent researcher in the field of history of astronomy.

Anurag Garg has an M.Sc./M.Ed. degree with more than 11 years' experience in teaching and school administration. In 2016, he received a 2 million grant from the Ministry of Planning and established the Atal Tinkering Laboratory with support from NITI Aayog. Anurag is computer literate and is actively involved in observational astronomy research.

Martin George is the Collections and Research Manager at the Queen Victoria Museum and Art Gallery in Launceston, Tasmania (Australia), and also is responsible for the Museum's planetarium and astronomy collections. He is a Former President of the International Planetarium Society. Martin has a special research interest in the history of radio astronomy and recently completed a part-time Ph.D. on the development of low-frequency radio astronomy in Tasmania through the Centre for Astrophysics at the University of Southern Queensland, supervised by Professors Wayne Orchiston and Richard Wielebinski (and originally also by the late Professor Bruce Slee). Martin is the Administrator of the Grote Reber Medal for Radio Astronomy and is a Member of the IAU Working Group on Historic Radio Astronomy. He also carries out research on the seventeenth-century Jesuit astronomy in Siam.



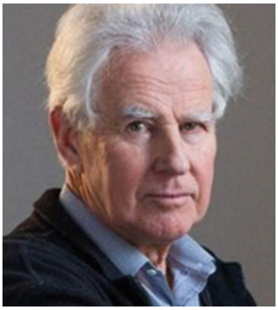
Lars Gislén is a Former Lector in the Department of Theoretical Physics at the University of Lund, Sweden, and retired in 2003. In 1970 and 1971, he pursued his Ph.D. in the Faculté des Sciences at Orsay, France. He has been doing research in elementary particle physics, complex systems and applications of physics in biology and with atmospheric physics. During the past 15 years, he has developed several computer programs and Excel spreadsheets implementing calendars and medieval astronomical models from Europe, India and Southeast Asia (see http://home.thep.lu.se/~larsg/). Lars also carries out research on the seventeenth-century Jesuit astronomy in Siam.

Carmen Pérez González studied Astrophysics (1993) and Photography (2005) at the University of Barcelona, and she holds a Doctorate in Art History from Leiden University (2010). A revised and expanded version of her dissertation was published as a book titled *Local Portraiture: Through the Lens of the 19th-Century Iranian Photographers* (Leiden University Press, Iranian Studies Series, 2012). She has worked as a Curator in the Science Museum in Barcelona and the Museum für Ostasiatische Kunst in Cologne and has written the catalogue *From Istanbul to Yokohama: The Camera Meets Asia, 1839–1900* (Walter König Publisher, 2014).

Currently Carmen is working as a Post-doctoral Research Associate and Lecturer at the IZWT (Interdisciplinary Centre for Science and Technology Studies) at Bergische Universität Wuppertal (Germany), from where she has edited a book for Brill (in their Nuncius Series) titled *Selene's Two Faces: From 17th Century Drawings to Spacecraft Imaging* (August 2018).

Priyanka Gupta is a Science Educator and Communicator. She has worked with various organisations like Mars Education, Thinklabs, etc. and has also been part of CSR projects led by Bajaj, Rolls Royce. The focus of these CSR projects was to encourage a hands-on learning approach in the government schools of Delhi. Currently, she is working as a STEM Instructor in Manav Rachna School, Noida. She is also associated with Bihar Bal Bhawan, Patna.

Ganesh Halkare is an Advocate in Amravati, a town in Maharashtra. He also has a postgraduate degree in Archaeology and Anthropology from Nagpur University. He has a deep interest in tribal education, particularly in the removal of superstition among tribe members. He also is deeply interested in tribal anthropology and is highly respected among the tribesmen for his work in ensuring that they are aware of and can exercise their rights within the nation state. Ganesh has published more than a dozen research papers on the archaeology of the Nagpur region. He is now working on the astronomy of various tribes in the Nagpur region of Central India.



Terry Hardaker has a degree in Cartography, Geography, Numismatics and Palaeolithic Archaeology. He researches Palaeolithic sites in the UK and Southern Africa, but he also is a numismatist working on ancient Indian punch-marked coins. Terry is an Honorary Research Fellow in the School of Archaeology, Classics and Egyptology at the University of Liverpool and an Honorary Research Associate at the Heberden Coin Room, Ashmolean Museum, Oxford.

Taufiq Hidayat was born in Surabaya (Indonesia) in 1965 and obtained his Bachelor's degree in Astronomy from the Institut Teknologi Bandung (ITB), Indonesia. His Master's and Ph.D. degrees in Astrophysics were obtained from Université Paris Diderot, France. His main research interest is in millimetre/submillimetre radio astronomy observations for planetary atmospheres. Recently, he also joined a research group to study the deep field environment of radio galaxies using ALMA data.

Taufiq has served as Head of the Astronomy Department at the ITB and also as Director of Bosscha Observatory. Presently, he is a Member of the National Committee to develop a National Observatory on the island of Timor in the eastern part of Indonesia. He has written several physics textbooks for undergraduate and graduate students and popular books on astronomy for children. He also has edited several conference proceedings. Taufiq has supervised some undergraduate students to do research on Indonesian archaeoastronomy and ethnoastronomy. In 2010, the IAU named main belt asteroid 12179 "Taufiq" (5030 T-3).

Matthieu Husson is a CNRS Researcher based in l'Observatoire de Paris. His research focus is mainly on the history of astronomy and mathematics in late medieval Europe, Alphonsine astronomy and an intellectual biography of Jean de Murs. Currently, Matthieu leads two international research projects: (1) "Shaping a European Scientific Scene: Alfonsine Astronomy" and (2) "Digital Analysis Tools for the History of Astral Sciences". He also has a number of co-authored books in preparation.

Ramesh Chander Kapoor was born in India in 1948. In 1971, he joined the staff of the Uttar Pradesh State Observatory (now the Aryabhatta Research Institute of Observational Sciences, ARIES), Nainital, with an initial interest in flare stars. In 1974, he moved to the Indian Institute of Astrophysics (IIA) in Bangalore, remaining there until he retired in September 2010. In 1980, he obtained a Ph.D. from Agra University. While at the IIA, Ramesh worked on observational aspects of black holes, white holes, quasars and pulsars. He participated as observer and organiser in a few IIA solar eclipse expeditions (India in 1980, 1995, 1999, 2009 and 2010 and Indonesia in 1983). His current interest is the history of astronomy in India. All along, he has been active in popularising astronomy and has also published on Indian systems of medicine.

Ramesh has been an IAU Member since 1985 and became a Life Member of the Astronomical Society of India in 1973. He has been an Associate of the National Institute of Advanced Studies (NIAS, IISc) since 2002 and a COSPAR Commission E Associate since 2005.

Sneh Kesari is currently the Director and CEO of "Astrophile" brand. This is an astronomy and science outreach division of his company Arun and Sons Innovations (OPC) Pvt. Ltd. The brand website is www.astro-phile.com.

Sang Hyuk Kim was born in Seoul (Republic of Korea) in 1971 and received his Ph.D. from Chung-Ang University. He has been a Post-doctoral Researcher at the National Research Institute of Cultural Heritage (2007) and Chungbuk National University (2009–2010). From 2010 to the present day, he has worked at the Korea Astronomy and Space Science Institute (KASI) conducting research on the history of astronomy and the restoration of ancient Korean astronomical instruments.

Dr. Kim's major publications include *The Armillary Clock of Song I-yeong* (2012), *Apparatus for*

Construing the Heavens (2014, co-authored), *Astronomical Instruments of the Joseon Dynasty* (2016, co-authored) and *Heumgyeonggak-nu of Jang Young-sil and Thinking About Science Cultural Properties* (2017; co-authored). Kim is an IAU Member and continues his research activities through ICOA, ISHEASTM and ICHST.

Naresh Kumar is an Assistant Technician at the Nehru Planetarium, Nehru Memorial Museum and Library, New Delhi. Through his hands-on skills, he has contributed to the many outreach activities of the planetarium, like construction of material for educational activities and calibration of the Jantar Mantar observatory instruments.

Eun Hee Lee was born in Incheon (Republic of Korea) in 1957 and has B.Sc., M.Sc. and Ph.D. degrees in Astronomy from Yonsei University in Seoul. She is currently a Senior Researcher at the Yonsei University Observatory. She is one of the founding members of the International Society for Science and Civilization on the Silk Road (ISSCSR) and a Member of the Organising Committee of IAU Commission C3 (History of Astronomy) and IAU Commission C4 (Astronomy and World Heritage), the International Society for the History of East Asian Science (ISHEA), the International Congress for the History of Science and Technology (ICHST) and the Organising Committee of the International Conference on Oriental Astronomy (ICOA).

Eun Hee's main research interests are in ancient Chinese and Islamic calendars and space climate changes and events. She has numerous publications. Recently, she published a new edition of the translation and annotation of the Korean astronomical calendar *Chiljeongsan Naepyeon* (七政算内篇) (2016, Institute for the Translation of Korean Classics). Now, she is preparing to publish a new edition of the translation and annotation of the Korean version of the Chinese-Islamic calendar *Chiljeongsan Oaepyeon* (七政算外篇)".

Siddharth Madan completed a Mechanical Engineering degree at Manav Rachna International University. He then worked for Grant Technical Equipments LLC in Muscat (Oman) from 2013 to 2016. He then returned to Delhi to pursue a career in astronomy. Siddharth has since participated in the calibration of the Jantar Mantar Observatory in New Delhi and the Delhi chapter of the Project Sky Watch Array Network (SWAN). He is currently working as an Educator at the Nehru Planetarium in New Delhi.

Srikumar M. Menon is an Architect who specialises in ancient and early architecture of the Indian subcontinent. His academic interests focus on ancient architecture: prehistoric and later monuments such as stupas and temples, as well as the origins of astronomy in the Indian subcontinent. His Ph.D. investigated Indian megaliths for possible intentional astronomical alignments, and his later studies at sites in the Malaprabha Valley and in the Hampi-Hire Benakal and Sannati-Sirival regions in northern Karnataka led to deep insights about the continuity of commemorative traditions from prehistoric to later times and the influence of prehistoric architecture on later monuments.

Currently, Srikumar is engaged in efforts to understand the evolution of the principles of construction and stone-working in early temple architecture and the practice of architecture in Early Historic to Medieval Periods in India, including tracking early artisans of ancient India.

Byeong-Hee Mihn was born in Busan (Republic of Korea) in 1974 and has a B.A. Honours from Yonsei University (Seoul) and a Ph.D. from Chungbuk National University (Cheongju). Since 2007, he has worked at the Korea Astronomy and Space Science Institute (KASI), researching historical astronomy and the calendrical method of astronomical almanacs. He also is an Assistant Professor of Astronomy and Space Science at the Korea University of Science and Technology (UST).

Dr. Mihn's publications include *Astronomical Instruments of the Joseon Dynasty* (2016, co-authored by Lee Yong Sam and Sang Hyuk Kim), *Astronomical Phenomena Recorded During the Three Kingdom Dynasty*

(2014, co-authored by Ahn Young Suk and Sang Hyuk Kim), *Apparatus for Construing the Heavens* (2014, co-authored by Sang Hyuk Kim et al.) and the *Korean Astronomical Almanac* (coedited by Ahn Young Suk) from 2007 to 2014. All of these publications are in the Korean language. Dr. Mihn's co-authored recent papers are "Estimation of the Latitude, the Gnomon's Length and Position About Sinbeop-Jipyeong-Ilgu in the Late Joseon Dynasty" (2017, *Journal of Astronomy and Space Sciences*); "Astronomical Instruments with Two Scales Drawn on Their Common Circumference of Rings in the Joseon Dynasty" (2017, *Journal of Astronomy and Space Sciences*); "Scale Marking Method on the Circumference of Circle Elements for Astronomical Instruments in the Early Joseon Dynasty" (2015, *Journal of Astronomy and Space Sciences*); and "Analysis of Interval Constants in Calendars Affiliated with the Shoushili" (2014, *Research in Astronomy and Astrophysics*).

Sonia Munjal completed a B.Sc. in Physics at Delhi University and currently is pursuing a Master's degree in Astrophysics at the Argelander-Institut für Astronomie (University of Bonn, Germany). Her primary research interests are the radio astronomical investigation of AGN activity and dust.

D. Narasimha is from a remote village in Kasaragod district of Northern Kerala (India) and graduated from Calicut University. He then did his Ph.D. at the Tata Institute of Fundamental Research with Professor S.M. Chitre. He pioneered the development from scratch of one of the earliest gravitational lens codes, which had good success in predicting the lensing galaxy or cluster as well as for other diagnostic values of lensing, the most important being the prediction of the Gravity Ring, now known as the Einstein Ring. In 2013, the Indo-French Centre for the Promotion of Advanced Research (CEFIPRA) considered his Project on Gravitational Lensing with Dr. Yannick Mellier of the Institut d'Astrophysique de Paris among the most successful projects in their 25 years history. Dr. Narasimha was awarded the Best Scientist of South India in 2017 by the international Association of Scientists, Developers and Faculty (ASDF). He was an Invitational Fellow of the Japan Society for the Promotion of Science in 2004–2005. Since his retirement from the Tata Institute of Fundamental Research in 2017, Dr. Narasimha has been a Visiting Professor at the Indian Institute of Technology Dharwad.

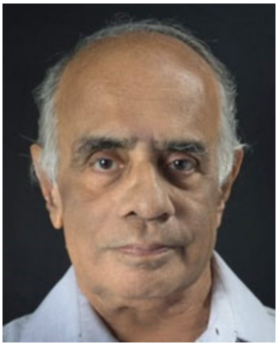
Lavanya Nemani is pursuing an M.Sc. in Astrophysics at the University of Bonn (Germany). She graduated from Delhi University with a B.Sc. Honours in Physics in 2017. She is interested in studying cosmology and looks forward to working on large-scale structure and formation of the Universe.

Upasana Neogi was born in Bengal (India) in 1989. In 2012, she completed her M.Sc. in Electronic Science from Dinabandhu Andrews College, which is affiliated with the University of Calcutta. She then worked for Megatherm Electronics Pvt. Ltd. in Kolkata as a Research and Development Engineer, but her deep interest in astronomy led to a Post-Graduate Diploma in Astronomy and Planetarium Science. She did a 6-month project on radio astronomy at the Giant Metrewave Radio Telescope in Khodad and also worked on an ancient astronomy project through the Tata Institute of Fundamental Research. Upasana has also worked as a Research Assistant at Jawaharlal Nehru University in Delhi.

Darunee Lingling Orchiston was born in Phrae (Thailand) in 1959 and has become involved in the history of astronomy research through working as a Research Assistant with her husband, Professor Wayne Orchiston. In recent years, Darunee Lingling has attended astronomy conferences, seminars and workshops in Australia, India, Malaysia, Myanmar, New Zealand, South Korea and Thailand and has carried out archival research in Australia, France and Singapore. She has co-authored research papers on the seventeenth-century Jesuit astronomy in Siam, the 1868 total solar eclipse and Maori astronomy and is involved in ethnoastronomical studies in India and in northern Thailand in collaboration with Ganesh Halkare, Professor Mayank Vahia and her husband. She also joined her husband in researching the history of meteoritics in Thailand.

Venketeswara Pai completed his post-graduate studies in Physics at the Cochin University of Science and Technology (CUSAT) in Kerala and a Ph.D. in the History of Astronomy from the Indian Institute of Technology (IIT), Bombay. His broad area of research is the history of science, with a research focus on the history and development of astronomy and mathematics in India from the twelfth to the seventeenth century AD. He is at present an Assistant Professor at the Indian Institutes of Science Education and Research (IISER) in Pune, Maharashtra. His particular expertise resides in deciphering scientific manuscripts written in Sanskrit and Malayalam. He is currently researching the history and development of the *Vākya* School of Astronomy as well as Bhāskara's innovations by studying his auto-commentary known as "Vāsanā-Bhāṣya" (in collaboration with Professor M.S. Sriram of Chennai) which will throw some light on the advancement of astronomy in the twelfth century AD. Dr. Pai has won the INSA Medal for "Young Historian of Science", and he is a Founding Member of the Indian National Young Academy of Science (INYAS).

Megha Rajoria is a graduate in Physics from the University of Delhi with higher education in the field of Journalism and Science Communication. She is presently an e-astronomer in RAD@home Astronomy Collaboratory, India, which is a nationwide network of 130-plus trained citizen-scientists. Her interest is in serving society through science.



S. Balachandra Rao was born in 1944 at Sagar in Karnataka (India) and has an M.Sc. (Mathematics) from the University of Mysore and a Ph.D. (Fluid Mechanics) from Bangalore University. Professor Rao served at the National Colleges at Gauribidanur and Bangalore, teaching mathematics for 35 years, and he retired in 2002 as Principal. Currently he is (i) Honorary Director, Gandhi Centre of Science and Human Values, Bharatiya Vidya Bhavan, Bengaluru; (ii) a Member of the National Commission for History of Science, INSA, New Delhi; and (iii) an Honorary Senior Fellow at the National Institute of Advanced Studies (NIAS) in Bengaluru.

Professor Rao has been researching in the field of classical Indian astronomy since 1993 under successive research projects from INSA. He has authored, singly and jointly, quite a few papers in reputed journals and books on Indian mathematics and astronomy. The books published so far are about 30, half in English and the remainder in Kannada. The more popular ones among them are (1) *Indian Mathematics and Astronomy: Some Landmarks*; (2) *Indian Astronomy: Concepts and Procedures*; (3) *Eclipses in Indian Astronomy*; (4) *Transits and Occultations in India Astronomy* [titles (3) and (4) were co-authored by Dr. Padmaja Venugopal]; (5) *Grahalaghavam of Ganesha Daivajna*, *English Translation and Notes*; (6) *Karanakutuhalam of Bhaskara II*, *English Translation and Notes* [titles (5) and (6) were co-authored by Dr. S.K. Uma]; (7) *Astrology: Believe it or Not?*; (8) *Traditions, Science and Society*, *etc*. While title (7) was translated into the Kannada and Marathi languages, title (8) was rendered into Kannada, Telugu and Malayalam versions. The Kannada versions of books (7) and (8) have won awards as "The Best Works of Rational Literature" from the Kannada Sahitya Parishat (Kannada Literary Authority).

Nandivada Rathnasree is the Director of the Nehru Planetarium at the Nehru Memorial Museum in New Delhi and has been working in the fields of astronomy education and archaeoastronomy research since 1999. Prior to that, she researched stellar evolution and pulsars.

Through involving students in hands-on observations using the instruments at all of the extant Jantar Mantar observatories in India, she has contributed to their continuing usage as astronomical teaching devices. Nandivada also has worked as a Chief Advisor for text books and science workbooks for the Junior classes for the CBSE and NCERT. At the Nehru Planetarium, she has contributed extensively towards the in-house creation of topical and locally relevant content for full-dome shows and live interactions in the sky theatre, and she also has produced many innovative hand activities for outside the sky theatre.

Al Khansa Rodhiyah was born in Sukoharjo (Indonesia) in 1994. She completed her undergraduate studies in 2017, with the Department of Astronomy at the Institut Teknologi Bandung. Her research interests are mainly in the history of astronomy, ethnoastronomy and archaeoastronomy, but she also has carried out research on lunar crescent visibility to define new criteria for the Muslim calendar. In 1917, she attended the NARIT/UNESCO Training Workshop in Chiang Mai (Thailand) and has presented papers at a number of Asian history of astronomy conferences. Al Khansa now works in the Indonesian Agency of Meteorology, Climatology, and Geophysics in the Time-Keeping Division.

K. Rupa was born in Bangalore (India) in 1974 and has an M.Sc. from Bangalore University and a Ph. D. from Anna University, Chennai. The title of her doctoral thesis is *Planetary Models in Classical Indian Astronomy in Comparison with Ptolemaic, Copernican and Keplerian Models – A Mathematical Analysis.* Currently she is an Associate Professor in the Department of Mathematics at the Global Academy of Technology in Bangalore. She has presented papers at various conferences and published a few papers in the *Indian Journal of History of Science* and other journals. Currently she is working on the INSA research project "Occultation and Transits in Indian Astronomy – A Mathematical Analysis". She has co-authored the book *Bharathada Suprasidda Ganitajnaru* (*Famous Indian Mathematicians*).

Pritpal Kaur Sandhu was born in Delhi (India) in 1986. She has B.Sc. (Hons.) and M.Sc. degrees in Physics from Delhi University, and recently, she submitted a Ph.D. thesis on *Diffuse Radio Emission in Galaxy Cluster Merger at a Frequency Ranging from 150 MHz to 18 GHz* to the Indian Institute of Technology, Indore. She has published papers on "Transit of Venus: quantitative observing with simple equipment" (2012, co-authored by N. Rathnasree), "Gravitational collapse and structure formation in an expanding Universe" (2015, co-authored by J.S. Bagla), "First detection at 5.5 and 9 GHz of the radio relics in bullet cluster with ATCA" (2016, *Astrophysics and Space Science*) and "The peculiar cluster MACSJ0417-1154 in the C & X-bands" (2018, *Astrophysics and Space Science*). Pritpal also has 3 years teaching experience at undergraduate and post-graduate levels at various colleges and a university in Delhi. She has gained insights into the topics she has worked on, but, more importantly, she has developed a positive and proactive attitude to scientific research and has determined to pursue an academic career in instrumentation, observational astrophysics and data analysis.

B. S. Shylaja hails from Bengaluru. After completing an M.Sc. in Physics at Bangalore University, she had a brief tenure at the National Aerospace Laboratories and the Central Power Research Institute before joining the Indian Institute of Astrophysics. She studied binary stars with Wolf-Rayet companions for her Ph.D. thesis (1987), under the guidance of late Professor M.K.V. Bappu. She also studied comets (including 1P/Halley), metallic line stars and cataclysmic variables. The rapid oscillations of the CVs were recorded with a fast photometer which was designed to record lunar occultations. She also studied the signatures of winds of massive stars in the infra-red at the Physical Research Laboratory, Ahmedabad.

Since joining the Jawaharlal Nehru Planetarium in Bengaluru in 1994, she has been studying historical aspects of Indian astronomy. She translated into English the monograph on the 1874 transit of Venus written by Chintamani Ragoonatha Charry in Kannada, a language of South India; this throws light on the techniques used by the Indian astronomers of that era. She has also written many books in Kannada and in English. These include books on the transit of Venus and a book on understanding Jantar Mantar, with pop-up pages. She has studied the temples in India for their astronomical significance. She has found a new source of astronomical records—stone inscriptions—all over India and South Asia, and her book *History of the Sky – On Stones* (2016) is a compilation of the eclipse and planetary conjunctions cited in these inscriptions. They have been found very useful in that they extend back more than 1500 years. As an Observational Astrophysicist, Dr. Shylaja has studied the records of observations of stars from various texts and from the traditions of the navigators, with the aim of deducing the earlier observational techniques that were prevalent in India.

K. Sinha completed an M.Sc. in Physics, with special papers in Astrophysics, at the University at Gorakhpur, in 1971. He then worked at the Uttar Pradesh State Observatory and its successor ARIES for a little more than 37 years in various R&D capacities, mainly in the Solar Section. On deputation to the Council of Science and Technology of Uttar Pradesh, he helped them complete the Indira Gandhi Planetarium in Lucknow. The unique feature of this planetarium, found nowhere else in the world, is that the building mimics the shape of Saturn, i.e. it is a huge sphere with five rings around it. A body of water surrounds the building to indicate that the planet itself is lighter than water—again a unique feature of the Solar System.

Mitsuru Sôma was born in Kuroiso (Japan) in 1954 and has M.Sc. and Ph.D. degrees in Astronomy from the University of Tokyo. He is currently an Assistant Professor at the National Astronomical Observatory of Japan. Mitsuru was an Organising Committee Member of IAU Commission 41 (History of Astronomy) during 2009–2015. He is also a Member of IAU Divisions A (Fundamental Astronomy), B (Facilities, Technologies and Data Science), C (Education, Outreach and Heritage) and F (Planetary Systems and Bioastronomy). In addition, he is a Vice President for Grazing Occultation Services of the International Occultation Timing Association. His research interests include linkage of stellar reference frames with dynamical reference frames using observations of lunar occultations and changes in the Earth's rotation during ancient times using ancient records of eclipses and occultations. His many publications in the history of astronomy include the book *Mapping the Oriental Sky: Proceedings of the Seventh International Conference on Oriental Astronomy (ICOA-7)* (2011, coedited by Tsuko Nakamura, Wayne Orchiston and Richard Strom).

Boonrucksar Soonthornthum is the Former Founding Executive Director of the National Astronomical Research Institute of Thailand (NARIT) and has D.Sc. degrees in Physics and in Astrophysics. He has research interests in astrophysics (especially binary stars), the history of Thailand astronomy and astronomical education, and he has published on all of these areas. He is a longstanding Member of the IAU and is currently Vice President of Commission C1 (Astronomy Education and Development). He is very actively involved in the Astronomy Olympiad movement and is the Founder and Chairman of the Southeast Asia Astronomy Network (SEAAN). Boonrucksar has arranged many international conferences and research collaborations between NARIT and overseas institutions. Now that he is no longer Director of NARIT, he looks forward to spending more time researching the history of SE Asian astronomy.

M. S. Sriram (b. 1950) has a B.Sc. (Honours) in Physics from Bangalore University, an M.Sc. (also in Physics) from the Indian Institute of Technology in Kanpur and a Ph.D. in Theoretical Particle Physics from the same institute. He worked in the University of Allahabad, India, during 1981–1986, before joining the Department of Theoretical Physics, University of Madras, in 1986, from where he retired in 2011. He has done research in the areas of quantum field theory, particle physics and nonlinear dynamics. He also has been working in the area of history of Indian mathematics and astronomy for the past 25 years. He is the co-author of the *Ganitayuktibhasa*, *Tantrasangraha* and *Karanapaddhati*, three important ancient Kerala texts on astronomy, published by the Hindustan Book Agency, New Delhi, and Springer. Currently he is associated with the Prof. K.V. Sarma Research Foundation.

Govind Swarup was born at Thakurdwara (India) in 1929. He received his B.Sc. and M.Sc. degrees in Physics from Allahabad University, India, and a Ph.D. from Stanford University in 1961. He has been awarded a D. Sc. (Honoris Causa) by Roorkee University, Banaras Hindu University and Raipur University. After completing his M.Sc., he spent 4 years at the National Physical Laboratory in Delhi; 2 years at CSIRO, Australia; 1 year at Harvard University; and 6 years at Stanford University. He joined the Tata Institute of Fundamental Research (TIFR) in Mumbai in 1963 and retired in 1994. He is currently an Honorary Professor at the TIFR.

During 1965–1969, he set up a 530-m-long and 30-m-wide radio telescope of unique design in South India at Ooty. From 1987 to 1996, he directed the design of the Giant Metrewave Radio Telescope (GMRT) near Pune, which consists of an array of 30 45-m diameter dishes. This is the world's largest radio telescope operating in the frequency range of about 130–1430 MHz. The GMRT has been used by hundreds of astronomers from India and 34 other countries.

Govind is internationally renowned for his pioneering contributions in the fields of solar radio astronomy, radio galaxies, quasars, cosmology and radio instrumentation. He has authored more than 125 research papers, guided 23 Ph.D. students, edited 4 books and has 2 patents. He is a Fellow of the Royal Society of London and of all the National Science Academies in India, a Fellow of The World Academy of Sciences, an Academician of the Pontifical Academy of Science and an Academician of the International Academy of Astronautics.

Kiyotaka Tanikawa was born in Gamagoori (Japan) in 1944 and has B.A. and Ph.D. degrees from the University of Tokyo. He has been working in celestial mechanics, low-dimensional chaos and historical astronomy in Japan. He is now a Visiting Astronomer at the National Astronomical Observatory of Japan. Kiyotaka and Mitsuru Sôma have organised around 15 symposia on the history of astronomy and historical astronomy since 2006 and published the corresponding proceedings. The most recent of these are *The Proceedings of the Sixth Symposium on "History of Astronomy"* (2017) and *The Proceedings of the Fifth Symposium on "Historical Records and Modern Science"* (2018). Among others, *The Proceedings of Intensive Workshop on Ancient Medieval Eclipse Data: Compilation of Eclipse Data and Examination of their Reliability* contains the article "Indian records of eclipses" by Professor B.V. Subbarayappa (IUHPS, India). Kiyotaka and Mitsuru invited researchers from China, England, Holland, India, Korea and New Zealand to this workshop. Kiyotaka has a particular interest in historical solar eclipses. He compiles worldwide records of historical solar eclipses to accurately determine the long-term variations of ΔT with short variations of a hundred to a few hundred years.

His recent publications include *Roads to Chaos* (2016, Kyoritsu Shuppan, in Japanese) on two-dimensional mapping. Kiyotaka is currently translating this book into English. He co-authored a book *The Three-Body Problem from Pythagoras to Hawking* (2016, Springer). His public lecture "The Astronomical Aspects of the Locality of Civilizations" has been printed in the form of a booklet (Nanzan University, 2018, in Japanese). Kiyotaka's astronomical interests extend to the ancient history of Japan, motivated by the joint work with Mitsuru Sôma on "The Japanese astronomy in the seventh century AD" (2008, *Astronomical Herald* of NAOJ) in which they discussed the start of observational astronomy in Japan. Minor planet 10117 "Tanikawa" has been named after him.

S. Venkatesh was born in Madurai (India) in 1975. He has B.Sc. and M.Sc. degrees in Physics from The American College, Madurai, India, and M.S. and PhD degrees (Physics) from Clarkson University, Potsdam, NY (USA), and Wayne State University, Detroit (USA), respectively. He is now a Senior Process Analyst at the Aparajitha Group in Madurai, India. Previously he was Faculty in the Department of Sciences, Amrita University, Coimbatore, India. He is an Experimental Condensed Matter Physicist by training. Having more than 15 years of experience in academia and industry, he has published more than a dozen research papers in top journals including *Nature Nanotechnology* and in various conference proceedings (including the American Chemical Society). He was honoured with various fellowship and awards, to name a few: Wayne State University's Thomas C. Rumble Fellowship; the Outstanding Teaching Assistant Award, for scholastic achievement, and commitment to physics education, from the American Association of Physics Teachers; and the Commendable Service Award for teaching, given by the Phalanx Senior Honorary Leadership Society at Clarkson University. Recently he has developed interests in Indian indigenous instruments and measurements.

T. V. Venkateswaran was born in Chennai (India) in 1963 and has a B.Sc. (Mathematics) and an M.A. (History) from the University of Madras, a Post-Graduate Diploma in Science Communication from Pondicherry University and Ph.D. degree from Tamil University in Thanjavur. He formerly worked as the Managing Editor of a science periodical for children in Tamil and later as the Course Director for the Post-Graduate Diploma in Science and Development Communication in CDIT, Thiruvananthapuram. He is now Scientist "F", at "Vigyan Prasar", National Institute for Science Communication, Department of Science and Technology in New Delhi. He is also the Chief Editor of "India Science Wire", an online science and technology news feature service published by the Department of Science and Technology.

Dr. Venkateswaran has wide-raging research interests that include the history of science popularisation in Tamil Nadu, the evolution of calendars and history of astronomy and science, colonialism and modernity in India. His R&D profile includes the development of science communication software as well as innovative strategies for science education and informal learning. He is also a prolific popular Science Writer with more than 25 popular science books and 300 popular science articles to his credit. His recent publications include "Star Wars in colonial Tamil region: contours of a discourse between European missionary and a 'native'pañcāngkam computer on 'modern' astronomy" (2016, *Journal of Scientific Temper*) and "Influence of Ibn al-haytham on vision, optics, and experimental sciences" (2016, *Science and Culture*). He conducts a weekly television science show and writes weekly columns for many newspapers.

Padmaja Venugopal was born in Tirupathi (India) in 1967 and has a Ph.D. from Bangalore University. Currently she is Professor and Head of the Department of Mathematics at the SJB Institute of Technology in Bangalore. Her recent publications include *Eclipses, Transits, Occultations and Heliacal Rising and Setting of Planets*. She has been working in the field of Indian astronomy for the past two decades and has presented papers at various conferences and published a few papers in the *Indian Journal of History of Science* and other journals. She worked on the INSA research project "Comparative Study of Planetary Models in Respect of Epicycles in Classical Indian Astronomy vis-à-vis Ptolemaic and Copernican Models". Currently she is working on another INSA project: "Gankananda – English Translation, a Critical Analysis & Comparison with other Indian Astronomical Tables". She is guiding Ph.D. candidates in the field of astronomy. She has authored books on *Eclipses in Indian Astronomy* and *Transits and Occultations in Indian Astronomy*. She presented a stand-alone paper on "Eclipses – inscriptional and literary references, a survey" at the 25th International Congress of History of Science and Technology in Rio de Janeiro, Brazil, in July 2017.

Nisha Yadav is a Young Scientist at the Tata Institute of Fundamental Research. She has largely worked on various aspects of the Harappan Civilisation and its script and has wide-ranging interests in the origin and growth of astronomy in India. She has published several papers in leading international and Indian journals. She is a recipient of the INSA Young Historian of Science Award in 2017.

Part I
Astronomical Instruments and Observatories

Towards the Restoration of the Jantar Mantar Observatory Instruments at Delhi: Calibration and Observations with the Jaiprakas and Ram Yantra

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Abstract A database of positional astronomy observations using the Jaiprakas and the Ram Yantra of the Jantar Mantar Observatory in Delhi, is presented here. The purpose of this database is to give an overall idea of the state of the instrument at present, prior to the planned restoration of the instrument surface markings by the Archaeological Survey of India. The observations and the related documentation of procedures involved, are also aimed at providing templates for the planned restoration of the instrument surface markings. The restoration process can utilise the methods outlined here, for the drawing/etching of the markings for the measurements of altitude and azimuth on the one hand, and right ascension and declination

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(for the Jaiprakas) on the other, using these methods. The time markings along the equator can also be undertaken with the procedures discussed.

Markings relating to the rising and/or culmination of the Zodiac signs, which may have been present originally on the Jaiprakas, have not been investigated. The required markings for the same would have shifted with precession of the axis of rotation of Earth, and drawing them according to current positions would be different from the original markings. Conservation practice requires a restoration to the original design, but in this particular case such a restoration would not make any astronomical sense.

1 Introduction

Jantar Mantar Observatory instruments are tactile manifestations of spherical trigonometry concepts, which are usually difficult to comprehend for a beginner, particularly from laminar pages in a text book. Thus, active observational and measurement work with different aspects of these instruments gives a very good grounding in basic astronomy for any beginner, and fosters a retention of this interest for a student who may go on to undertake research in astronomy in a more modern setup later. In this spirit, outreach activities of the Nehru Planetarium, Nehru Memorial Museum and Library, New Delhi, involved many students with an interest in astronomy, towards undertaking positional astronomy measurements with the observatory instruments as a learning exercise.

Since the Delhi Jantar Mantar Observatory instruments, for the most part, do not have any markings left on their surfaces, this exercise involved making overall measurements of the dimensions of the instruments and length measurements involved in the actual data taking. Through this process, the complete geometry of the construction of two of the instruments at the Observatory—the Jaiprakas and the Ram Yantra—was thoroughly explored. A database of positional astronomy observations, for the most part in the horizon coordinate system, emerged from these exercises.

In all of the literature about the Jaiprakas Yantra and the Ram Yantra instruments built by Jai Singh, and in particular the one at Delhi, the current work is the only one that gives detailed observations using the instruments, and arrives at an understanding of the actual condition and functioning of the instrument based on these observations.

It also emerged from the process of facilitating these observations, that our methods can function as templates during the restoration of the instrument markings. With the Jaiprakas in particular, in the absence of any surviving instrument-markings, many different methods of making observations were tried. The one method that seemed to work the best, perhaps reflects how the original markings were made, and could be used to make the markings during the restoration process.

The various observing methods used with the Jaiprakas and the Ram Yantra, and the observations themselves, are detailed in the following sections.

2 The Jaiprakas Yantra

The Jaiprakas Yantra at the Delhi and Jaipur Jantar Mantar Observatories are hemispherical instruments installed as sunken bowls facing the sky (see Fig. 1), with a horizontal crosswire stretched on the surface, to act as a gnomon.

They can function as complete positional astronomy instruments—one has the sky in a bowl—and celestial measurements in any coordinate system should be easy to calibrate and mark on the instrument. In practice, the actual calibration does turn out to be a very complex exercise.

One major complication arises from the fact that these gigantic instruments are not complete hemispherical bowls. The Jaiprakas is built as two complementary instruments with sections of the hemisphere cut along hour angle-related great circles. This absence of spherical continuity and the large scale of the instrument

Fig. 1 A view looking towards the south from the stairs of the Delhi Samrat Yantra. The twin bowl-shaped Jaiprakas instruments can be seen either side of the stairs. The cylindrical Ram Yantra is in the background

made it rather difficult to implement calibrations that were accurate to a millimetre. One additional factor which may have played a role in the difficulties we faced in calibrating the Jaiprakas in its current condition, could be departures from sphericity that may be present on the surface of the instrument. These may have crept in during its initial construction or during any subsequent renovation (or both). These are under investigation in our ongoing calibration project.

The process of preparing the markings for celestial measurements in local and equatorial coordinate systems has been fine-tuned for the Delhi Jaiprakas instruments, and templates for marking the instrument surface have been prepared for any current or future renovation of similar instruments.

The most detailed discussions of the different functions of the Jantar Mantar instruments in all of the Indian observatories is in the book *Sawai Jai Singh and his Astronomy* (Sharma, 1995). However, while this comprehensive book describes the use of the Jai Prakash instruments both in Delhi and Jaipur, there is no mention of the actual observations taken with the Delhi instrument.

Given its extreme state of disrepair, the Delhi instrument has not been considered to be in a usable state for positional astronomical observations (Babu and Venugopal, 1993; Sharma, 1995). No observations with this instrument are reported in the literature until 2004.

In March 2004, one of the first public uses of the Delhi Jantar Mantar Observatory took place when an educational activity associated with the June 2004 transit of Venus took place. A team from the Nehru Planetarium, New Delhi, and a group of students and amateur astronomers measured the altitude and azimuth of the Sun using Ramyantra and the Jaiprakas (Rathnasree, 2004). These observations were confined to only the central sector of the West Jaiprakash Yantra where some remnants of the altitude and azimuth markings are still faintly visible. Outreach activities at the Delhi Jantar Mantar Observatory, including measurements, have been ongoing since then.

Currently, there is an ongoing process of restoration of the instrument's surfaces and other required renovations relating to the positional astronomy instruments at the Jantar Mantar Observatory, Delhi. The first instrument being renovated is the Jaiprakash Yantra. Our observational project with the Jaiprakash started in May 2016, with a small team assembling a database of positional astronomy measurements and observations using the Jaiprakash instrument. After trying several different methods of making positional astronomy observations with the instrument in its current state of disrepair, the database project evolved towards employing a method for making temporary markings within the bowl of the instrument. We hope that this will be a useful methodology for the final restoration of the markings within the instrument.

2.1 Description of the Jaiprakas

The Jaiprakas are twin hemispherical bowl-shaped instruments (Fig. 1), each a reflection of the sky above and marked in sectors and gap regions. The reflection

Fig. 2 The Jaiprakas Yantra of Jaipur (left) and Delhi (right). The markings visible on the Jaipur instrument are mostly absent in the Delhi instrument except for a few markings left near the center of the instrument

of a cross wire stretched north-south and east-west over the surface of the bowl shows the position of the Sun in the sky.

The center of the bowl is a reflection of the zenith. Starting from the center, lines are marked along the bowl to indicate the azimuth (Fig. 2). Altitude circles are marked along the length of the bowl. From these markings, local coordinate measurements can be made with this instrument. There should also be markings on the instrument that will allow measurements in equatorial coordinates.

The bowls are complementary, in the sense that the gap region in one bowl is the sector region in the other, and *vice versa*. The idea is that the observer needs to be inside the bowl to take readings—which means that readings would not be possible in the regions where the observer would be able to walk—and hence the complementary bowl.

At the surface level of the depressed bowl there are broken pegs in the north-south and east-west directions to hold the cross wires. One has to view the shadow of the junction of the cross wires on the bowl of the instrument to determine the co-ordinates of the Sun in the sky. The sectors on the surface of the hemisphere are marked with altitude and azimuth circles, declination circles, and hour circles.

The Jaipur instruments also have markings related to the rise and culmination of the zodiac signs, however it is difficult to find traces of these amongst the remnants of instrument-markings in the Delhi instrument.

In the Delhi instrument most of the markings have rubbed off, although the altitude and azimuth circles towards the center of the bowl are still visible. Remnants of declination circles and hour circles can also be seen here and there on the instruments. Position measurements in local coordinates, close to noon are still relatively easy to make. For measurements at other times, and for equatorial coordinate measurements, more rigorous temporary calibrations are currently being used by our team and a complete restoration of the markings (an ongoing process being undertaken by the Archaeological Survey of India) is awaited. The results presented in this paper could serve as templates for this process.

2.2 *Calibration of the Jaiprakas*

Observations of altitude and azimuth of the Sun were taken with the Delhi instrument. In the absence of markings, a variety of methods was used to obtain the measurements.

Work undertaken from March to July 2016 involved:

1. Tracing all of the existing markings inside the bowls of the instrument on large rolls of tracing paper, in order to preserve a record of all existing markings prior to restoration.
2. Taking a few observations using remnants of altitude and azimuth markings that still existed on the instrument.
3. Taking some observations of the position of the Sun on the tracing sheets; extrapolating the markings for altitude and azimuth on these sheets; thereby obtaining some data on the position of the Sun in horizon co-ordinates.
4. Marking the positions of the Sun directly on the instrument; measuring the positions of these markings with respect to the point at the base of the bowl reflecting the zenith using tape measures; thereby obtaining the altitude and azimuth of the Sun.

And finally, 5. Making temporary markings on the bowl for altitude and azimuth, corresponding to the inferred original least counts of 1.5° in altitude and 3° in azimuth. This least count inference is based on remnants of markings left on the instrument.

Figures 3, 4 and 5 show some of the results of these efforts to make observations with the Jaiprakas Yantra at the Delhi Observatory. The data were collected over an extended period during the summer of 2016. Clearly, issues of obtainable accuracy remain with methods (3) and (4) listed above. So far, the most accurate is given by

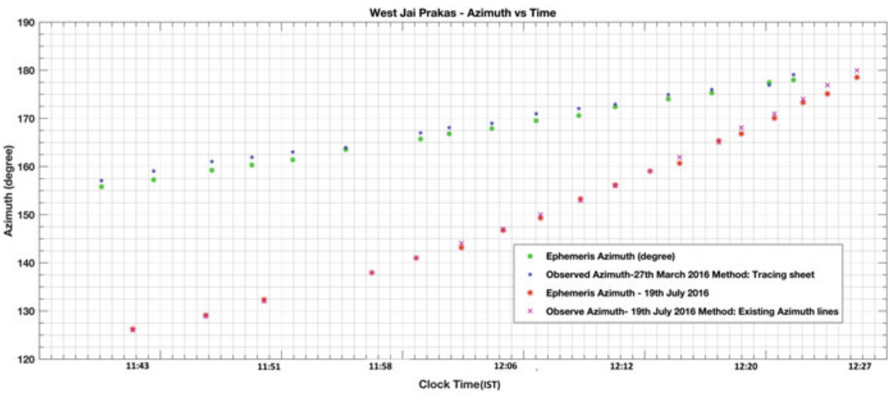

Fig. 3 A comparison of observed Azimuth with ephemeris values from the Jaiprakas Yantra Western bowl

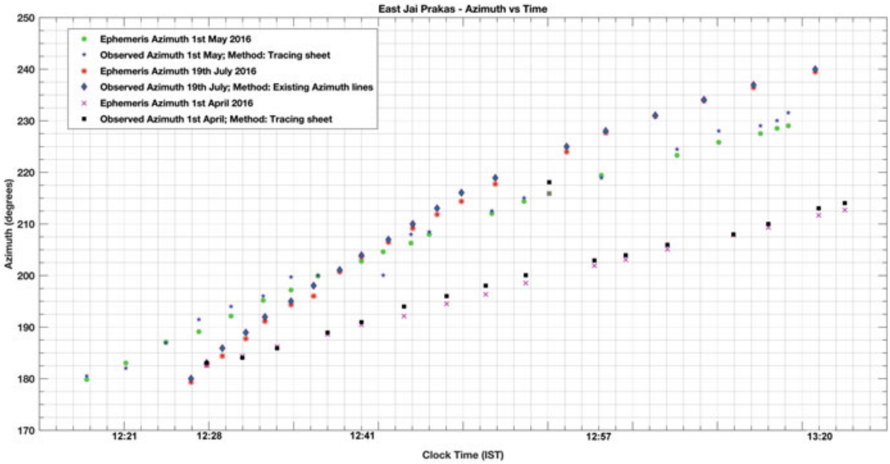

Fig. 4 A comparison of observed azimuth with ephemeris values from the Jaiprakas Yantra Eastern bowl

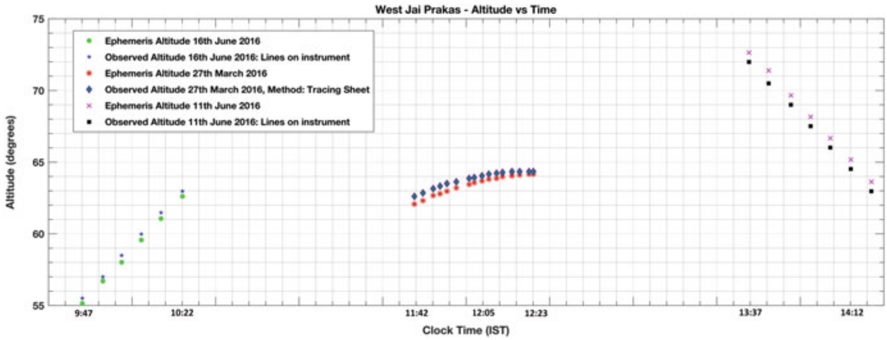

Fig. 5 A comparison of the observed altitude with ephemeris values from the Jaiprakas Yantra Western bowl

(5). This method is discussed below, and seems to be the best method for making the actual markings during the restoration process.

After accounting for the many possible errors and corrections in the observations, including.

refraction and dip corrections, and arriving at a method for drawing the markings, we continue to see systematic errors in altitude measurements on either side of central segments of the Jaiprakas Yantra East and West. The errors are negligible at the solar noon edge and increase on either side.

One major explanation of these errors is possible departures from sphericity of the bowl surfaces, and we do find evidence of this. Details of these studies will be reported elsewhere.

2.3 Templates for the Restoration of the Jaiprakas

Templates for marking the altitude and declination circles and the great circle lines for azimuth and right ascension measurements are outlined here. This will be possible, following the restoration of the spherical shape of bowl of the instrument to an accuracy of ±1 mm. The Delhi Observatory bowls are each 8.34 m in diameter.

Marking circles on the surface of the Jaiprakas bowl corresponding to altitude values 1.5° apart is the first step to be undertaken. These can be drawn using corresponding chord lengths between the zenith reflection point (ZRP) and the circumference of the altitude circle. A taut wire corresponding to that length is stretched from the ZRP holding a pencil at the end, and the circle is drawn using the stretched chord as a compass.

This procedure was initially adopted to draw altitude circles close to the ZRP. To draw larger altitude circles it was found that pinning a measuring tape to the ZRP point and using a drawing instrument pierced at the appropriate chord length on the tape itself allowed for a more accurate drawing of the altitude circles.

For the drawing of the azimuth lines, a special metal strip about 6.5 m in length was fabricated which can be placed between the ZRP and the appropriate azimuth location on the surface of the bowl, and drawing the azimuth lines along this strip. In order to ensure that the strip sat accurately along the appropriate azimuth on the surface of the bowl, some intermediate points corresponding to that azimuth were drawn on selected altitude circles by marking the appropriate chord lengths from azimuth to azimuth on that circle.

This procedure makes the drawing of the altitude and azimuth markings tractable. Declination and hour circles also can be marked using the same method, but keeping the center as the reflection of the North Celestial Pole on the southern side of the instrument instead of the ZRP. Some temporary markings have been successfully made using this method, and further consistency checks are ongoing.

3 The Ram Yantra

The Ram Yantra are twin cylindrical instruments built for determination of the location of the Sun (and other celestial objects) in the sky, in local or horizon coordinates. The inner surface of these cylindrical instruments reflects the sky. Every point in the sky has a reflection point in the inner surface of the cylinder. The reflection point, is the top edge of the gnomon, which is the central pillar. The instrument is constructed in such a way that the height of the central pillar is equal to the radial floor length of the sectors and also the outer wall height of the instrument.

The instrument is divided into various sectors so that observers can walk inside the gaps to make measurements, particularly at night time. As this removes a half of the cylinder surface, two instruments were constructed, but where there is a gap in one instrument there is a sector present at the corresponding location in the other

Fig. 6 Looking for Venus during the day using its ephemeris coordinates and the Ram Yantra. The gap regions of the Ram Yantra are used and the eye is placed in line with the floor/wall surface, then the sky is scanned around the central gnomon

instrument, and *vice versa*. Spliced together, the two instruments make a complete cylinder.

The floor is divided into 30 sectors, and 30 gaps with the same dimensions as the sectors. Each of the sectors thus spans 6° of azimuth. The sectors are marked with six radial lines—so that each marking corresponds to 1° of azimuth. Some of the original markings for altitude and azimuth are visible on the instrument.

The current project of positional astronomy data collection with the Ram Yantra at the Delhi Jantar Mantar Observatory started during the 2009 winter solstice, and included discussions and observations using the Ram Yantra—a very user-friendly instrument for easy measurement of the altitude and azimuth of the Sun during the day and stars and planets at night. The Ram Yantra also was used successfully to locate Venus during the daytime, by placing the observer's eye at the appropriate position in the instrument, based on the ephemeris values of its altitude and azimuth (see Fig. 6). The first successful observations with the Ram Yantra had been undertaken in March 2004, during outreach activities.

In the absence of complete markings on the Delhi instrument, the following procedure was used for all measurements with this instrument. Azimuth angles are measured using the number of sectors to the shadow, any existing 1 ° markings, and further sub-divisions measured using a string and measuring tape.

Altitude measurements were made using the following procedure. The instrument was built in such a way that the height of the central pillar was exactly equal to the length of the floor sector. The average value of several sector lengths was then taken to be the height of the pillar. Another length measured was the distance of the shadow edge from the central pillar. Tan-1 (Gnomon length/distance to the shadow) then gives the altitude.

We measured the altitude and azimuth of Sun during daily sessions of 5–6 hours over an extended period of time. The idea behind these observations was to characterise the current status of this historical instrument through direct observations. Histograms of errors in measuring altitude and azimuth with this instrument are shown in Figs. 7 and 8.

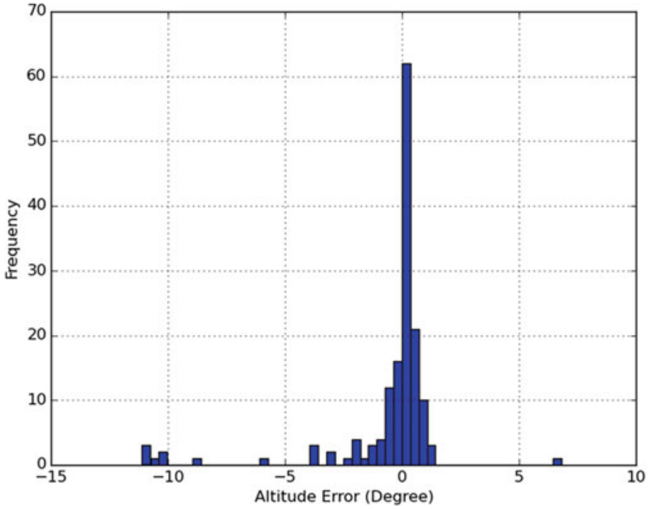

Fig. 7 Histogram of errors in the measurement of Altitude, using the Ram Yantra

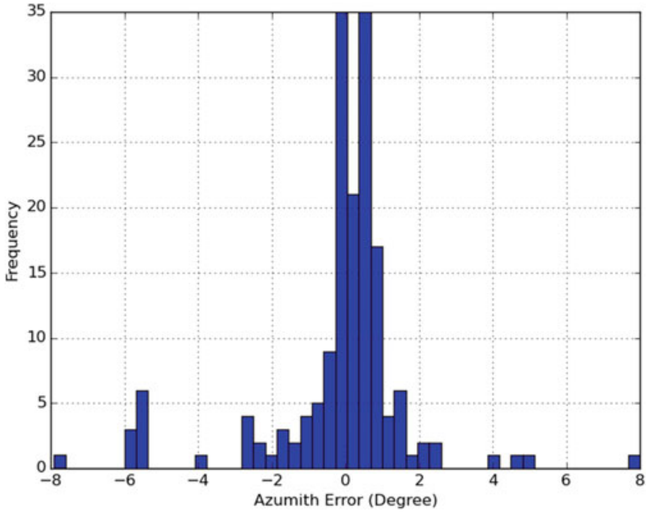

Fig. 8 Histogram of errors in the measurement of Azimuth, using the Ram Yantra

4 Concluding Remarks

The restoration of markings on the surface of the Jaiprakas bowl instruments at the Delhi Observatory can be undertaken using the mechanical constructions outlined in this work. The same procedure can be utilised for work on any large bowl-shaped instrument made for naked eye positional astronomy measurements. Before the restoration process begins and the markings are applied, it is essential that there is an exact spherical bowl shape with a smooth surface.

The one aspect about the Jantar Mantar Observatories is their inspiring presence in public space, allowing a very hands-on astronomical experience for visitors. Notwithstanding their current state of relative disrepair (in some cases), the Jantar Mantar instruments are still in a good enough condition to allow observations to be made for basic astronomical learning. In this context, the Nehru Planetarium's recent outreach activities represent the first astronomical use of the Delhi Jantar Mantar Observatory since it fell into disuse in the late eighteenth century. We believe that this Observatory is an outstanding astronomical teaching laboratory, and that these out-reach activities should be continued.

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On the Accuracy of some Ancient Indian Astronomical Instruments

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Abstract There are references to astronomical instruments in various Indian works, from the *Kātyāyana Śulbasūtra* dated earlier than 350 BCE, to the later *Siddhānta* (mathematical astronomy) texts from the fifth century CE onwards. The simplest of these instruments is the gnomon (*sañku*) which initially was used for fixing the east-west direction and finding the time, and later for finding the latitude of a location, the Sun's declination on any day, and other astronomical quantities. More advanced instruments would follow. Bhāskara-II (twelfth century) devised a board-instrument called *phalakayantra* to measure the hour angle of the Sun.

While these instruments have been described in the literature on history of astronomy in recent times, we are not aware of any study assessing the feasibility of construction, and the accuracy of these instruments. This paper is a very preliminary attempt in that direction. Here, we present our measurements relating to the determination of the east-west direction, and the declination of the Sun, using simple gnomons. The accuracy can be of the order of 1°, even with simple versions of them. We also report our findings on the measurement of the hour angle of the Sun, using a simple variant of the board-instrument of Bhāskara-II. At least with this version, the maximum error was of the order of 5°.

1 Introduction

The *Śulbasūtras* were perhaps the earliest texts in India that contain significant geometrical results, and were associated with the construction of Vedic altars (Datta 1932; Sarasvati Amma 1979; Sen and Bag 1983). All the geometrical constructions in the *Śulba* texts are described with reference to the east-west line, and its perpendicular (north-south line). In the *Kātyāyana Śulbasūtra* which is dated

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prior to 350 BCE, the method of determination of the east-west direction by using a gnomon is described (Sen and Bag 1983). Immediately following the *Vedāṅga* era, to which the *Śulbasūtras* belong, there are texts like *Arthaśāstra* and some Buddhist and Jaina works that describe the use of the gnomon for finding time on some particular days of the year (Ohashi 1993).

Various astronomical instruments have been described in the *Siddhāntic* (mathematical astronomy) texts in India, from the sixth century CE onwards. They find mention in the works of Āryabhata (476–550 CE), Bhāskara-I (ca. 600–680 CE) and Brahmagupta (ca 598–after 665 CE), Lalla (ca. 720–790 CE), Śrīpati (1019–1066 CE), Bhāskara-II (1114–1185 CE), and in the popular 'modern' *Sūryasiddhānta* (around the tenth century). For a comprehensive account of astronomical instruments in the Siddhāntic period, see the excellent paper by Ohashi (1994) and references therein. Often, there would be a *yantrādhyāya* (chapter on instruments) in the *Siddhānta* texts. The instruments described include:

1. the *sañku* (gnomon), for fixing the east-west direction, and measuring the zenith distance, latitude of a place, the Sun's declination, and time;
2. the *cakra* (circle) for the altitude of the Sun and time;
3. the *yaṣṭi* (staff);
4. the *nalaka* (tube), for locating a celestial object;
5. the *nādivalaya* (equatorial sundial) for time;
6. various kinds of clepsydra and water instruments for time;
7. the *gola* (celestial globe or armillary sphere) for demonstrations; and
8. the *phalakayantra* (board-instrument), devised by Bhāskara-II to measure the hour angle of the Sun (Ohashi 1994; Sriram 2016).

While detailed descriptions of most of the instruments mentioned above are now available, we are not aware of any published study involving actual observations using these instruments, and the assessment of their accuracy. This paper is a very preliminary attempt in that direction. Its scope is limited, and we report our observations using simple gnomons for (i) fixing the east-west direction by tracing the tip of the shadow on an equinoctial day, and (ii) determination of the declination of the Sun. We also report on our initial observations with a board instrument (*phalakayantra*) to find the hour-angle of the Sun by measuring its zenith distance.

2 The Gnomon and Direction

2.1 Finding the East-West Line at a Location

The *Kātyāyana śulbasūtra* (I.2) describes the determination of the east-west line in the following manner:

> Having put a gnomon (*śaṅku*) on a level ground, and having described a circle with a cord whose length is equal to the gnomon, two pins are placed on each of the two points where the tip of the gnomon-shadow touches [the circle in the forenoon and afternoon respectively].

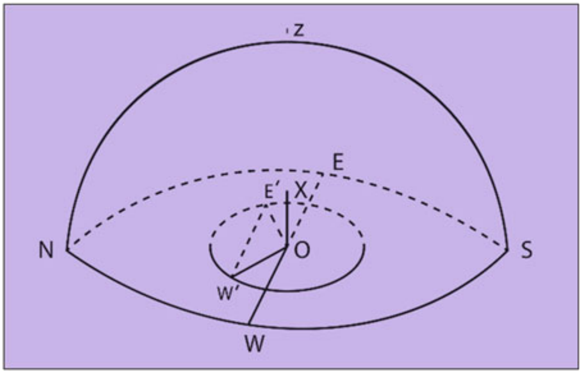

Fig. 1 The 'Circle method' for finding the east-west direction

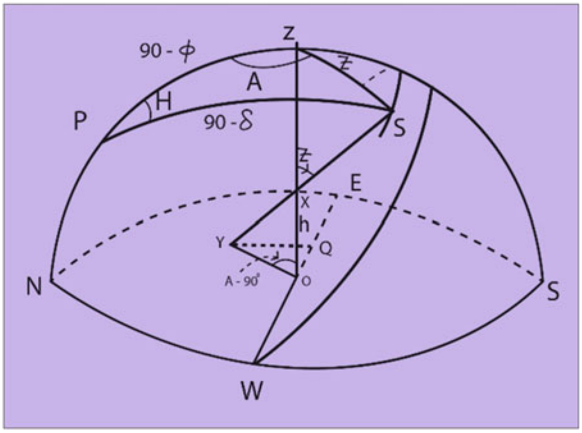

Fig. 2 The coordinates of the Sun (S), the gnomon (OX), and the shadow (OY)

> This [line joining the two points] is the east-west line (*prācī*). (Ohashi 1993, 206–208; cf. Sen and Bag 1983: 54, 120).

This is illustrated in Fig. 1, where OX is a gnomon on level ground, and Z is the zenith. A circle with a radius equal to the height of the gnomon is drawn. W′ and E' are the points where the tip of the shadow intersects the circle, in the forenoon and afternoon, respectively. If the variation of the declination of the Sun during the day is ignored, then it can be seen that these two points are symmetrically situated with respect to the north-south line, and E'W′ is parallel to the east-west line through O. In fact, we will prove shortly that it is indeed so by proving that E' and W′ are at the same distance from the east-west line. This is the 'circle method' for finding the east and west directions. Actually, it is not necessary that the radius of the circle is equal to the height of the gnomon.

In Fig. 2, we consider the Sun at S, corresponding to a declination δ, when its zenith distance is z, azimuth is A, and the hour angle is H, at a location with a latitude, ϕ. OX is the gnomon of height h, and OY is its shadow. YQ is perpendicular to the east-west line, EW. Applying the cosine formula to the side PS in the spherical triangle ZPS,

$$\begin{aligned}\cos(90-\delta) = \sin\delta &= \cos(90-\phi)\cos z + \sin(90-\phi)\sin z \cos A, \quad \text{or} \\ \sin\delta &= \sin(\phi)\cos(z) + \cos(\phi)\sin(z)\cos(A).\end{aligned} \tag{1}$$

It is clear that the length of the shadow, s is given by the expression.

$$s = OY = OX\tan(z) = h\tan(z), \tag{2}$$

and the distance of the shadow of the tip of the shadow, Y from the east-west line is.

$$YQ = L = s\sin(A-90) = -s\cos(A) = -h\tan(z)\cos(A). \tag{3}$$

Consider the tips of the shadow corresponding to two different points, with the same value of z (same shadow lengths), and cos A (same value of A, clockwise or anti-clockwise). Then these two points are at the same distance from the east-west line. Hence, the straight line passing through the two points is parallel to the east-west line, which is the basis of the 'circle method'.

2.2 The Locus of the Tip of the Shadow on the Equinoctial Day, and the East-West Line

According to many Indian texts, the tip of the shadow of a gnomon moves along a line parallel to the east-west line on the equinoctial day. For instance, in the explanation (*upapatti*) to verse 46 of the chapter on *Tripraśna* of his work *Graha-gaṇita* (the first part of *Siddhāntaśiromaṇi*), Bhāskara says:

> On an equinoctial day, the Sun moves on the equatorial circle. On such a day, the shadow [of the gnomon] in the desired direction due to the moving Sunis being determined. The extremity of the tip of the shadow of a 12-*aṅgula* gnomon is situated on the plane [of the horizon] such that it is at a constant distance equal to the equinoctial [mid-day] shadow from the east-west line. (BāpūdevaŚāstri and GanapatiŚāstri 2005: 83; my English translation).

We now prove this statement from Eq. (1). Consider the equinoctial day on which the declination $\delta = 0$. Then from (1), we have.

$$0 = \sin\phi\cos z + \cos\phi\sin z\cos A \tag{4}$$

or,

$$-\tan z\cos A = \tan\phi, \tag{5}$$

or,

$$YQ = L = -h\tan z\cos A = h\tan\phi. \tag{6}$$

Fig. 3 A crude gnomon and the locus of the tip of shadow on an equinoctial day

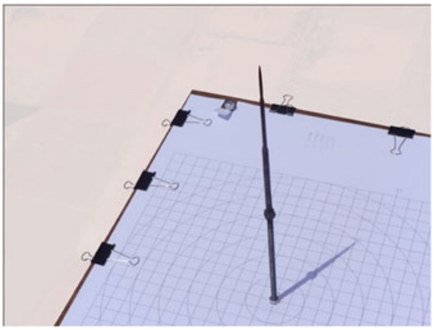

Fig. 4 A 'well-constructed' gnomon and its shadow

YQ is the distance of the tip of the shadow from the east-west line. The above relation implies that this has a constant value equal to h tanϕ at all instants or, the tip of the shadow moves along a straight line parallel to the east-west line on the equinoctial day. Bhāskara takes h = 12-aṅgulas, by convention.

In Fig. 3, we have a crude gnomon, whose shadow was observed at Chennai (latitude of 13.08°) on 22 September 2016, which was an equinoctial day. Even with such a crude device, it was observed that the tip of the shadow traced a straight line.

In Fig. 4, we have a 'well-constructed' gnomon, of height h = 49.9 cm. The gnomon was made from two long 0.5 inch threaded bolts each of length 20 cm, which were welded together. At the top, a 12 cm long nail (diameter ~1 cm) was welded. The tip of the nail was machined to get an appropriate tapered geometry (refer to the figure). This was placed on a wooden board that was adjusted to be a horizontal plane, using a spirit level. The shadow was observed through the day from 10 am to 2 pm, Indian standard time at Chennai (latitude of 13.08°), on 22 September 2016, an equinoctial day, when the declination of the Sun was zero. The tip of the shadow was marked on a drawing sheet of good quality at different instants, and the locus of this was traced. It was found to be a straight line. This is shown in Fig. 5. It was measured to be inclined at an angle of nearly 1° with respect to the true east-west line, as indicated by a GPS device. Considering the simplicity of the device, this is significant.

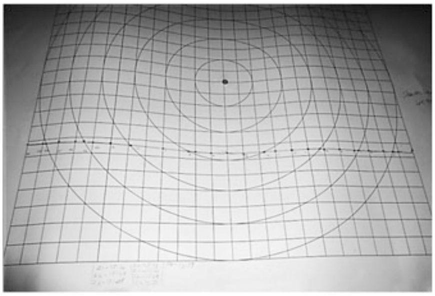

Fig. 5 The locus of the tip of the shadow of the gnomon on the equinoctial day (a straight line)

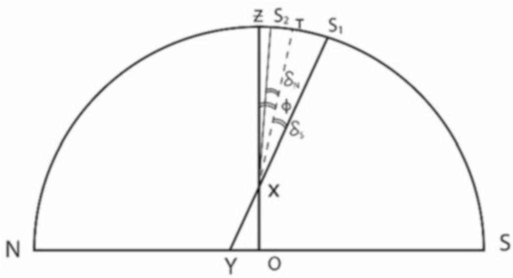

Fig. 6 The Sun on the meridian when it is on the equator (T), and when it has a southern declination, δS, (S1), or a northern declination, δN (S2)

The shortest shadow (at noon, corresponding to the true Sun) was measured to be 13.0 cm. This would be equal to h tanϕ, where $h = 49.9$ cm for our gnomon. Hence, the observed value of the latitude using the shadow, is $\phi = \tan^{-1}(13/49.9) = 14.6°$. The error of nearly 1.5° is possibly due to the fact the gnomon was not exactly vertical.

3 Instruments and Measurements

3.1 Measuring the Declination of the Sun from its Meridian Zenith Distance

In Fig. 6, T, S_1, and S_2 correspond to the position of the Sun at the meridian transit, when (i) it is on the equator, (ii) its declination δ_S is south, and (iii) its declination δ_N is north. Then the corresponding zenith distances are: (i) $z_m = Z\ \hat{X}\ T = \phi$, (ii) $z_m = Z\ \hat{X}\ S_1 = \phi + \delta_S$, or (iii) $z_m = Z\ \hat{X}\ S_2 = \phi - \delta_N$, when $\delta_N < \phi$, respectively. When the declination is north, and $\delta_N > \phi$, $z_m = \delta_N - \phi$. Hence, when the shadow is north, $\delta_S = z_m - \phi$ when the declination is south, and $\delta_N = \phi - z_m$, when the declination is north and $\delta_N < \phi$. When the shadow is south, $\delta_N = \phi + z_m$, when the declination is north, and $\delta_N > \phi$. So, the declination of the Sun can be found by observing the meridian zenith distance.

Fig. 7 The 'plumb-line gnomon'

This method of finding the declination of the Sun is mentioned in many Indian texts. For instance, in the explanation (*upapatti*) *to* verse 70 of the chapter on Tripraśna of his work *Grahagaṇita*, Bhāskara says:

> Therefore its arc is *nata*. That the shadow is in the direction opposite to that (direction of the Sun) is well-known. If the Sun is in the south (that is, the shadow is north), then the latitude can be subtracted from the *nata*, and the remainder is the declination, south of the equator. If the latitude cannot be subtracted from the *nata*, then the *nata* can be subtracted from the latitude, and the resulting remainder can be understood to be the declination, north of the equator. The learned can easily understand that if the *nata* is to the north (that is, the Sun is to the north of the zenith, and the shadow is south), then the *nata* should be added to the latitude, and the result is the northern declination. (BāpūdevaŚāstri and GanapatiŚāstri 2005: 92; my English translation).

Earlier, in the explanation, Bhāskara had defined the nata (in this context) as *khamadhyārkān-tara* (the arc between the zenith and the Sun) at noon, that is, the meridian zenith distance. It is clear that Bhāskara is stating the same expressions for the declination, δ_S or δ_N in terms of the latitude, ϕ, and the meridian zenith distance, z_m, as elaborated earlier by us.

We used a plumb line for the gnomon, where a weight is suspended from the top of a stand using a thread, as shown in Fig. 7. This ensures the verticality of the gnomon. The height of the gnomon, h is the distance between the point of contact of the thread and the stand at the top, and the point on the ground below the middle of the weight. In our case, h was 108 cm. The observations were made at Chennai with a latitude, $\phi = 13.08°$, on 3 days in 2016, namely, 24 October, 31 October, and 11 November, when the declination of the Sun was south. The length of the shortest shadow, s (corresponding to the true noon) was measured. The meridian zenith

Table 1 Observations of the declination of the Sun in 2016

Date 2016	Shadow Length at Meridian Transit	Meridian Zenith Distance $z_m = \tan^{-1}(s/h)$	Observed Declination, $\delta_S = z_m - \varphi$	Actual value of the Declination	Error
24 Oct.	49 cm	24.4°	11.32°	11.55°	0.23°
31 Oct.	56 cm	27.41°	14.33°	13.92°	0.41°
11 Nov.	63 cm	30.26°	17.18°	17.25°	0.07°

distance, z_m can be found from the relation, $s = h \tan z_m$, or $z_m = \tan^{-1}(s/h)$. The declination which is southern is given by: $\delta_S = z_m - \phi$. We tabulate the results in Table 1, and compare the observed and the actual value of the declination from a reliable source (Table of Declination of the Sun 2016). Considering the simplicity of the device, it is remarkable that the values of the declination measured from the meridian zenith distance are fairly accurate.

3.2 Bhāskara's Phalakayantra (Board Instrument] for Measuring the Hour Angle of the Sun

In Fig. 2, $Z\hat{P}S = H$ is the hour angle of the Sun when it is at S. Applying the cosine formula to the side ZS = z in the spherical triangle ZPS,

$$\cos(z) = \cos(90 - \phi)\cos(90 - \delta) + \sin(90 - \phi)\sin(90 - \delta)\cos(H),$$

or,

$$\cos(z) = \sin(\phi)\sin(\delta) + \cos\phi\cos\delta\cos H. \tag{7}$$

Hence,

$$\begin{aligned} R\cos(H) &= R\cos(z)/(\cos(\phi)\,,\cos\,,(\delta)) - R\tan(\phi)\tan\delta, \\ R\cos(H) &= R\cos(z)/(\cos(\phi)\,,\cos\,,(\delta)) + R\tan(\phi)\,|\tan(\delta)|\,,(\delta < 0) \end{aligned} \tag{8}$$

Here, R is the radius of a pertinent circle, to appear later. $R \tan\phi \tan\delta$ is the *carajyā*, which determines the hour angle at sunrise/sunset for given values of the latitude of the place, and the Sun's declination (if H_t is the hour angle at sunrise or sunset, $\cos H_t = -\tan\phi\tan\delta$). Hence, for a given ϕ and δ, the hour angle H can be determined from z, using this relation. This is the principle of the *phalakayantra*, or the board instrument devised by Bhāskara, and described by him in verses 18–26 in *Yantrādhyāya,* the chapter on instruments in the *Golādhyāya*, the second part of *Siddhāntaśiromaṇi* (BāpūdevaŚāstri and GanapatiŚāstri 2005: 237–240). We

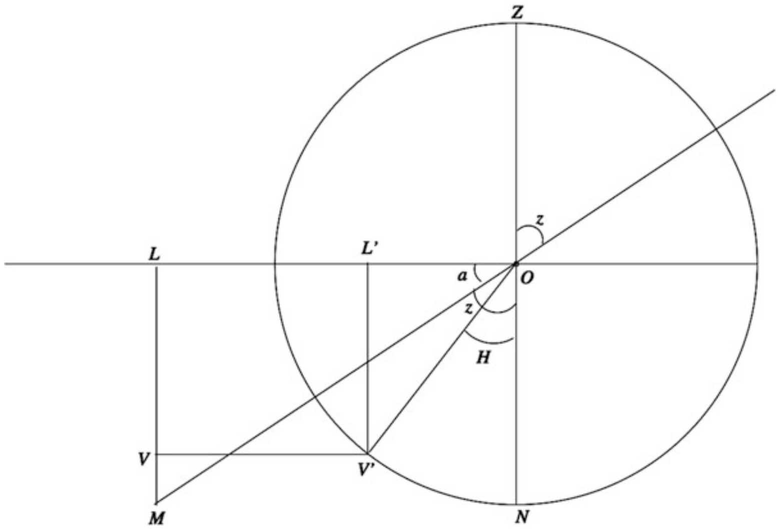

Fig. 8 A schematic diagram explaining the *phalakayantra*

describe the essential features of the instrument below, the sketch of which is given in Fig. 8. For more details, readers are referred to a paper by one of the authors (Sriram 2016: 373–376).

The instrument is just a rectangular board or *phalaka*, in the upper part of which a circle with a radius R (30 digits according to Bhāskara) is drawn (with O as the centre in the figure; ON = R). A small hole is bored at the centre, and a pin of suitable dimension is placed in it. One also has a *paṭṭikā*, or an index arm with a hole at the centre, which is suspended along the above-mentioned pin such that its length is along the ioned pin such that its length is along the vertical through the central hole. The instrument is held so that the rays of the Sun illuminate both the sides equally (so that the plane of the board is a vertical one, in which the Sun is situated). The index arm is placed along the direction of the shadow of the pin (OM in Fig. 8). Then, z = $N\hat{O}M$ is the zenith distance of the Sun, and a = $L\hat{O}M = 90 - z$ is the altitude. Now, a point M is located such that OM = R/(cosϕcosδ). Draw a line ML in the vertical direction, and locate a point V on it such that it is above M, if δ is north, and below it if δ is south, and such that MV = Rtanϕ |tanδ|. From V, draw a horizontal line, VV′, intersecting the original circle of radius R at V′. The angle $N\hat{O}V'$ is claimed to be the hour angle H. This can be directly read off, if the circle is graduated.

We will now show that $N\hat{O}V'$ can be identified with the hour angle H. Draw V′L′ parallel to VL. Then,

$$\begin{aligned} \mathrm{V'L'} &= \mathrm{VL} = \mathrm{ML} - \mathrm{MV} = \mathrm{OM}\sin \mathrm{a} - \mathrm{MV} \\ &= \mathrm{R}\cos \mathrm{z}/(\cos\phi\cos\delta) - \mathrm{R}\tan\phi\tan\delta \end{aligned} \tag{9}$$

But,

Fig. 9 A photograph of a *phalakayantra*

$$\mathrm{V'L'} = \mathrm{OV'} \cos\ O\hat{V}'L' = \mathrm{OV'} \cos N\hat{O}V' = \mathrm{R} \cos N\hat{O}V' \tag{10}$$

Hence,

$$\mathrm{R} \cos N\hat{O}V'. = \mathrm{R} \cos \mathrm{z}/(\cos \phi \cos \delta) - \mathrm{R} \tan \phi \tan \delta. \tag{11}$$

Comparing Eqs. (8) and (11), we find that $N\hat{O}V'$ is indeed the hour angle H.

We consider a variant of this instrument, where we work with a rectangular board that can be placed on an elevated surface that is horizontal and flat, exposed to Sun's rays as shown in Fig. 9. A nail protrudes from a hole made at the top of the board. We essentially observe the direction of the shadow of the nail at different instants, from which the corresponding zenith distances, z are measured. In fact, if X and Y are the horizontal and vertical (downwards) coordinates of a point on the shadow line, tan z = X/Y, or z = $\tan^{-1}$ (X/Y).

After noting these coordinates, we work with a plain sheet of paper with horizontal and vertical directions marked, as shown in Fig. 10. We draw a circle with a suitable radius, R, with O as the centre, where O represents the hole in the rectangular board. ON represents the vertical downward direction. Draw another circle with a larger radius, R/(cosϕcosδ), where ϕ is the latitude, and δ is Sun's declination on that day. Now, consider a point, I on the larger circle, correspond-ing to a zenith distance, z = $N\hat{O}I$. As we made observations on a day when the Sun had a southern declination, we draw a short line of length Rtanϕ|tanδ| from I vertically downwards (if the declination was north, the line would have been drawn vertically upwards). From the lower end of this short line, we draw a horizontal line towards ON.

Let it intersect the original circle radius R at I′. Then it can be seen that H = $N\hat{O}I'$ represents the hour angle corresponding to the zenith distance, z = $N\hat{O}I$, as it satisfies the relation.

$$\mathrm{R} \cos \mathrm{H} = \mathrm{R} \cos \mathrm{z}/(\cos \phi \cos \delta) + \mathrm{R} \tan \phi \mid \tan \delta \mid . \tag{12}$$

We made our observations on 25 October 2016 at Chennai with latitude of 13.08°, and longitude of 80.27°. As the equation of time on that day was 15.54 minutes (Equation of time table 2016), and the Indian Standard Time (IST) cor-responds to a longitude of 82.5°, we have to add 15.54 – (82.5 –

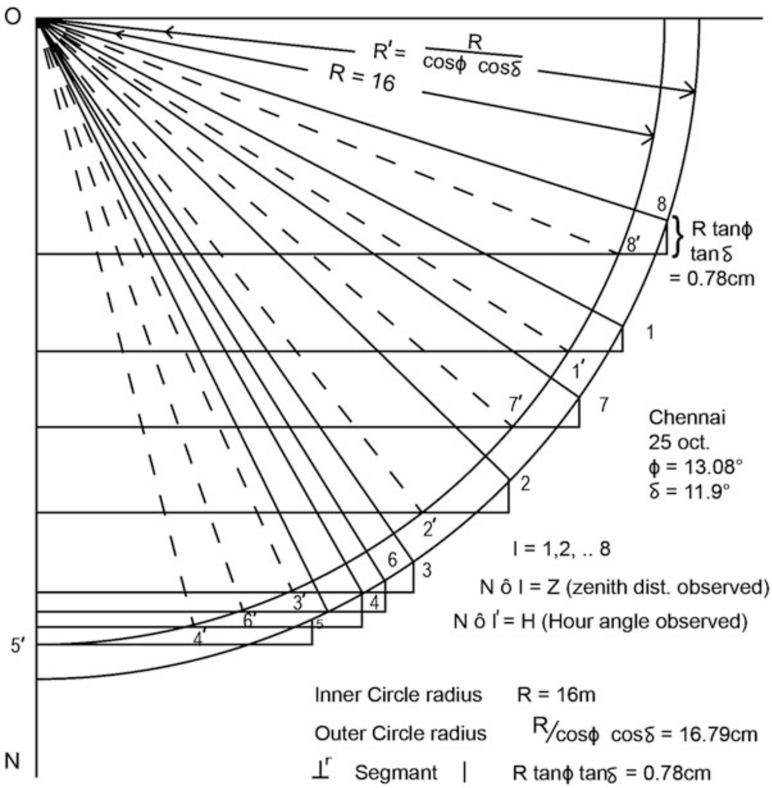

Fig. 10 Our worksheet for finding the hour angle, H, from the zenith distance, z

80.27) × 4 = 6.62 minutes to IST in minutes to obtain the hour angle of the true Sun, H_{tr} in Chennai on that day. We report our data on the zenith distance, z, and the hour angle, H, calculated from z, using Bhaskara's method, and compare this with the actual value of the hour angle of the true Sun, H_{tr}, in Table 2. We note that the error ranges from 0° to 5°.

The best fit for the data is presented in Fig. 11, where we plot the measured hour angle of the Sun against the observed (calculated) hour angle. This does not indicate high accuracy, but at least indicates that we are on the right track!

Considering the very rough nature of the device that we used, there is scope for improvement. Also, there should be a way of measuring the hour angle directly from the board itself, without having to determine the hour angle using a later reconstruction.

Table 2 Observations of the hour angle and zenith distance of the Sun, made from Chennai on 25 October 2016, using Bhaskara's method

No.	IST	IST (minutes before noon)	True Sun Time (before noon)	Hour Angle of the True Sun, $\|H_{tr}\|$ (°)	X,Y Coordinates (cm)	Zenith Distance, z measured (°)	Hour Angle, $\|H\|$ measured (°)	Error, $\|H_{tr}\| - \|H\|$ (°)
1	08:20	−220	−213.38	53.35	18,2, 9.25	63.07	58.39	−5.04
2	09:35	−145	−138.38	34.6	7.7, 7.45	45.95	38.87	−4.27
3	10:29	−91	−84.38	21.1	5.2, 7.45	24.51	21.1	0
4	11:02	−58	−51.38	16.72	4.3, 7.45	16.72	12.85	3.87
5	11:53	−7	−0.38	0.1	3.5, 7.45	25.02	1.28	−1.18
6	13:07	67	73.62	18.41	3.2, 5	32.62	21.11	−2.7
7	15:18	198	204.62	51.15	9.25, 6.05	56.81	51.44	−0.29
8	16:30	270	276.62	69.16	15.0, 5.15	72.11	68.2	0.96

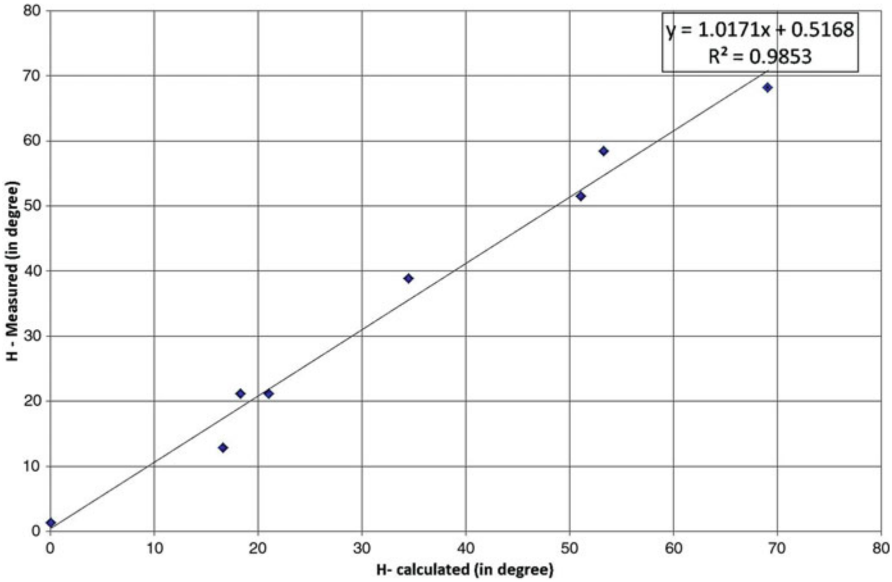

Fig. 11 A plot of the measured hour angle (from the *phalakayantra*) against the calculated (actual) value, and the best fit for the data

4 Conclusion

In this paper, we have reported our preliminary studies on the use of simple gnomons for fixing the cardinal directions, and for the measurement of the declination of the Sun, and also the measurement of the hour angle of the Sun using a board instrument. These were based on the descriptions of these devices and the procedure for observations in some Indian texts. A wide variety of instruments has been described in the texts, most of them for observations, but some for demonstration purposes. The preliminary results of this work, demonstrated the feasibility and viability of the instruments considered. In the case of the gnomons, the results have acceptable precision and accuracy, quantitatively. In the case of the board instrument, the measured results showed qualitative agreement with the actual ones. Admittedly, our study has been limited, and there is scope for more detailed studies of this nature.

Acknowledgements MSS is grateful to A.V. Ramani of Bengaluru for helping with the design of the 'plumb-line gnomon', and taking measurements with it. SV acknowledges the generous support (including but not limited to funding) from Amrita Vishwa Vidyapeetham (Amrita University), Coimbatore, in carrying out this work, and travel support for collaboration. He also acknowledges the support of Bharat K Sharma, Nandakumar, Iyappan and Yashmita of Amrita University who helped with the instrumentation and measurements. The support of Aditya of Coimbatore towards computer design of the charts and image processing is duly acknowledged.

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A Quantitative Study of Accuracies in Positions of Star Markers on Historical Astrolabes

Nandivada Rathnasree, Patrick Das Gupta, and Anurag Garg

Abstract The relative accuracies of the positions of star markers on the retes of some historical astrolabes, studied using images of these retes, is presented. These images are superposed on planetarium software sky views with fisheye stereographic projections. Almost all astrolabes studied, other than a modern electronic one, do show some inaccuracies in the positions of star markers on the retes. This would likely arise from their small sizes, the complications of metalwork involved and transfer of technology to artisans. Two historical astrolabes, presumably from Jai Singh's Jaipur karkhana for astrolabes, are studied for depiction of the accuracies in star markers. The analysis can be extended to tympans for studying historical astrolabe functional accuracies. The method can be utilised for studies of any historical instrument which has laminar structure, and which may currently be too fragile for actual handling and quantitative measurement of any kind.

1 Introduction

The rete of an astrolabe is one of the most aesthetic representations of aspects of the celestial sky. Loving attention to detail, and addition of decorative motifs, while sticking to the overall mathematical framework of stereographic projections of the sky, seems to have been the hallmark of many medieval astrolabes. The rete of an astrolabe consists of a stereographic projection on a two dimensional disk, of a few selected star markers, and the ecliptic as an offset circle.

Figure 1 shows the rete of an astrolabe (catalogue number 52478 in the collection at the Museum of History of Science, University of Oxford). Astrolabe 52,478 shown here, is marked as eighteenth century, India, in the Museum catalogue. It is thought to be from Jaipur, based on similarities in features with other Jaipur

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Fig. 1 The rete of Astrolabe 52,478 in the collection of the Museum of History of Science, University of Oxford (http://www.mhs.ox.ac.uk/astrolabe/)

astrolabes and from the fact that it has one single latitude plate for 27° (the latitude of Jaipur). This astrolabe is also thought to be unfinished, as several scales and lines have not been marked on it.

The rete is listed as having 27 stars, and the mediations and declinations of the stars inferred from the rete are listed in the catalogue. Several stars are identified and listed. Six stars on the rete are not identified and of these, two of the star pointers on the rete are not named. Some of the star names engraved on the rete are abbreviations.

Of the four unidentified named stars, Marichi, is a reasonably well-identified star amongst Indian star names. It is usually identified with Alkaid in Ursa Major. The earliest reference with this identification to be inferred from the description, is in the sixth century AD *Brihat Samhita* of Varāhamihira.

The remaining unidentified stars on this rete are Na. Pra., Aswamu and Aa. Na. These do not seem to be mentioned in any literature on Sanskrit astrolabes from India.

A rete from another astrolabe in the same museum collection, also presumably from Jaipur, is shown in Fig. 2. This astrolabe is marked as late eighteenth century/early nineteenth century in the catalogue, and has a single plate for a latitude of 27°. This is the largest astrolabe in the Oxford Museum of the History of Science collection.

Of the 38 star markers on the rete of this astrolabe, the Oxford website for this astrolabe has identified 25 stars with modern names. There are three star markers with no name. Of the other 10 unidentified named stars on the website, seven stars have identifications commonly made: Matsyodarpad = Almaak (γ And), Aslesha = Acubens (α Cnc), Pulah = Merak, Hasta = Algorab, Vasishtha = Mizar, Marichi = Alkaid and Shatabhish = Hudoor (λ Aqr) (Sarma, 1999; 2012; Pai and Shylaja, 2016). This leaves three unidentified named stars on this rete: ntkalishir, sarpadharishir, and aswamush.

In the present work, these two images of retes of historical astrolabes have been used to study the accuracies of the positions of the star markers using a graphical method wherein the images are imported and placed appropriately into planetarium software. With this procedure it becomes possible to identify those unidentified stars on historical astrolabes, and also make a quantitative assessment of overall

Fig. 2 Rete of the Astrolabe (Catalogue number 30402) from the Astrolabe collection of the Museum of History of Science, University of Oxford

accuracies in the placing of the star markers. The details of this process and the outcome are discussed in Sect. 3.

2 Astrolabe Accuracies

In his fifteenth century *Disputationes Adversus Astrologium Divinatricem* Pico Della Mirandola laments about 2 min of difference obtained with two astrolabes of the same size, when the Sun's altitude was measured (North, 1989). It is interesting that such small differences in time were of concern in the fifteenth century.

However, **quantitative** studies of accuracies in the construction of astrolabes are not extensive. Some studies have been undertaken to look at geometrical accuracies in marking the scales on some historical astrolabes (see Chapman 1986; Lamprey 2006).

The most detailed work which reflects on the accuracy with which star markers are placed on the retes of historical astrolabes is by Torode (1992). He undertook a study of 170 astrolabe retes to determine their precessional dates and thereby also arrive at an idea of relative accuracies of star marker positions. In Torode's study, some actual astrolabes and retes were utilised, while photographs were used in other cases.

In Torode's work, the star names were not utilised in any way. The positions of star markers were measured in equatorial co-ordinates, converted to ecliptical co-ordinates and the precession age was derived through a least square fit. Torode has discussed extensively the possible reasons for the difficulties encountered in making quantitative comparisons of rete star positions arising from construction issues related to historical astrolabes: the bluntness of the ends of the star pointers, possible deformities with age, and so on.

3 Image Overlays with Planetarium Software

In the current study, rete images from the Oxford collection (http://www.mhs.ox.ac.uk/astrolabe/), have been used. The rete image was transformed through fisheye stereographic projection using Weinhaus' (http://fmwconcepts.com/) 'fisheye' routine in Imagemagick image processing software. The fisheye-transformed image was then imported into the planetarium software Digitalsky that was being used with the Skyskan projection system installed at the Nehru Planetarium, Nehru Memorial Museum and Library, New Delhi. The rete image was then overlaid onto the sky generated by Digitalsky, using the appropriate stretching defined by the stereographic projection.

This required that the center of the rete image was placed at the North Celestial Pole in the software. Equatorial co-ordinates were used to define the position of the rete image, and its extent defined by its outer circle was stretched to meet the Tropic of Capricorn. A rotation in RA for the rete image sometimes was required following this, to make the planetarium software ecliptic parallel to the offset ecliptic circle on the rete image. These two would coincide exactly if everything was correct—both in our procedure, as well as in the initial construction of the rete itself.

What we found was that the two do coincide for a modern electronic astrolabe designed for a latitude of 52° (Ford, 2012), showing that our procedure was correct. However, there were minute displacements for some stars, even with the electronic rete image (see Fig. 3), which may arise from differences in fisheye projection algorithms being used for the two processes: (1) fisheye projection for the sky map being done through the Digitalsky software of Skyskan, and (2) fisheye projection being done for the rete image through Fred Weinhaus' Imagemagick. This minute discrepancy is under investigation and the authors have requested the original

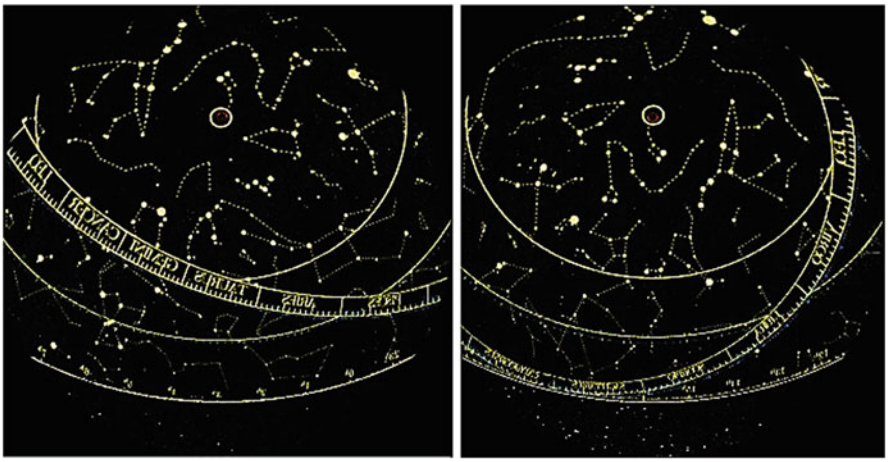


Fig. 3 A comparison of Digital sky star positions (left) with those of the rete of a modern electronic astrolabe (right) with all naked eye stars marked. The astrolabe was made for latitude of 52°, and its star positions are marked by yellow disks. The Digitalsky (Skyskan) stars are white dots

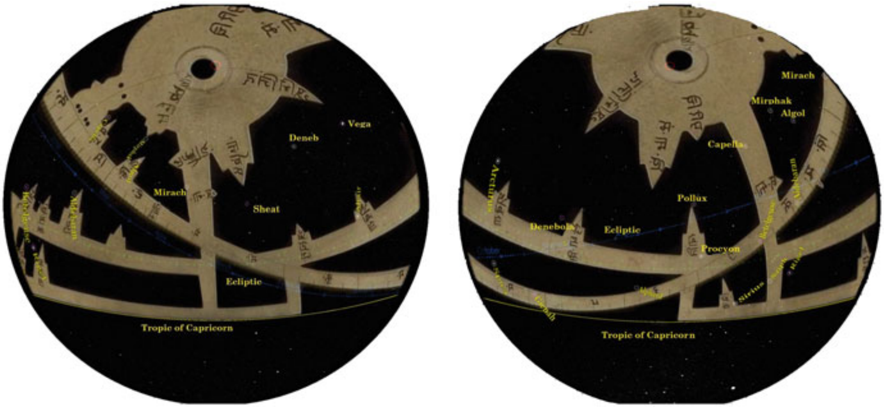


Fig. 4 Planetarium software and rete overlay for astrolabe 53,478. The rete image was mirror inverted to give the same sense of direction as the Digitalsky planetarium software. The Tropic of Capricorn, Equator and Ecliptic from the planetarium software are labelled

sources of the software for the detailed algorithms. However, this should not affect the conclusions reached in this work, as the magnitude of this discrepancy was so much smaller than all the other errors under investigation.

Carrying on this superposition exercise for Astrolabe 53,478, we get Fig. 4.

Identification of stars became very easy through this method, even if their coordinates were considerably in error. Most of the literature that looks at Indian star names concentrates on the names of the 27/28 nakshatras and their identifications, and very little is systematised relating to Indian names of stars that are not a part of these groups. Sanskrit astrolabes allow a reasonably accurate identification of these stars with modern ones. To a large extent, this identification is already done for the two Sanskrit astrolabes shown on the Oxford website, and they become a rich resource for identifying relatively less-known Indian star names. There are a few stars unidentified on the Oxford site and these unidentified stars as well as unnamed stars on the retes of historical astrolabes can be identified by our graphical method that is described here.

Applying the procedure to the rete of astrolabe 30,402 produces the results shown in Fig. 5.

The identification of the rete stars of astrolabes 53,478 and 30,402 with modern names and their declinations as discerned from the rete star marker positions in the Oxford web site are listed in Tables 1 and 2 respectively. In the last column, the identifications obtained through the graphical planetarium software overlay procedure are commented on, and remarks about the accuracy of the star pointer positions are also included.

With our graphical analysis of this rete it has been possible to name the unidentified stars na. pra., aswamu and a. na. as Hamal (α Ari), Enif (ε Peg) and Alpheratz (α And), respectively. The declination values as inferred on the Oxford

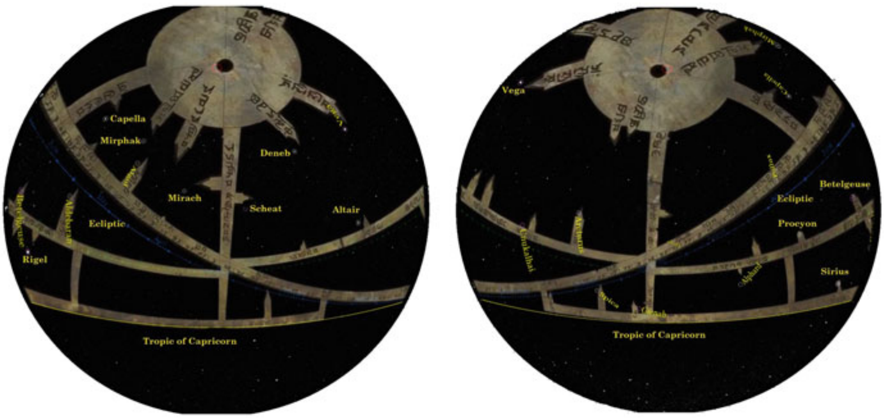


Fig. 5 Planetarium software and rete overlay for astrolabe 30,402. The rete image was mirror inverted to give the same sense of direction as the Digitalsky planetarium software. The Tropic of Cancer, Equator and Ecliptic from the planetarium software are labelled

site from the star marker positions on the rete are in reasonable agreement with those of the identified stars, precessed to AD 1750, particularly for Hamal and Enif.

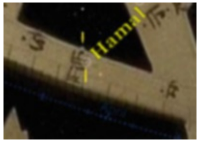
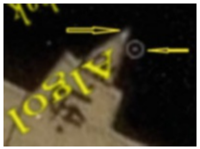
Two unnamed stars are identified as Menkar (α Cet) and Prajapati (δ Aur). Their positions are somewhat in error with respect to the corresponding co-ordinates. However, there are no other reasonably bright stars in that vicinity. The star marker near the position of Menkar could be for μ Ceti, which would fit the position better, but, whose magnitude is 4.25. Mekalinan agrees better with respect to the declination, even though it is a little off from the star marker position.

Identifications of unidentified stars on the rete of astrolabe 30,402, and our graphical analysis, are discussed in Table 3.

4 Conclusion

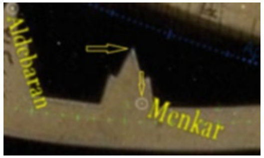
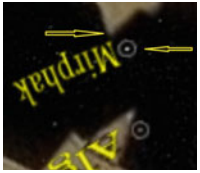
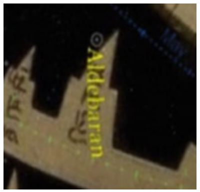
The graphical method utilised in this work, to analyse accuracies in the positions of star markers on the astrolabe rete images, has considerable utility in identifying star markers on retes which have not been identified through other procedures. In particular, if the original depiction of a star marker is in error, graphical depiction procedures may allow identifications that would otherwise not be possible through mathematical-fitting techniques. The two astrolabes studied in this paper may be from the Jaipur astrolabe karkhana built by Sawai Jai Singh. Many of the star markers on the retes of these two astrolabes are in reasonably accurate positions.

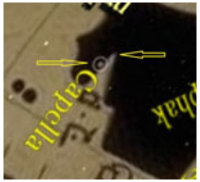
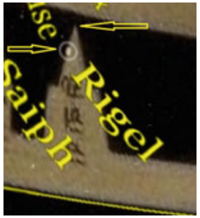
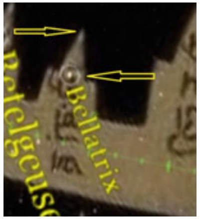
Table 1 Stars on the rete of astrolabe 52,478

Star Name on Rete (corrected/expanded where necessary)	Modern Star Name as identified on the Oxford Site	Identification indicated with the graphical procedure outlined in this paper/Comments	Declination read from the Rete as Quoted on the Oxford Site (Ephemeris Declination of the corresponding star precessed to 1750 AD)	Remarks
न. प्र.	Not identified	Hamal (α Ari) 	23° (22° 15′ 14.3″)	Hamal not usually mentioned in Indian star names in literature.
मत्स्योदरपाद	Mirach	Mirach (β And) 	41° (34° 16′ 46″)	Position considerably in error on the rete.
प्रेतशिर	Algol	Algol (β Per) 	41° (39° 58′ 16″)	Relatively accurate position on the rete.

(continued)

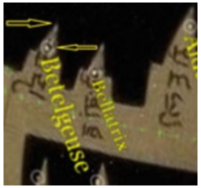
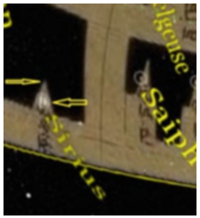
Table 1 (continued)

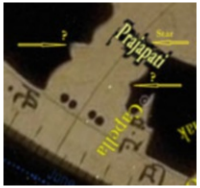
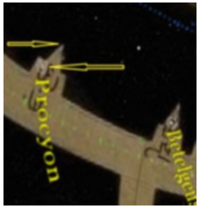
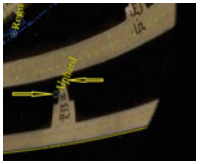
Star Name on Rete (corrected/expanded where necessary)	Modern Star Name as identified on the Oxford Site	Identification indicated with the graphical procedure outlined in this paper/Comments	Declination read from the Rete as Quoted on the Oxford Site (Ephemeris Declination of the corresponding star precessed to 1750 AD)	Remarks
[no name]	Not identified	Menkar (α Cet) 	10° (3° 5′ 12.3″) (For μ Ceti 9° 2′ 25.1″)	The much fainter μ Ceti would better fit the location.
मनुष्यपार्श्[	Mirfak	Mirfak (α Per) 	49° (48° 56′ 41.6″	Position relatively accurate.
(रोहिणी)	Aldebaran	Aldebaran (α Tau) 	17° (15° 58′ 9.6″)	

प्र.हृ. (ब्रह्म हृदय)	Capella	Capella (α Aur) 	48° (45° 40′ 53.9″)	
मि. व. प. (मिथुन बा पाद)	Rigel	Rigel (β Ori) 	−8° (−8° 30′ 42.5″)	
मि. व. हृ.	Bellatrix	Bellatrix (γ Ori) 	8° (6° 5′ 54.3″)	

(continued)

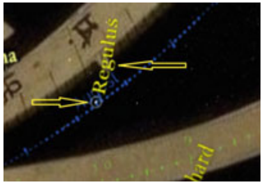
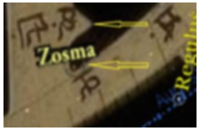
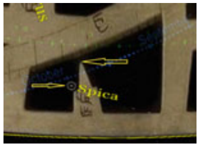
Table 1 (continued)

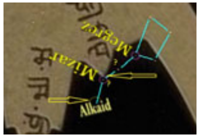
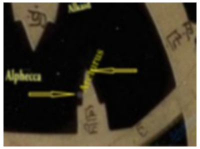
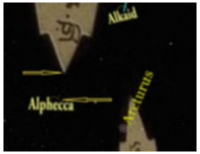
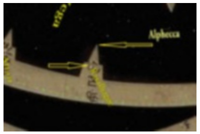
Star Name on Rete (corrected/expanded where necessary)	Modern Star Name as identified on the Oxford Site	Identification indicated with the graphical procedure outlined in this paper/Comments	Declination read from the Rete as Quoted on the Oxford Site (Ephemeris Declination of the corresponding star precessed to 1750 AD)	Remarks
मि. द. प. (मिथुन द पाद)	Saiph	Saiph (κ Ori) 	−9° (−9° 46′ 47.8″)	
आर्द्र	Betelgeuse	Betelgeuse (α Ori) 	8° (7° 20′ 11.9″)	
लुब्धक	Sirius	Sirius (α C.Ma.) 	−16° (−16° 28′ 36.7″)	

No Name	Not identified	Prajapati (δ Aur) 	45° (54° 13′ 9.8″)	Position of Prajapati is considerably in error, however, there is no other reasonably bright star in this vicinity.
लू. व्. (लुब्धक बंधु)	Procyon	Procyon (α C.Mi.) 	7° (5° 46′ 22.3″)	
महा. पु. (महा पुरुष)	Alphard	Alphard (α Hyd) 	−8° −7° 35′ 9.7″)	Reasonably accurate.

(continued)

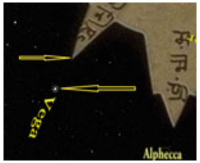
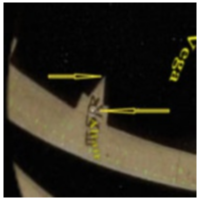
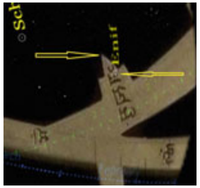
Table 1 (continued)

Star Name on Rete (corrected/expanded where necessary)	Modern Star Name as identified on the Oxford Site	Identification indicated with the graphical procedure outlined in this paper/Comments	Declination read from the Rete as Quoted on the Oxford Site (Ephemeris Declination of the corresponding star precessed to 1750 AD)	Remarks
म. (मघ)	Regulus	Regulus (α Leo)  	12° (13° 12′ 26.7″)	
पु. फ. (पूर्व फाल्गुनी)	Zosma	Zosma (δ Leo)  	22° (21° 52′ 48.3″)	Reasonably accurate.
चित्रा	Spica	Spica (α Vir)  	−9° (−9° 50′ 58.7″)	

मरीचि	Not identified	Alkaid (η UMa) 	49° (50° 34′ 8.1″)	Closer to the position of Vashistha, however, as it is labelled Marichi, this will be an error in the positioning by the star marker.
स्वाति	Arcturus	Arcturus (α Boo) 	21° (20° 21′ 27.3″)	
वि. माँ. मं.	Alphecca	Alphecca (α CBor) 	26° (27° 33′ 55.6″)	Position considerably in error.
सु. ध. शि.	Rasalhague	Rasalhague (α Oph) 	14° (12° 44′ 49.1″)	

(continued)

Table 1 (continued)

Star Name on Rete (corrected/expanded where necessary)	Modern Star Name as identified on the Oxford Site	Identification indicated with the graphical procedure outlined in this paper/Comments	Declination read from the Rete as Quoted on the Oxford Site (Ephemeris Declination of the corresponding star precessed to 1750 AD)	Remarks
अभिजीत	Vega	Vega (α Lyr) 	38° (38° 35′ 7.3″)	
श्रवण	Altair	Altair (α Aquila) 	10° (8° 15′ 12.1″)	
अष्वमु	Not identified	Enif (ε Peg) 	9° (8° 44′ 27.3″)	Reasonably accurate position.

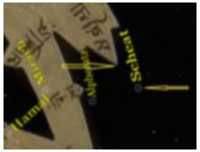
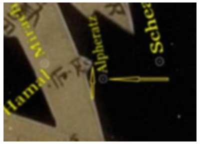
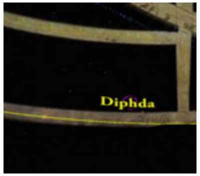
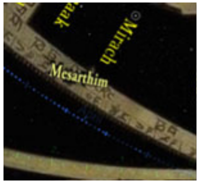
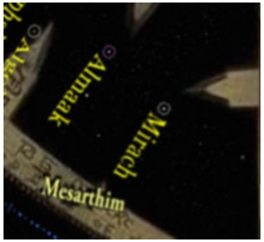
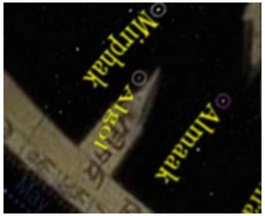
पूर्वाभा. (पूर्वा भाद्रपद)	Scheat	Scheat (β Peg) 	30° (26° 44′ 27.7″)	Position considerably in error.
अ. न.	Not Identified	Alpheratz (α And) 	29° (27° 41′ 55.6″)	Although position is somewhat in error, it is similar for some stars in this vicinity, on the rete.

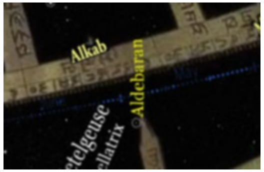
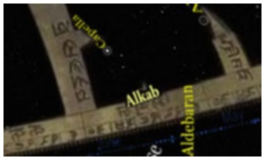
Table 2 Stars on the rete of astrolabe 30,402

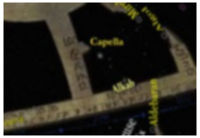
Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
No Name	Not identified	Caph (β Cas) 	57° (57° 55′ 27.7″)	
समदरपकष	Deneb Kaitos Shemali	Diphda (β Cet) 	−20° (−19° 11′ 42″)	
मत्स्योदर	Mirach	Mirach (β And) 	35° (34° 26′ 30.9″)	

अश्विनी	Mesarthim	Mesarthim (γ Ari) 	19° (18° 12′ 2.5″)	
मत्स्योदरपाद	Not identified	Almaak (γ And) 	40° (41° 15′ 39.3″)	
प्रेतशिर	Algol	Algol (β Per) 	39° (40° 5′ 34.7″)	

(continued)

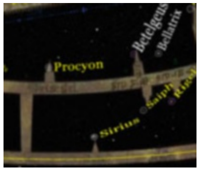
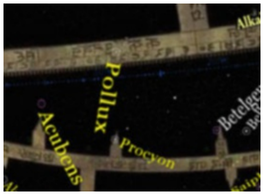
Table 2 (continued)

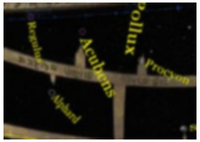
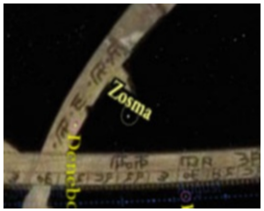
Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
मनुष्यपार्श्व	Mirfak	Mirfak (α Per) 	49° (49° 3′ 33″)	
रोहिणी	Aldebaran	Aldebaran (α Tau) 	16° (16° 2′ 18.3″)	
[no name]	Not identified	Alkab (ι Aur) 	34° (32° 47′ 48.2″)	

मिथुन ब पाद	Rigel	Rigel (β Ori) 	$-8°$ ($-8° 28' 14.9''$)	
ब्रह्महृदय	Capella	Capella (α Aur) 	$46°$ ($45° 43' 31.3''$)	
मिथुन द पाद	Saiph	Saiph (κ Ori) 	$-9°$ ($-9° 45' 46.4''$)	
आर्द्र	Betelgeuse	Betelgeuse (α Ori) 	$7°$ ($7° 20' 57.9''$)	

(continued)

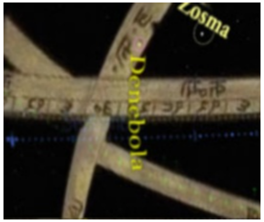
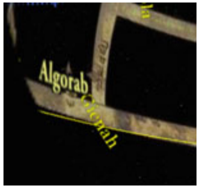
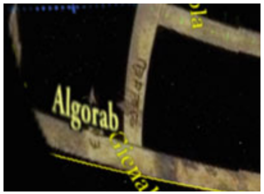
Table 2 (continued)

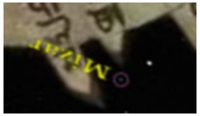
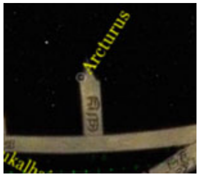
Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
लुब्धक	Sirius	Sirius (α CMa) 	−17° (−16° 30′ 7.4″)	
लुब्धाकबंधु	Procyon	Procyon (α CMi) 	6° (5° 42′ 39.6″)	
पुनर्वसु	Pollux	Pollux (β Gem) 	28° (28° 32′ 12.4″)	

अश्लेषा	Not identified	Acubens (α Cnc) 	7° (12° 41′ 43.2″)	ε Hydrae would be a better fit to the position.
महापुरुष	Alphard	Alphard (α Hyd) 	−8° (−7° 42′ 44.4″)	
पुलह	Not identified	Merak (β UMa) 	57° (57° 33′ 33.3″)	
पु. फ.	Zosma	Zosma (δ Leo) 	22° (21° 43′ 5.5″)	

(continued)

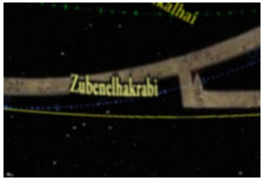
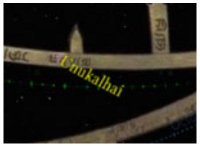
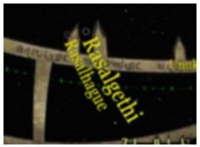
Table 2 (continued)

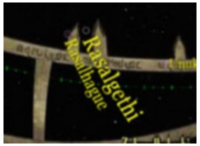
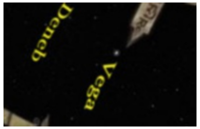
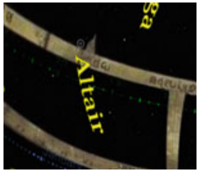
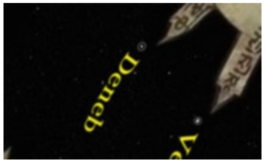
Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
उ फ	Denebola	Denebola (β Leo) 	17° (15° 47′ 39.8″)	
काकपक्षी	Gienah	Gienah (γ Cor) 	−16° (−16° 19′ 3.2″)	
हस्त	Not identified	Algorab (δ Cor) 	−15° (−15° 17′ 48″)	

चित्रा	Spica	Spica (α Vir) 	−8° (−10° 0′ 30.9″)	
वशिष्ठ	Not identified	Mizar (ζ UMa) 	55° (56° 4′ 40.3″)	
[no name]	Not identified	Not identified		
मरीचि	Not identified	Alkaid (η UMa) 	51° (50° 25′ 0.3″)	
स्वाति	Arcturus	Arcturus (α Boo) 	21° (20° 12′ 51.9″)	

(continued)

Table 2 (continued)

Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
विशाख	Zubenelhakrabi	Zubenelhakrabi (γ Lib) 	$-15°$ ($-13° 42' 27.4''$)	
सर्पग्रिवा	Unukalhai	Unukalhai (α Ser) 	$12°$ ($7° 8' 0.7''$)	
न तकालिशिर	Not identified	Rasalgethi (α Her) 	$15°$ ($14° 39' 26.9''$)	

सर्पधारिषिर	Not identified	Rasalhague (α Oph) 	13° (12° 43′ 14.1″)	
अभिजीत	Vega	Vega (α Lyr) 	39° (38° 36′ 23.5″)	
श्रवण	Altair	Altair (α Aquila) 	8° (8° 19′ 26.2″)	
कुकुटपुछ	Deneb	Deneb (α Cyg) 	45° (44° 30′ 7.2″)	

(continued)

Table 2 (continued)

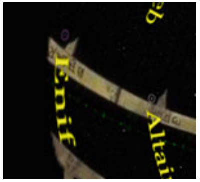
Star name on Rete	Modern star name as identified on the Oxford site	Identification indicated with the graphical procedure outlined in this paper	Declination read from the rete as quoted on the Oxford site (Ephemeris Declination of the corresponding star precessed to 1780 AD)	Remarks on accuracy and other aspects
अश्वमुष	Not identified	Enif (ε Pegasi) 	8° (8° 52′ 29.3″)	
शतभिष	Not identified	Hudoor (λ Aqu) 	−10° (−8° 44′ 35.8″)	
पूर्वा भाद्रपद	Scheat	Scheat (β Peg) 	27^0 (26° 54′ 4″)	

Table 3 Star identifications on rete 30,402

Star as named on the Rete	Identification from current analysis	Remarks
No Name	Caph (β Cas)	The declination agrees reasonably well. On the rete, the star marker is a very small projection.
मतसयदरपद *Matsyodarpad*	Almaak (γ And)	There is an error of 1° in the position of the identified star. Upsilon Andromedae, a 4.09 magnitude star, would be a better fit as far as the location of the star marker is concerned.
अशलष *Aslesha*	ε Hydrae is a better fit than Acubens (α Cnc)	Both of these identifications are also discussed by Pai and Shylaja (2016).
पलह *Pulah*	Merak (β Uma)	Commonly identified with this star in the literature.
हसत *Hasta*	Algorab (δ Cor)	Agrees reasonably well. The identification is also discussed by Pai and Shylaja (2016).
वशषठ *Vasisth*	Mizar (ζ UMa)	Commonly identified with this star in the literature.
मरच Marichi	Alkaid (η UMa)	Commonly identified with this star in the literature.
न तकलशर *ntkalishir*	Rasalgethi (α Her)	The declination agrees reasonably well. Our paper provides the only know identification of this Indian star name.
सरपधरशर Sarpadharishir	Rasalhague (α Oph)	The declination agrees reasonably well. Our paper provides the only know identification of this Indian star name.
अशवमष Ashwamush	Enif (ε Pegasi)	Our paper provides the only know identification of this Indian star name.
शतभष Shatabhish	Hudoor (λ Aqu)	This identification is also discussed by Pai and Shylaja (2016).

Many of the Indian star names in Devnagari script on these astrolabe retes do not appear in the literature relating to Indian star names, and our study has provided the first identifications, and modern star names, for these.

Our study will later be extended to the tympans of these astrolabes, which contain the markings for positional astronomy measurements. Other astrolabe images are also under study to extend this analysis for sets of astrolabes from specific locations, in order to arrive at a conclusion relating to accuracies achieved of the depictions.

Acknowledgements We are grateful to the Oxford Museum of History of Science for making a rich library of astrolabe images available for researchers; to Skyskan for the planetarium software Digitalsky; to Image-magick (http://imagemagick.org/); and to Fred Weinhause for providing software used in our analysis.

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The First Astronomical Use of the Telescope in India

R. C. Kapoor

Abstract For astronomical observations, a telescopic device was used in India, within a decade of its invention. The year was 1618 but what astronomical objects were observed? That is connected with the tale of two great comets of November 1618.

1 The Bright Comets of 1618

The year 1618 was a unique one in that it presented three Great Comets within a short span of 3 months. It also saw the novel use of the telescope for observations of all three Great Comets. In order of occurrence, the comets were:

- 1618 I (C/1618 Q1; perihelion August 17.627 UT),
- 1618 III (C/1618 V1; October 27.9) and
- 1618 II (C/1618 W1; November 8.851).

All the comets were naked eye objects, with long tails and motion direct, and they were noticed after their perihelion passages. The last two comets were sighted in November, within a short span of time, in the same region of the sky, and they were visible together for several successive days.

These comets belong to the era when Galileo's telescopic observations had just created a paradigm shift in our perception of the heavens and Johannes Kepler was busy introducing a fundamental change in mathematical astronomy by redefining the orbits of planets around the Sun. With three sightings in quick succession, these comets were a sensation in European astronomical circles. They even drew Galileo Galilei (1564–1642) into a controversy with the Jesuit mathematician Father Horatio Grassi (1583–1654) over the nature of comets. Grassi stressed that these apparitions were against the Copernican worldview. These comets also generated grave concern among the general population, and left an indelible imprint on many minds.

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Comet 1618 I (C/1618 Q1) was discovered at Caschau in Hungary on 25 August in the morning skies at magnitude 2–3, and then independently by Johannes Kepler (1571–1630) at Linz on 27 August. This holds the distinction of being the first comet ever to be observed with a telescope—by Kepler—on 6 September.

Comet 1618 II (C/1618 W1) was probably first seen on 23 or 24 November by Garcia de Silva y Figueroa (1550–1624) from Isfahan in Persia, toward the east as a diffuse form and having the same colour as Venus. Garcia de Silva was the Ambassador of Philip III, the King of Spain and Portugal, to the court of the renowned ruler Shāh Abbās (1571–1629).

There is some confusion about the date when this comet was first sighted. Actually, the earliest to record it were the Chinese who found the comet in Libra on 25.9 November (Kronk, 1999: 338–341). Father Johann Cysatus (1587–1657), then at Ingolstadt, was the first to use a telescope and detect structure in a comet's head—a nucleus, a nebulous envelope (coma) around the nucleus, and a relatively fainter appearance—the halo—around that. He noted that the comet followed a path that began to deviate from a stipulated straight line, commenting that "This curvature (of the orbit) would be a phenomenon of great importance, if it could be confirmed by more observations." (Schreiber, 1904:100).

Comet 1618 III (C/1618 V1) was spotted earlier than 1618 II, on 11.04 November, by Garcia de Silva y Figueroa from Isfahan in Iran. It was in the south-eastern sky and had a tail ~60° long.

For detailed account of these three comets, see Kronk (1999), Vsekhsvyatskii (1964) and Williams (1871).

2 The Comets of November 1618

The last two Great Comets of 1618 were observed from India too.

The Emperor Jahāngīr (1569–1627, Fig. 1) recorded these comets appearing in succession during a Royal journey from Dohad (Dahod) in Gujarat to Agra, the capital of the Mughal Empire, via Ujjain, in the year 1027 A.H. (1618 CE).

At around the same time, these comets were observed by a number of Jesuit missionary-astronomers what at that time were based in India. Father Wenceslaus Kirwitzer (1588–1626) observed the Comet 1618 III from Goa, and was joined by brother Jesuits in Goa and in Cochin. In quick succession they then observed the second Great Comet of November 1618.

The observations of two of the three Great Comets of 1618 from India in November turned into a unique occasion when the same targets of opportunity were followed independently by astronomers from two very different cultures, and their observations were recorded quantitatively.

Fig. 1 Nūr ud-Dīn Jahāngīr (1569–1627) (Wikimedia Commons)

3 Jahāngīr, The Naturalist

Jahāngīr, the fourth Mughal Emperor of India (r. 1605–1627) was a great naturalist and a gifted author. Apart from ornithology, biology and lexicography, he had an interest in astronomy and maintained records of his observations in his journal *Tūzūk-i Jahāngīrī*. In the other Memoir he wrote, the *Wāki'āt-i Jahāngīrī*, we find very similar descriptions. In these Memoirs, we find descriptions of a few natural phenomena that he observed. In the *Tūzūk-i Jahangīrī* he writes about the fall of a meteorite in a village in the Jalandhar district in Punjab in his 16th regnal year (i.e., 19 April 1621 Greg); a few solar and lunar eclipses; and two bright comets that he observed. Jahāngīr's Memoirs clearly demonstrate his interest in astronomy and the level of accuracy he reached with his observations. We find the recorded information in excellent agreement with modern computations. For their observations, Jahāngīr's astronomers used astrolabes, accurate water-driven clocks (clepsydras), sundials and sandglasses (e.g. see Fig. 2).

Fig. 2 An astrologer and his equipment; margin drawing from the folio of Jahāngīr's Album depicting an astrologer surrounded by his equipment—an astrolabe, zodiac tables and an hour glass. (Courtesy: Werner Forman Archive/ Naprestek Museum, Prague)

3.1 Jahāngīr's Observations of the Comets

The following passage from Jahāngīr's Memoirs, *Tūzūk-i Jahāngīrī*, pertains to the account of the 13th year of his reign, i.e., 1027 A.H. (Rogers and Beveridge 1909, 1914):

> On Saturday the 18th (Aban), the camp was at Ramgarh. For some nights before this there appeared, at three gharis before sunrise, in the atmosphere, a luminous vapour in the shape of a pillar. At each succeeding night it rose a ghari earlier. When it assumed its full form, it took the shape of a spear, thin at two ends, and thick in the middle. It was curved like a sickle, and had its back to the south, and its face to the north. It now showed itself a watch (pahar) before sunrise. Astronomers took its shape and size by the astrolabe, and ascertained that with differences of appearance it extended over twenty-four degrees. It moved in high heaven, for it was first in Scorpio and afterwards in Libra. Its declination (harakat-i-arz) was mainly southerly.
>
> Sixteen nights after this phenomenon, a star showed itself in the same quarter. Its head was luminous and its tail was two or three yards long, but the tail was not luminous. It has now appeared for eight nights; when it disappears, the fact will be noticed, as well as the results of it.

The Persian and A.H. dates in the Memoirs help us follow the course of the Royal traverse from Ahmedabad to Agra, through Dohad and Ujjain. Some of the halts between Dohad and Ujjain, including Ramgarh where the first observation of the comet was made, are no longer readily identifiable.

We have looked into the District Census Handbooks of the Census of India 2011 released in 2015 by the Registrar General & Census Commissioner, India, of the districts of Dohad in the state of Gujarat and Jhabua, Dhar and Ujjain in western Madhya Pradesh. It was through these districts, spread roughly along a west-east corridor, which the Royal entourage would have passed. In the respective census listings there is a Ramgarh near Thandla (*Registrar General* …, 2015: 138; see Fig. 3).

In the Memoirs, the celestial positions of the comets are given zodiac-wise only, but the comet's ephemerides generated from its orbital elements can help us fix the dates of the first sightings. In the *Tūzuk-i-Jahangīri*, the first date of observation is

Fig. 3 An outline map of western part of India showing the approximate route of the royal entourage in relation to a few modern locations in the states of Gujarat and Madhya Pradesh that may have lain on or near the stipulated route (map: Ramesh Kapoor)

Saturday, 21 Dhu-al-Qa‘dah 1027 A.H. (the 18th of Ābān, 997, Saturday). The morning of this date corresponds to the morning of Saturday November 10, 1618 (Greg).

Jahāngīr's records bear testimony to him having a robust regime, equipped and with ability to carry out accurate astronomical observations. Some idea of the observational precision that Jahāngīr's astronomers could reach can be formed from just one instance. In the matter of the solar eclipse of 29 March 1615 that he observed from Agra, Jahāngīr wrote down the maximum eclipse magnitude attained as four out of five parts of the Sun (0.8) and that the eclipse lasted 8 gharis (3 h 12 min), both very close to the values derivable today. Sheikh Alāhādād's family in Lahore that flourished during the period 1570–1660 CE was highly acclaimed for producing high-precision astrolabes and other scientific equipment.

From Jahāngīr's records, it is clear that Comet 1618 III was first sighted on 10 November, around 00 UT and Comet 1618 II on the morning of 26 November, both post-perihelion. These dates make Jahāngīr an independent discoverer of both Great Comets.

3.2 The Comet Tales from Goa

In its astronomical column, the journal *Nature* (1878) carried in the 24 January 1878 issue a contribution by an unnamed author that stated that the Jesuit astronomer Giovanni Riccioli (1598–1671) had mentioned observations of the comets of 1618 made by a Jesuit astronomer named Kirwitzer from Goa in India. It may be noted that the Jesuits were in Goa from 1542, in order to spread the faith.

'Kirwitzer' was Father Wenzel Pantaleon Kirwitzer (ca. 1588–1626), a member of the Collegium Romanum belonging to the 'Society of Jesus'. Recall that many of the Jesuits of that era were mathematicians, geographers and astronomers, and they carried with them new developments in European science when they went on their missions to different parts of the world. As part of the group of missionaries led by Nicolas Trigault (1577–1628) destined for China that included Giacomo Rho

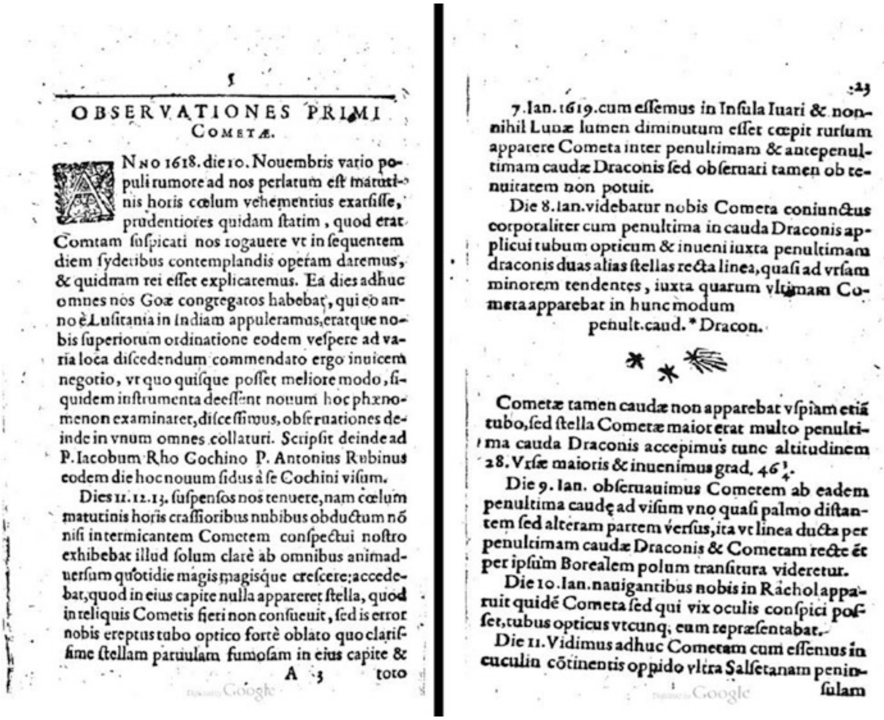

OBSERVATIONES
COMETARVM
ANNI 1616.
IN INDIA ORIENTALI FACTÆ A
Societatis IESV Mathematicis in Sinense Regnum
nauigantibus ex itinere eo delatis.
Ad eiusdem Societatis Mathematicos & alios amicos
Europaeos transmissa.
PER P. WENCESLAVM PANTA-
leonem Kirwitzer, eiusdem nauigatio-
nis Comitem.
VRSELLIS
Excudebat IOAN. THEOBALD. SCHÖN-
WETTER.
ANNO 1620.

Fig. 4 The cover page of Fr. Kirwitzer's treatise; digitized in 2014 by The Austrian National Library (after Google Books)

(1592–1638), Johannes Schreck-Terrentius (also Terrenz; 1576–1630) and Adam Schall von Bell (1592–1666), Father Kirwitzer set sail from Lisbon in April 1618 and braving the rigours of the voyage, sickness and the death of 5 of the 22 China missionaries, sailed into Goa on 4 October 1618. The group was carrying a few telescopes, some measuring instruments, and a large number of books.[1]

While he was in Goa waiting for the opportunity to proceed to China Father Kirwitzer took advantage of the unfamiliar skies over India to carry out some astronomical observations. Fortuitously, during his sojourn two Great Comets were visible in the morning skies in November 1618, one after the other, and Father Kirwitzer presented a detailed description of his observations of these spectacular objects in Latin in a monograph titled *Observationes Cometarvm Anni 1618. In India Orientali Factæ A Societatis Iesv Mathematicis in Sinense Regnum Nauigantibus ex itinere eo delatis*. Subsequently, it was published in Ursellis by Schönwetter in 1620 (see Fig. 4).

[1]Along with Terrenz and Adam Schall, Kirwitzer would subsequently proceed to China, leaving Goa on 15 May 1619 and reaching Macao on 22 July 1619. In 1621, Terrenz presented the Emperor with a telescope as a gift.



5

OBSERVATIONES PRIMI COMETÆ.

ANNO 1618. die 10. Nouembris vario populi rumore ad nos perlatum est matutinis horis cœlum vehementius exarsisse, prudentiores quidam statim, quod erat Comtam suspicati nos rogauere vt in sequentem diem sydetibus contemplandis operam daremus, & quidnam rei esset explicaremus. Ea dies adhuc omnes nos Goæ congregatos habebat, qui eo anno è Lusitania in Indiam appuleramus, eratque nobis superiorum ordinatione eodem vespere ad varia loca discedendum commendato ergo inuicem negotio, vt quo quisque posset meliore modo, siquidem instrumenta deessent nouum hoc phænomenon examinaret, discessimus, obseruationes deinde in vnum omnes collaturi. Scripsit deinde ad P. Iacobum Rho Cochino P. Antonius Rubinus eodem die hoc nouum sidus à se Cochini visum.

Dies 11. 12. 13. suspensos nos tenuere, nam cœlum matutinis horis crassioribus nubibus obductum nō nisi intermicantem Cometem conspectui nostro exhibebat illud solum claré ab omnibus animaduersum quotidie magis magisque crescere; accedebat, quod in eius capite nulla appareret stella, quod in reliquis Cometis fieri non consueuit, sed is error nobis ereptus tubo optico forté oblato quo clarissime stellam paruulam fumosam in eius capite &

A 3 toto

23

7. Ian. 1619. cum essemus in Insula Iuari & nonnihil Lunæ lumen diminutum esset cœpit rursum apparere Cometa inter penultimam & antepenultimam caudæ Draconis sed obseruari tamen ob tenuitatem non potuit.

Die 8. Ian. videbatur nobis Cometa coniunctus corporaliter cum penultima in cauda Draconis applicui tubum opticum & inueni iuxta penultimam draconis duas alias stellas recta linea, quasi ad vrsam minorem tendentes, iuxta quarum vltimam Cometa apparebat in hunc modum

penult. caud. * Dracon.

Cometæ tamen caudæ non apparebat vspiam etiā tubo, sed stella Cometæ maior erat multo penultima cauda Draconis accepimus tunc altitudinem 28. Vrsæ maioris & inuenimus grad. 46 $\frac{3}{4}$.

Die 9. Ian. obseruauimus Cometem ab eadem penultima caudę ad visum vno quasi palmo distantem sed alteram partem versus, ita vt linea ducta per penultimam caudæ Draconis & Cometam rectè et per ipsum Borealem polum transitura videretur.

Die 10. Ian. nauigantibus nobis in Rachol apparuit quidē Cometa sed qui vix oculis conspici posset, tubus opticus vtcunq; eum repræsentabat.

Die 11. Vidimus adhuc Cometam cum essemus in cuculin cōtinentis oppido vltra Salsetanam peninsulam

Fig. 5 The pages 5 and 23 from Father Kirwitzer's book of 1620 on his observations of the two Great Comets that appeared in November 1618. Both the pages mention the use of a telescope for viewing the comets (after Google Books)

3.3 *Father Kirwitzer's Treatise*

The treatise is short, consisting of 24 pages only and signed ex 'Goæ in India Orientali 11. Febr. 1619' (Kirwitzer, 1620). In the Preface he refers to being dispatched to India by Muzio Vitelleschi (1563–1645), the Sixth General of the Society of Jesus, to bring the light of the Gospel in the great Empire of the Chinese. The significance of Father Kirwitzer's treatise lies in the fact that it reports the first-ever modern astronomical observations carried out in India. Also, it records the first-ever use in India of an optical device for astronomical observations soon after the introduction of the astronomical telescope in Europe (Fig. 5).

3.4 *The* Tubo Optico *Reference*

His first recorded use of the telescope in India dates to 10 November when Father Kirwitzer said that many people from the locality approached to tell him of and seek explanation for a vehement flaring up in the morning sky. Father Kirwitzer suspected that it was a comet and told them he would explain the next day after watching it. He felt that to be examined, the new phenomenon needed instruments and joint efforts. The same day he wrote to Father Jacobus Rho, and to Father Antonius Rubinus at Cochin, 660 km south of Goa, about the new star that had been seen. However, their baggage was still on board the ship, so they had no access to astronomical instruments or books.

In his treatise, Father Kirwitzer refers to a few places where the Jesuits had made astronomical observations. One was Rachol, a town south of Panjim (now Panaji) and home to the Patriarchal Seminary of Rachol, since 1610, which was built by the Jesuits atop a small hillock and evolved into a multipurpose institution. Father Kirwitzer wrote that he sometimes observed from ‘Insula Ivari’ and sometimes from ‘S. Paul’. The Insula Ivari must be the Island of Divar in North Goa, 10 km north of Panjim. The Mandovi River is forked around the island, and the Jesuits used canoes to reach the island. S. Paul would be the famous New College of St. Paul, east of Panjim. It was initially known as the Convent of St. Roch, but in 1610 it changed into a college and was given the name New College of St. Paul.

Father Kirwitzer records in detail what the observers saw and measured, namely, the altitudes and azimuths, angular distance from stars like Spica etc. in grad (degrees), and the observers’ visual impressions, including difficulty from illumination due to the Moon and sunlight. The only astronomical instruments the Jesuits were able to access while they were in transit were the sole *astrolabium* (astrolabe) and *radium astronomicum* (astronomical radius, i.e., cross-staff) belonging to Goa College. A cross-staff consists of a staff with a smaller, sliding transversal arm, generally made of wood but sometimes of brass and bearing a scale that could read in degrees directly. Notably, the measurements given by Father Kirwitzer were in arc minutes, to a fraction of a degree.

3.4.1 The First Comet

As Father Kirwitzer writes, dark clouds in the morning hours held them in suspense of any observations through 11, 12 and 13 November, but providence intermittently showed that the comet was growing day-by-day. Father Kirwitzer looked for a star in the head, as is typical of the comets, but found none. However, when he fetched a *tubo optico* (Fig. 5) it clearly revealed a star with a little nebulous head that appeared pale in colour. The comet’s figure could not be better explained than palm leaves, and it stretched as a straight smoky column from the east to the midst of heaven, with the tip a little turned to the north.

3.4.2 The Second Comet

> On 24 November, before the sunrise, in the dawn, this comet appeared that we saw in the Insula Ivari. Its star was clear even in comparison of Venus, with short tail and a straight line with Arcturus and Mars also passed to the Comet star, so that the distance between Arcturus and Mars was three times that between the star of the Comet and Mars.

From 28 November, two sets of observations for each comet were being taken from a given location. The comets were both observed until 30 November. The Jesuits continued to make angular measurements of 1618 II until 12 January, 1619.

However, Father Kirwitzer's treatise contains only the record of observations, at times adding a phenomenological description. There is no theorizing about comets and nothing about what they are, where they came from or where they belong. While summing up, Kirwitzer (1620, 24) notes that

> For a fuller understanding of those observations, it remains to make known the true longitude and latitude of the places where the observations have been done. However, we have not seen yet any Moon Eclipse and from others nothing we learned that we can accept with confidence, we will work diligently in order no latitude and longitude of this or other places of Asia remain unknown . . .

The credit for the first use of a telescope in India for astronomical observations has until now belonged to Jeremiah Shakerley (1626–1655). He had specially come to India to observe the transit of Mercury of 3 November 1651 from Surat in Gujarat. What telescope, timing device and the method of observations he used is not known (see Kochhar, 1989).

For further details of the research discussed here see Kapoor (2016).

Acknowledgements I am grateful to Dr. Sabino Maffeo S.J., Professors Anna Reale and Armando Reale, who translated on request a major portion of Father Kirwitzer's treatise from Latin to Italian and to Dr. Richard Boyle S.J., Vatican Observatory, for all his help in this matter. For any errors in my translation of it into English including my own directly from Latin to English and the final adoption here, the responsibility is solely mine. I thank Dr. R. Vasundhara for correspondence on critical visibility of comets. Thanks are due to Dr. Baba Varghese, Indian Institute of Astrophysics (IIA), for preparing the outline map of India marked with specific locations and to Mr. Manu Kapoor for crucial help at the computer. I thank the Werner Forman Archive/Naprestek Museum, Prague, for providing an image of a margin drawing from the folio of Jahangir's Album (IDS Ref: 55403395-67).

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Structural Changes of the Sun-and-Stars Time-Determining Instrument

Sang Hyuk Kim and Byeong-Hee Mihn

Abstract We will show the structure and usage of the Sun-and-Stars Time-Determining Instrument (日星定時儀) that was first made under King Sejong (fifteenth century) during the Joseon Dynasty. It can measure solar time in the daytime and sidereal time at night. At the same time, a Simplified Sun-and-Stars Time-Determining Instrument (小日星定時儀) which evolved from the Sun-and-Stars Time-Determining Instrument, simplified the graduated scale to '*du*', not '*fen*' in the celestial-circumference degree (that is, 365.25 *du*). It also got rid of the pole-fixing ring (正極環) by which its instrument can be aligned to the meridian line. Lastly, the Simplified Sundial (小日影) manufactured at the time of King Sejong can still be found in Korea today. This eliminated the need to measure sidereal time by removing the celestial-circumference ring and the star-dial hundred-interval ring of the Sun-and-Stars Time-Determining Instrument. We suggest that the Sun-and-Stars Time-Determining Instrument evolved into the Simplified Sun-and-Stars Time-Determining Instrument, and then the Simplified Sundial. This family of Sun-and-Stars Time-Determining Instruments was used both for timekeeping and for military purposes and in ritual ceremonies.

1 Introduction

In this paper we will show the structure and usage of the Sun-and-Stars Time-Determining Instrument (henceforth STI), which was first made under King Sejong (fifteenth century) in the Joseon Dynasty. It can measure the solar time in the daytime and the sidereal time at night.

The STI became widely known to scholars around the world thanks to the study conducted by Needham et al. (1986). After that, a study was carried out on the role of

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the STI for the clock adjustment of *Borugak-nu* (報漏閣漏, the automatic striking clepsydra), which was the standard water clock in the Joseon Dynasty period (Lee and Nam, 1998). In addition, there was a study highlighting the innovative structure of the STI (Kim et al., 2012). Recently, Lee et al. (2016) examined the usage of the STI in detail, and mentioned that the extant hundred-interval ring artifact is the product of the STI lineage. In the present study, the structure and usage of the STI were analyzed by extending the contents of the previous study (Lee et al., 2016), and the change in the STI structure is reviewed and discussed in more detail by applying the angular distance equal division method to the extant hundred-interval ring artifact.

2 Structure of The STI

According to the *Sejong Sillok* (*Veritable Records of King Sejong*), there were initially four STIs produced between 1434 and 1437. Of these four STIs, one STI was decorated with a dragon. In addition, a Simplified STI was produced and delivered to military camps. In his *Introduction to the Sun-and-Stars Time-Determining Instrument* (日星定時儀銘), Kim Don (金墩, 1385–1440) describe the development and use of the STI and the simplified STI in detail.

In the STI's structure (Fig. 1), the three rings of the STI are mounted on the wheel, which is aligned to the plane of the celestial equator. The outer, middle and inner rings are referred to as the celestial-circumference degrees-and-fractions ring, the sundial hundred-interval ring and the star-dial hundred-interval ring, respectively.

On the three rings there is an alidade that rotates at the center of the rings. Over the alidade, a pole-fixing ring is supported by straight pillars. The center of the alidade and the wheels have a pinhole similar in size to a mustard seed.

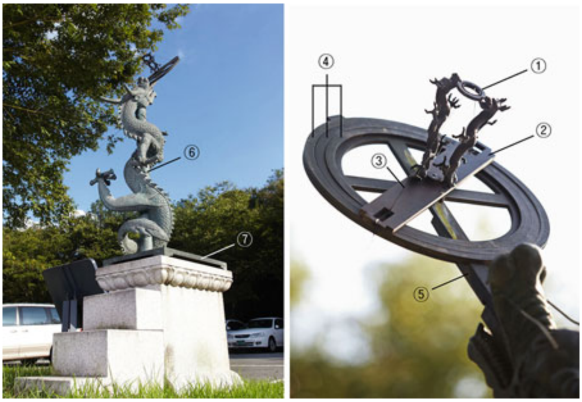

Fig. 1 The reconstructed Sun-and-Stars Time-Determining Instrument at the Korea Astronomy and Space Science Institute. Key: ① pole-fixing ring, ② an alidade, ③ triangular thread gnomons, ④ three rings (outer, middle, and inner rings), ⑤ a wheel and handle, ⑥ the dragon column, ⑦ the stand

3 Measurement Methods

3.1 Polar Adjustment

Figure 2 shows the pole-axis observed through the STI. It shows that the North Pole is observed using the hole in the center where the wheels cross and the pole-fixing ring. The pole-fixing rings in the maps of the constellation are shown at the top right. If α UMi star moves between the external ring and internal ring of the pole-fixing rings, this center becomes the North Pole.

3.2 Daytime Measurement

The measurement of daytime is relatively simple. We can tell the time by setting the meridian direction and then using the triangular gnomon thread on top of the sundial hundred-interval ring. As shown in Fig. 3, the position of the sun (③) is aligned using the triangular gnomon (②–②'), where the alidade (① in Fig. 3) and the pole-fixing ring are connected. In this regard, the time is read using the sundial hundred-interval ring (④) located below the alidade. As observing the Sun directly will be

Fig. 2 The pole-axis observed through the STI

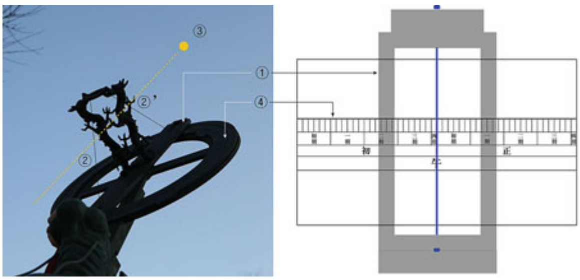

Fig. 3 Using the triangular gnomon thread on top of the sundial hundred-interval ring. ① an alidade, ② & ②' triangular thread gnomons, ③ sun, ④ sundial hundred-interval ring

blinding, it is convenient to use the shadow of the front thread (②) and the rear thread (②') during actual observations.

3.3 Night-time Measurement

The measurement of night-time is slightly more complicated. This is because solar time and sidereal time are fundamentally different. In other words, a fixed time plate with the solar transit time as noon is used for the measurement of daytime using the STI. Of course, the night-time is also decided by the rotation angle of the stars. However, the stars always stand at their meridian altitude a little bit earlier each day. Therefore, the time plate, which becomes the criterion, should be moved slightly each day. The Earth revolves while rotating on its axis, so it should be moved by 1° more, where one *du* corresponds to about 360/365.25 Therefore, the star-dial hundred-interval ring, which is the star time-measurement component, should be rotated by 1 *du* each day.

The night-time measurement methods for the STI and the simplified STI are described in the *Sejong Sillok*. The ring used for the night-time measurement is the star-dial hundred-interval ring mentioned earlier. In addition, the celestial-circumference (degrees-and-fractions) ring is needed to set the reference point of the night-time measurement (i.e., the point at which the mid-night position of the star-dial hundred-interval ring is aligned). Thus, the celestial-circumference ring is not used every day. When the zero point of the celestial-circumference (degrees-and-fractions) ring (0 *du*) is determined, the star-dial ring is rotated and aligned so that the midnight time of the star-dial hundred-interval ring can be properly positioned.

Lee et al. (2016) presented the rings for the STI and simplified STI as shown in Fig. 4. In Table 1 we summarized the measurement methods of the celestial-circumference (degrees-and-fractions) ring and the star-dial hundred-interval ring suggested in the *Sejong Sillok*, so they can be compared and examined based on Fig. 4.

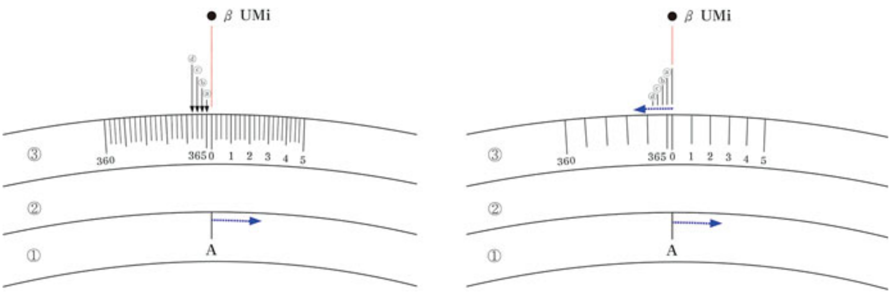

Fig. 4 Operation of the celestial-circumference ring and the star-dial hundred-interval ring on (a) the STI (left) and (b) the Simplified STI (right) (after Lee et al. 2016). ① star-dial hundred-interval ring (1 *du* right-handed rotation per 1 day), ② sundial hundred-interval ring (attached to the wheel), ③ celestial-circumference (degrees-and-fractions) ring

Table 1 Measurement methods of the celestial-circumference (degrees-and-fractions) ring and the star-dial hundred-interval ring for the STI and the simplified STI

Ring	The STI	The Simplified STI
Using the celestial-circumference (degrees-and-fractions) ring	1. Find *β* UMi at midnight on the winter solstice and set the time at midnight with a clepsydra. Find the position of *β* UMi with the triangular gnomon thread of the alidade.	1. Find *β* UMi at midnight on the winter solstice and set the time at midnight with a clepsydra. Find the position of *β* UMi with the triangular gnomon thread of the alidade.
	2. Mark the position of *β* UMi on the lateral side of the wheel.	2. Mark a long tick at the position of *β* UMi on the lateral side of the wheel. Three ticks counter-clockwise are drawn while becoming shorter, and keeping a ¼ du interval for each line.
	3. Align the zero point (0 *du*) of the celestial-circumference (degrees-and-fractions) ring on the marked position of the wheel.	3. Set the zero point (0 *du*) of the celestial-circumference ring at the longest line (1st line on the wheel side during the winter solstice in the first year.
		4. Set the zero point (0 *du)* of the celestial-circumference ring at the next line (the 2nd, 3rd and 4th lines) on the wheel side every winter solstice for 3 years (2nd, 3rd and 4th years, respectively).
		5. In the 5th year, return to the longest line and repeat, as in the new 1st year.
Using the star-dial hundred-interval ring	1. On the winter solstice, align the midnight (子正) mark of the star-dial hundred-interval ring with the zero point of the celestial-circumference (degrees-and-fractions) ring.	1. During the winter solstice, align the midnight mark of the star-dial hundred-interval ring with the new zero point of the celestial-circumference ring.
	2. Observe *β* UMi through the triangle gnomon thread and read the time indicated by the alidade thread.	2. Observe *β* UMi through the triangle gnomon thread and read the time as indicated by the alidade thread.
	3. Turn the star-dial hundred-interval ring clockwise every day by 1 *du*.	3. Turn the star-dial hundred-interval ring clockwise by 1° every *du* day.

In Fig. 4a, the star-dial hundred-interval ring moves clockwise by 1 *du* each day, and when 365 days have passed, it reaches the position of ⓐ as shown here, and when 1 year has passed again, it reaches the position of ⓑ, and when 1 year has passed again, it reaches the position of ⓒ, and when 1 year has passed again, it reaches the position of ⓓ. If one more day passes, it will reach its starting point. In other words, it returns to its starting point on the 366th day in this year.

In Fig. 4b, the celestial-circumference ring is rotated counter-clockwise by 0.25 *du* every year, so the first time of the celestial-circumference ring always coincides with the midnight position of the star-dial hundred-interval ring. Unlike the STI, the star-dial hundred-interval ring is placed on the whole numbers corresponding to 1, 2, 3 and 4 of the celestial-circumference ring every day, making it more convenient for measuring.

4 The Simplified Sundial

Rufus (1936) introduced two relics of hundred-interval rings from the Joseon Dynasty (see Fig. 5). Needham et al. (1986) noted that these two relics were similar to the STI. Since the Korean War, the hundred-interval ring and the holder have been stored separately by different agencies, and the (b) hundred-interval ring has been held together with the (a) holder. Although the (b) hundred-interval ring and the (a) holder do not belong together, they were produced during the reign of King Seongjong.

In relic (a), there is a hole at the center where the wheels cross. The 100 intervals are also engraved on both the front and the back of the ring. Relic (b) has an alidade and triangular gnomon thread. The ring is supported by two straight pillars to the center of the alidade. This ring is not the pole-fixing ring, and it is connected to threads on both ends of the alidade, aiding in time measurement. As shown in Fig. 5a, time can be read using both sides of the time plate, and in Fig. 5b, the sun position can be set using the thread connected to the alidade.

There are records of the Simplified Sundial during the reigns of King Sejong and King Seongjong. This Simplified Sundial was manufactured within 10 months after the STI was completed. The relic in (b) is reminiscent of the STI's alidade and pole-fixing ring. It utilizes the ring, straight pillars, alidade and triangular gnomon threads. The relic in (a) was made in 1487, and it is a simplified model of the relic in (b) after the ring, straight pillars and triangular gnomon threads were removed.

Lee et al. (2016) suggest that the relic in (a) is considered as a Simplified Sundial, which was a relic from the reign of King Seongjong. There is a record of an

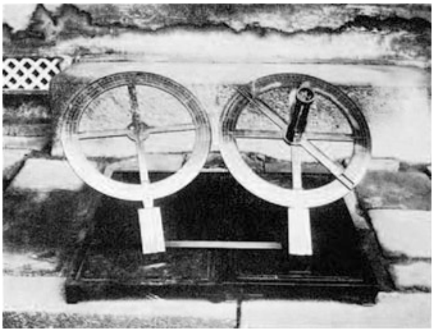

Fig. 5 Two types of hundred-interval ring instrument relics. (a) Made in 1487 (left); (b) Made in 1430s (right) (after Rufus 1936)

observational platform being created in 1489, and this is supported by the fact that it was not sent to a military camp as in the reign of King Sejong. The relic in (b) has a similar shape to the STI, as it was first produced. Therefore, it is considered that it also dates to the reign of King Sejong (1418–1450).

5 Discussion

5.1 Structure of STI and Simplified STI

The structures of the STI and the Simplified STI can be compared as follows. First, only the STI has the pole-fixing ring. The STI needs the pole-fixing ring with a double-ring structure so that the diurnal motion of β UMi can be observed. But for the simplified STI, the thread of the triangular gnomon is supported by only a single ring.

Secondly, the usage of the celestial-circumference ring is different for the simplified STI. This is largely because the detailed ticks of 1/4 *du* were omitted for this ring in the Simplified STI. As a result, the ring of the STI is almost fixed (1 du adjustment every 66 years), while the ring of the Simplified STI needs to be rotated counter-clockwise by 0.25 *du* every year. Table 2 summarizes the usage of each ring for the STI.

Table 2 Usage of each ring for STIs

Part name	Main Usage	Note
Pole-fixing ring	Polar adjustment: α UMi (Polaris)'s diurnal motion	Fixed ring
Alidade	Daytime: Sun's location measure;	When observed
	Night-time: β UMi's location measure	
Sundial hundred-interval ring	Utilizing daytime measurements	Fixed ring
Star-dial hundred-interval ring	Utilizing night-time measurements	1 *du* right-handed rotation per 1 day
	Align the zero point (0 *du*) of the celestial-circumference ring	
Celestial-circumference degrees-and-fractions ring	STI: As the zero point of the celestial-circumference degrees-and-fractions ring is set at the β UMi position throughout observation precession correction	STI: almost fixed (adjustment of 1 *du* every 66 years)
	Simplified STI: Same as STI function. However, there is no precession correction function	Simplified STI: rotated counter-clockwise by ¼ *du* every year

5.2 Analysis of the Hundred-Interval Ring Sundial Depending on the Angular Distance Equal Division

The outer and middle rings of the STI have different ticks. The outer ring has ticks of 365.25 *du* (i.e., celestial-circumference degree), and the middle and inner rings have ticks of 100 intervals. However, in the 1500s, it was manufactured by selecting the circumference of the ring where the number of notched ticks can be drawn (Mihn et al., 2015). Thus, it was difficult to match the circumference of the ring where 365 and 1/4 ticks (i.e., a total of 366 ticks) can be drawn with the circumference of the ring where 100 ticks can be drawn. However, in the case of the STI, one circumference where the ticks that can satisfy 365.25 *du* and 100 intervals at the same time can be drawn was selected (Mihn et al. 2017). It is noteworthy that the diameters of the outer and middle rings of the STI were expressed by using a π value of 3.14, unlike the astronomical instruments of China. The diameter of the circle where the two rings meet each other is 1.92 *ja* (i.e. 39.7 cm). For the circumference of the inner circle of the outer ring, the celestial-circumference degrees were drawn presuming that 5 *pun* = 3 *du*; and for the circumference of the outer circle of the middle ring, the 100 intervals were drawn presuming that 1 *gak* = 6 *pun* (Mihn et al. 2017). When the size of the ring for the STI was determined as described above, at least two problems could be resolved. Firstly, as every degree of the celestial-circumference degree is about 3.5 mm, ticks can be made that divide this again into four equal parts. Second, as the 100 intervals were again divided into six equal parts at the time, it was easy to draw the ticks of 600 equal parts for the hundred-interval ring with a diameter of 1.92 *ja*. One *ja*, as a the unit of length, corresponds to 20.7 cm.

In the case of the hundred-interval ring sun-dial artifact, the outer diameter of the ring is 40.2 cm (1.94 *ja*) (Song et al., 1994). This is close to the diameter of the middle ring for the sundial hundred-interval ring of the STI. In other words, the diameter of the hundred-interval ring for the hundred-interval ring sundial can be selected as 1.27 *ja*, 1.59 *ja*, or 2.23 *ja* (Mihn et al., 2017), but only 1.92 *ja* was used. In particular, the hundred-interval ring of the hundred-interval ring sundial is fixed, and this is consistent with the status of the sundial hundred-interval ring of the STI.

This hundred-interval ring sundial is the actual artifact shown in Figs. 5a, b. The size of the hundred-interval ring for the two simplified sundials is identical to the diameter of the sundial hundred-interval ring for the STI. In terms of the size and ticks on the observation instrument, the Simplified Sundial is thought to be a modification of a Simplified STI as a sundial that can measure 1/6 *gak* using only the middle ring, by removing the outer ring.

5.3 Significance of the Naming of the Simplified Sundial

There is a record of the STI and the Simplified STI being manufactured during the reign of King Sejong, and the Simplified Sundial was then manufactured and sent to military camps in Pyeongando and Uiju in 1438 (*Sejong Sillok*). However, researchers have rarely paid attention to the shape or usage of the Simplified Sundial.

They seem to have considered it as referring to a simple sun-dial or a clock, such as a small Hyeonjuilgu and Cheonpyeonilgu with an equatorial time plate. On the other hand, each part of the two extant hundred-interval ring sundials was stored by different agencies during and after the Korean War, and thus the manufacturing period was written incorrectly.

Lee et al. (2016) recently reported that the extant hundred-interval ring sundial (i.e., the Simplified Sundial) is a kind of STI, and that it was manufactured during the reigns of King Sejong and King Seongjong. This finding is significant because it shows that the STI manufacturing technique of during the Joseon Dynasty had continued to improve and gradually changed to emphasize practical usage. Also, the result is significant in that the Simplified Sundial mentioned in the literature has survived through to the present day and therefore can be named properly.

6 Conclusions

The STI was an astronomical clock that measured the true solar time and the sidereal time during the daytime and at night by observing the shadow of the Sun and the position of β UMi respectively. This daytime and night-time clock was at first modified to become a Simplified STI, so that it could be used during frequent travel. In the second modification, this daytime and night-time clock was converted into a Simplified Sun-dial that could just measure 1/6 *gak*, by simplifying the functions. These changes in the structure were downgrades to enable convenient usage in practical situations, rather than improvements in the measurement diversity or precision as an astronomical clock.

Through the present study, we were able to draw the following conclusions. Firstly, the two artifacts reported by Rufus (1936) are Simplified Sundials modified during the reigns of King Sejong and King Seongjong. Secondly, since the STI and the Simplified STI were first manufactured and were then modified to become the Simplified Sundial (i.e., hundred-interval ring sun-dial artifact), all of these can be classified as STIs. Thirdly, during the reign of King Sejong, the STIs and the Soganui were developed as the calibrators of the standard clock (Borugak-nu) and the astronomical observation instrument, respectively, and they became symbols of the small-scale observational instruments of the Joseon Dynasty.

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Part II
Observational Astronomy

Comets, Historical Records and Vedic Literature

Patrick Das Gupta

Abstract A verse in Book One of the *Rigveda* mentions a cosmic tree with rope-like aerial roots held up in the sky. Such an imagery might have ensued from the appearance of a comet having a 'tree stem'-like tail, with branched out portions resembling aerial roots. Interestingly, a comet referred to as 'heavenly tree' was seen in 162 BC, as reported by old Chinese records. Because of weak surface gravity, cometary appendages may possibly assume strange shapes depending on factors like rotation, structure and composition of the comet as well as solar wind patterns. Varāhamihira and Ballala Sena listed several comets having strange forms as reported originally by ancient seers such as Parashara, Vriddha Garga, Narada and Garga.

The *Mahābhārata* speaks of a mortal king Nahusha who ruled the heavens when Indra, King of Gods, went into hiding. Nahusha became luminous and egoistic after absorbing radiance from gods and seers. When he kicked Agastya (the southern star Canopus), the latter cursed him and he became a serpent and fell from the sky. We posit arguments to surmise that this *Mahābhārata* lore is a mythical recounting of a cometary event wherein a comet crossed Ursa Major, moved southwards with an elongated tail in the direction of Canopus and eventually went out of sight. In order to check whether such a conjecture is feasible, a preliminary list of comets (that could have, or did, come close to Canopus) drawn from various historical records is presented and discussed.

1 Introduction

Stars and constellations were observed with keen interest by Indo-Aryans, mainly to ascertain auspicious times to perform various Vedic rituals and sacrifices by frequently monitoring apparent stellar motions (Pingree, 1981). It is, therefore, inconceivable that comets of antiquity that were visible to the naked-eye would have

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escaped the attention of Vedic seers. After all, bright comets approach the Sun about every 5 years (Hasegawa, 1980; Ho, 1962). However, studies on ancient comets in traditional astronomy of India is handicapped by the fact that, unlike the existing systematic astronomical records of the Greeks and the Chinese that describe pre-telescopic era comets (Fotheringham, 1919; Ho, 1962; Pingre, 1783; Williams, 2014), ancient Sanskrit texts about cometary events have been lost in the ravages of time.

Because of the absence of older historical records, cometary references often get intermingled with myths and lore, making it difficult to firmly establish any inference on comets of antiquity in an Indian context. Varāhamihira's *Brhat Samhita* (BS) of AD 550 cites much older literature on comets attributed to ancient seers, such as Parashara, Garga, Vriddha Garga and Narada, that is no longer extant (Bhat, 1981). In order to salvage some accounts of comets that might have been sighted from India in ancient times, one is forced to fall back on commentaries provided in BS (Kochhar, 2010) and in Ballala Sena's *Adbhuta Sagara* (Iyengar, 2008; 2010).

Halley's own work shows that the study of historical records of comets is very important for astronomy. This is evident from extant medieval cometary records of AD 1337–1698 that enabled Halley (1705) to characterize the orbits of 24 comets. This was followed up with estimations of the orbital parameters of various comets using data gleaned from old Chinese and European sources (Hasegawa, 1979; Hasegawa, 1980; Ho, 1962; Kiang, 1972; Pingre, 1783). Records of comets and novae observed by Koreans in the bygone era were collected by Sekiguchi (1917a, b). Similarly, Kanda (1935, 1947) gathered old Japanese records of astronomical significance and published them. A large collection of Chinese records, along with Japanese and Korean ones, of past comets and novae, were compiled and translated into English by Ho (1962).

Kiang (1972) made use of these records to compute the orbital trajectory of Comet 1P/Halley over 28 past revolutions, extending back to 239 BC. Later, Yeomans and Kiang (1981) retraced the comet's trajectory to 1404 BC by numerically integrating the equations of motion. In an exciting development, sightings of Comet 1P/Halley in 164 BC and in 87 BC were discovered recorded on Babylonian clay tablets (Stephenson, Yau and Hunger, 1985) referred to as 'regular watchings' or Diaries, containing daily observations of the sky that were likely to have been commissioned by priests of Marduk Temple (Brown, 2002; Sachs, 1974). Several ancient Assyrian and Babylonian scholars had commented on a comet that appeared late in 675 BC which is yet to be identified (Brown, 2002).

In what follows, a brief vignette about comets in the context of Vedic literature is provided in Sect. 2. Sect. 3 gives a brief account of the Nahusha lore and surmises that this is a mythical retelling of a cometary event. Arguments are put forward in support of this conjecture, shortly thereafter. A preliminary study is undertaken in Sect. 4 mainly to shortlist and discuss comets described in historical records that either appeared near Canopus or could have been seen near it. Finally, in Sect. 5, we conclude by reflecting on the possible allusions to comets in Vedic texts.

2 Dhumaketu and Ketu

The Sanskrit word dhumaketu literally means ‘smoke banner’ and it appears in about half a dozen hymns in the *Rigveda*, while the *Atharvaveda* has a hymn about Saptarishi (Ursa Major) being veiled by a dhumaketu, entailing that this word connoted a comet (Iyengar, 2010) more than 3000 years ago. It should be noted that the mantra portions of the *Atharvaveda* have been dated to about 1150 BC because of their first direct mention of metallic iron (Witzel, 1995). Ketus (in the plural), meaning rays of light or fire-smoke combine, are also discussed in the *Atharvaveda*, and it is very likely that they represented comets or meteors (Kochhar, 2010).

Book One in the *Rigveda* has two hymns (1,24,7) and (1,24,8) which have been translated by Griffith (1896: 14) as follows:

> 7. Varuna, King, of hallowed might, sustaineth erect the Tree’s stem in the baseless region. Its rays, whose root is high above, stream downward. Deep may they sink within us, and be hidden.
>
> 8. King Varuna hath made a spacious pathway, a pathway for the Sun wherein to travel. Where no way was he made him set his footstep, and warned afar whate’er afflicts the spirit.

According to Parpola (2009, 2010), these verses were composed around 1000 BC, and could be interpreted as the God Varuna, the guardian of cosmic law, holding up the aerial roots of a cosmic banyan tree in the sky. Imagery of a tree’s trunk up in the sky, with long aerial roots, suggests that the simile was inspired by an apparition of a comet from a bygone era that possessed a ‘tree stem’-like tail with branched out portions resembling rope-like aerial roots (Das Gupta, 2015). It is noteworthy to point out that Chinese records speak of *tianchan* (a ‘heavenly tree’), a comet that appeared in the southwest on the evening of 6 February 162 BC (Ho, 1962). Owing to weak surface gravity, cometary appendages that result from interaction with the solar wind and radiation pressure may assume strange shapes, depending on spin, structure and composition of the comet, as well as the solar wind pattern.

Later texts belonging to *Puranas* (containing old Hindu Royal genealogies as well as mythologies) explain the phenomena of stars and planets going around a fixed Dhruva (Pole Star), instead of falling down, by invoking invisible rope like aerial roots growing outwards from the Dhruva and attaching themselves to celestial objects (Parpola, 2010). Again, one may speculate that this imagery owes its origin to a comet of antiquity that had appeared in the vicinity of the Pole Star.

Varāhamihira’s BS, after delineating features of 1000 comets, states that it is impossible to determine the rising and setting of comets from any kind of calculation (Subbarayappa and Sarma, 1985). Motion of a comet named Chala Ketu (literally, moving comet) was described vividly by Varāhamihira, emphasizing its rise on the west and increase in the tail size as it proceeded north, and eventually entered Ursa Major (Chandel and Sharma, 1991). Anticipating periodic paths, the seer Narada had stated that “… there is only one comet which comes time and again …”, while

Bhadrabahu estimated comets to be hundreds in number, each with a different period (Chandel and Sharma, 1991; Sharma, 1986).

Parashara (who is likely to have lived around 1000–700 BC) had catalogued 101 comets, 26 of which (that included Chala Ketu) were described in great detail (Iyengar, 2006). Seer Garga, who lived in about 100 BC (Kane, 1975; Kochhar, 2010), had listed 77 comets that were characterized by a dark reddish hue, as cited in BS (Bhat, 1981; Kochhar, 2010). It is possible that a descendant of Garga had composed the *Gargya Jyotisha* between 1 BC and AD 1, in which both Rahu and Ketu are included in the list of nine grahas (i.e. 'grabbers' or planets in the Indian context), with Ketu representing comets, and not the dismembered torso of Rahu (Yano, 2003). One may recall that Rahu and Ketu (as proper names) are associated with eclipses (Kochhar, 2010).

In Puranic texts, Rahu is a demon who partook celestial ambrosia in a clandestine way to attain immortality. To punish him, Lord Vishnu hurled his discus at Rahu and severed the head from the torso. The tail like torso was christened Ketu, most likely because ketus (comets) generically have tails (Das Gupta, 2015). Speaking of Lord Vishnu, it is interesting to note that Jayadeva (the twelfth century temple poet of the Puri Jagannath Temple) had described Kalki, the last avatara of Vishnu, carrying a scimitar that blazed like a comet. Could he have been influenced by Ballala Sena's commentaries on comets? Ballala Sena was a king of Mithila and Vanga (not far from Puri) who had written a treatise named *Adbhuta Sagara* (*Ocean of Wonders*) sometime around AD 1100–1200. *Adbhuta Sagara* described collections of comets originally due to seers Parashara, Vriddha Garga, Garga, Atharva, Varāhamihira and Asita-devala (Iyengar, 2008; 2010).

Several Hindu temples have sculptures on the lintels of their entrance doors representing the nava grahas (nine 'planets') with Ketu depicted as having an anthropomorphic bust along with a serpent-like tail. The *Atharvaveda-Parishishtha* contains verses not only about grahas, nakshatras (lunar mansions) and Rahu but also about Ketus (comets) classified according to seasons (Miki and Yano, 2010). However, many of its chapters were composed after Greek astrology was introduced into India around AD 300.

3 Canopus, Ursa Major and the Nahusha Myth

Canopus or Alpha Carinae is a -0.73 magnitude, spectral F0 type supergiant, which is about 200,000 times more luminous than Sun, and is located 60–80 pc away from us (Achmad et al., 1991). In the Northern Hemisphere, Canopus is visible during the winter season from regions south of 37° latitude. Agastya was a seer who composed around 27 hymns of *Rigveda* (Mahadevan, 1986). There is also a hymn in *Rigveda* likely to be due Agastya in which the Pleiades is mentioned (Das Gupta, 2015). In India, the southern star Alpha Carinae has been associated with the name Agastya since about 600 BC (Ghurye, 1977: 123–125). According to the Puranic literature, he was the first Vedic Aryan to cross the Vindhya Hills and explore the southern regions of India (Abhyankar, 2005). It is interesting to note that the older name of

Canopus, Alpha Argûs, is associated with the old southern constellation Argo Navis. Although this name sounds like Argha, a celestial ship steered by Agastya so that the Sun could sail across the sky (Allen, 1963: 66), it originated from the myth of Jason and the Argonauts. In Greek, 'argo' means swift and Argo Navis stands for the swift ship that was built by Argos for Jason. At this point, it is pertinent to point out that Arka, a Sanskrit word phonetically similar to Argha, is also a name of the Sun, with 'arka' connoting 'a ray of light' in Sanskrit, much like the word *ketu*.

In India, Ursa Major is called Saptarishi (i.e. seven seers), rishi being a Sanskrit word for sage or seer, and the stars of Ursa Major had been identified with the seven seers of the *Rigveda* since about 900 BC (Ghurye, 1972: 114–120). However, older Vedic literature refers to the Big Bear as rikshas, which means bears in archaic Sanskrit. This clearly indicates a common Indo-European origin of the Vedic people, as the older connotation of the Big Bear for the constellation can be traced back to about 1000 BC, or even earlier (Ghurye, 1972: 102–103). Later, rikshas may have been replaced by the similar-sounding rishis (which has a different meaning altogether) as far as this constellation was concerned.

The *Mahabharata*, which is often referred to as the fifth Veda, narrates the strange story of Nahusha, a human King, who took charge as the King of the Gods when Indra went incognito after killing his arch foe, Vrtra. According to Hiltebeitel (1977: 332), Nahusha then turned radiant with "... five hundred lights on his forehead burning ..." as he drew energy from seers, demons, gods, goblins, etc., and reigned over the sky. In order to seek the attention of Indra's consort Sachi, he forced the seven seers of Ursa Major to carry him around in a palanquin. Seer Bhrigu, one of the seven sages, seethed with rage because of this humiliation that he was subjected to. He asked Agastya to temporarily substitute for him and lend his shoulder to the carriage. As Agastya was quite short in stature, the palanquin with Nahusha in it lost its balance when he took Bhrigu's place as a bearer and this tilted the carriage. This infuriated Nahusha so much that he angrily kicked Agastya. An enraged Agastya then cursed the King and he turned into a serpent and fell from the sky (Hiltebeitel, 1977).

There are several features in the above legend that lead one to speculate that it refers to a very old cometary event in which the tailed visitor passed the Saptarishi constellation from the north with its tail gradually increasing in size as it moved southward towards the star Agastya, and eventually went out of sight as it dipped below the horizon. This metamorphosed into a mythical story (Das Gupta, 2015). Let us go through the key points one by one.

1. Nahusha is intimately linked with celestial objects since he is a son of the daughter of Svarbhanu, the eclipse-causing demon of the *Rigveda* (Griffith, 1896; Kochhar, 2010; Vahia and Subbarayappa, 2011), who was later associated with Rahu and Ketu (Kochhar, 2010).
2. He also belongs to the lunar dynasty, with ancestors such as the Moon, Mercury and Atri, who was one of the seers/stars of Ursa Major (Hiltebeitel, 1977).
3. The Big Bear is also referred to as a 'cart' or 'wain' (Ghurye, 1972; Hiltebeitel, 1977), and hence could have become a mythical 'carriage' or a 'palanquin' over the years when the comet-sighting story was being propagated.

4. Varāhamihira had mentioned (as paraphrased by Al Biruni) that

> Comets are such beings as have been on accounts of their merits raised to heaven, whose period of dwelling in heaven has elapsed and who are then redescending to the earth. (Allen, 1963: 27).

5. Furthermore, he prescribed worship of Agastya for kings, and had stated categorically that if this southern star was struck by a comet or a meteor there would be famine (verse 22 of BS; Bhat, 1981). An important question is: was he aware of the Nahusha legend?
6. According to many Puranic texts, the eclipse-causing demon, Rahu, had a serpent-like form with just a head and a tail (Kochhar, 2010), very much like a comet. After the demon had surreptitiously tasted the ambrosia that led to immortality, Rahu was struck by Vishnu's discus as an act of retribution (Das Gupta, 2015). Its severed tail was christened Ketu, a proper noun inspired by the common noun ketu that represents a tailed comet. Hence, it is not a far-fetched idea to associate a comet with Nahusha turning into a serpent.

In short, narration of the event wherein a comet traversed the Big Bear could have created an image in the listener's mind in which a radiant object was initially carried by Saptarishi (a 'cart' or 'wain'). Then the recounting of the comet's motion southwards with its tail growing longer, and eventually making apparent contact with Canopus before going out of sight, could have conjured up an image of Nahusha kicking Agastya and disappearing from the sky thereafter.

4 Historical Comets and Canopus

An interesting exercise that could be undertaken is to study comets that were observed in the vicinity of Canopus or those which could have been near the southern star, so that one may attempt to constrain the data set while keeping in mind the conjecture that the Nahusha myth was recalling a past cometary event. In the northern hemisphere, at places south of 37° N latitude Canopus can clearly be spotted below Sirius during the months of December to March.

To begin with, we looked at reports of comets that came very near this southern star. We also made a preliminary study of far Eastern historical records of ancient comets and, in particular, sightings of Comet 1P/Halley between 240 BC and AD 530. Although Lao-jen, meaning 'The longevity star' (Canopus), does not seem to be associated with any of the returns of Comet 1P/Halley in these records (Stephenson, 1988; Stephenson and Yau, 1985), it may still be a worthwhile exercise to list those with perihelion passage times that fell during the winter in the period from 240 BC to AD 530. As it is unlikely that the Nahusha myth was added to the Mahabharata post-Varāhamihira, we consider its return only up to AD 530.

Comets that came or could have come close to Canopus are discussed below.

While he was looking for Comet 2P/Encke from Italy in May 1822, J.L. Pons chanced upon Comet C/1822 K1 (Kronk, 2003). This comet quickly moved southward, and could not be viewed from the Northern Hemisphere thereafter. In June

1822 an observer in Rio de Janeiro spotted it near Canopus. C/1822 K1 was ~3° from Canopus on 18 June, but one night later the angular separation between them had increased to ~12° (Robertson, 1831). This object has been classified as a hyperbolic comet since it escaped the Solar System after making use of the Sun's gravity to gain speed by virtue of the slingshot effect, never to appear again.

Comet C/1853 G1 was discovered by K.G. Schweizer on 5 April 1853, south of Rho Aquilae and first appeared in Southern Hemisphere skies on 30 April 1853, with its tail pointing towards Canopus. The tail grew from ~4° to 8° in length within a day and was clearly seen on 11 June (Kronk, 2003). The estimated period of C/1853 G1 is about 782 years and, therefore, it could have been seen in 493 BC and in 289 AD (Das Gupta, 2015).

We are on much firmer grounds when we examine the catalogues published by Ho (1962) and Xu et al. (2000), as these list a very large number of comets that appeared in the winter (of the Northern Hemisphere). Of course, one is aware that a report of a winter apparition does not automatically mean that the perihelion passage also occurred during the winter months. In these records, comets are often referred to as fuzzy stars, broom stars, extended vapour or guest star. Due to a lack of space, Table 1 only lists those winter comets that appeared between 974 BC and AD 133.

One may safely ignore apparitions of Comet 1P/Halley in 240 and 87 BC, and AD 141, 218, 295, 451 and 530 since the corresponding perihelion passage times fell in or after March but before October. That leaves only its appearances in 164 and 12 BC, and AD 66 and 374 for which the perihelion passage months were November, October, January and February, respectively (Hughes, 1985; Kiang, 1972; Tsu, 1934; Yeomans et al., 1986). Past orbits of Comet 1P/Halley have been well studied, and so it should not be very difficult to rule out possible proximity to Canopus during its apparitions in 164 and 12 BC, and AD 66 and 374.

Of course, it is far from clear that any of the above comets listed in Table 1 actually came close to Canopus. However, comets 4, 6, 7, 13, 15, 16 and 19 appear promising as far as the possibility of their being seen near Canopus. It is interesting to note that the Chinese document of Se–ma Ts'ien mentions the apparition of the Standard of Tch 'e-yeou in 134 BC, which was a comet that had a serpent-like form in the shape of a standard (Chavannes, 1899). Its appearance also was reported by Hipparchus (Fotheringham, 1919). Perhaps this was the comet (no. 39) listed by Ho (1962) and by Xu et al. (2000) that was seen in the east between 31 August and 29 September in 135 BC, stretching across the entire sky.

According to the historical records (Ho, 1962), comet (no.39) of 135 BC was not sighted in the winter. However, if it is identified with the Standard of Tch'e-yeou, then it is plausible that it could have reached perihelion in or after January, and reappeared in 134 BC. Then, it makes sense to shortlist this comet too, particularly because of its serpent-like shape. It is noteworthy to point out that, according to Fotheringham (1919), this comet returned during 120–119 BC. In that case, it could correspond to the winter apparitions of either comet 9 or comet 10 in Table 1, making it a comet with a 15-year orbital period. According to Kochhar (2010), the date of the closure of the *Mahābhārata* is likely to be 100 BC, in which case one may surmise that the apparition of the Standard of Tch'e-yeou in 134 BC could have given rise to the Nahusha myth.

Table 1 Comets observed between 974 BC and AD 133 during the winter

No.	Year	Date (Range)	Description
01	974 BC	February–April	A star became fuzzy
02	525 BC	Winter	A broom star appeared
03	482 and 481 BC	October–December	Stars became fuzzy.
04	238 BC		A broom star appeared in the north and moved southwards for 80 days
05	234 BC	19 February–20 March	A broom star appeared in the east
06	162 BC	6 February	A ‘heavenly tree’, or comet, appeared in the southwest
07	154 BC	18 January–16 February	A star in the south-east became fuzzy
08	147 BC	12 October–10 November	A star became fuzzy
09	120 BC	February–April	A star became fuzzy
10	119 BC	February–April	A star turned fuzzy
11	69 BC	27 January–24 February	A star in the west became fuzzy
12	32 BC	6 February–7 March	A star turned fuzzy
13	5 BC	10 January–7 February	A streak of white vapour appeared in the southwest extending from the ground to the sky
14	AD 22	November 13–December 12	A star became fuzzy and moved south-east
15	AD 46–47	17 December–15 January	A fuzzy star appeared in the south
16	AD 55–56	6 December–6 April	A comet appeared travelling southwestwards
17	AD 78	January	A star became fuzzy
18	AD 101	January	A comet appeared
19	AD 110	9 January–6 February	A broom star appeared in the south
20	AD 117	9 January	A guest star appeared in the west
21	AD 132	29 January	A grayish star appeared with vapours in the form of rays
22	AD 133	8 February	A comet with a long tail appeared in the southwest.

5 Conclusion

While Halley’s pioneering work of extracting information on cometary orbits from medieval records proved so useful to astronomy, paving the way for further comet research based on far eastern historical catalogues, one encounters a serious setback in the Indian scenario since ancient Indian records of comets are no longer extant. As a consequence it is difficult to separate real cometary references from myths and lore. Nevertheless, it is important to look for allusions in Vedic texts to dhumaketu, ketus as well as strange forms (e.g. serpent-like or aerial root-like) in the sky (as Vedic priests were enamoured by celestial objects, chiefly for time-keeping purposes) in the hope that something significant on comets turn up.

Mention in a late *Rigvedic* verse of a cosmic banyan tree held up in the sky does allow one to speculate that it was inspired by a comet of antiquity, particularly because there is a reference in Chinese records from 162 BC to a comet as a 'heavenly tree'. Similarly, the myth in which Nahusha turned into a serpent after kicking Agastya and falling from the sky leads one to surmise that this was a description of a comet that passed through Ursa Major, moved southwards as the tail grew in length, crossed Canopus and went below the horizon. Gradually this account became folk lore as it was passed from generation to generation. The strongest argument in favour of this interpretation comes from Varāhamihira's statement that

> Comets are such beings as have been on account of their merits raised to heaven, whose period of dwelling in heaven has elapsed and who are then redescending to the earth.

and from his instruction that kings must worship Canopus (Agastya) and that if a comet strikes this southern star there will be calamities.

There are nineteenth century reports of comets that appeared very close to Canopus. Although, ancient Far Eastern records of comets do not directly refer to comets seen near Lao-jen (Canopus), citations to comets of older times that either moved southwards or were seen in the south survive. A comet that looks very promising is the Standard of Tch'e-yeou which was sighted in 134 BC and had a peculiar serpent-like form. If one takes 100 BC to be the epoch of closure of the *Mahābhārata* then it is plausible that the Nahusha lore grew out of the apparition of this strange comet. One must also study thoroughly the past trajectory of Comet 1P/Halley to check whether it could have appeared very close to Canopus during one or more of its apparitions.

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Stars as Recorded in Indian Texts

B. S. Shylaja and R. Venketeswara Pai

Abstract Based on their listed coordinates, we have compiled a catalogue of more than 100 bright stars included in various texts from the *Surya Siddhanta* to the *Siddhanta Darpana* by Chandrashekhara Samanta in the nineteenth century. Using the 27 *nakshatras* on the ecliptic, which fix the position of the Solar System bodies, the coordinates were matched for the epochs of the catalogues. This resolved some ambiguity in respect of the identification of faint stars and provided a means to extend the method to other stars outside the zodiac. We have specifically chosen those lists that are characterized by observations, which are highlighted in the discussion. Our study reveals that a scale similar to the magnitude scale of brightness (currently in use) was in vogue in ancient Indian astronomy. Stars used by navigators, not listed with coordinates but as practical tools, are also included. The origin of the names are described—some were indigenous, and some were borrowed from the Arabs and later from the Europeans. In this preliminary study we provide an overview of the positions of the stars.

1 Standardising the Coordinate System

Coordinates of stars in all texts on Indian astronomy are expressed in *Dhruvaka* and *Vikshepa*, which are different from those currently in use. The angle measured from the First Point of Aries along the ecliptic to the point of intersection of the great circle through the pole is called the *Dhruvaka*. The angle measured along the great circle passing through the pole of the ecliptic is called the *Vikshepa*. These are shown in Fig. 1.

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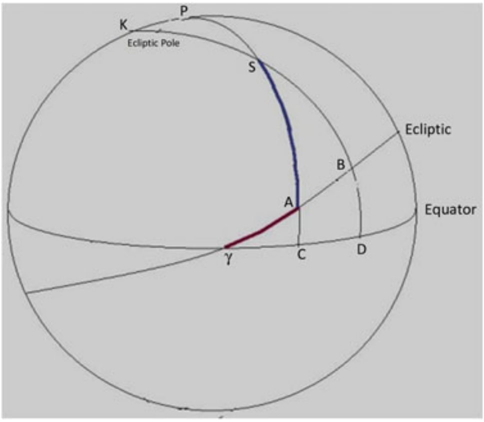

Fig. 1 The coordinates and their definitions. γA = *Dhruvaka*, γB = longitude, γC = right ascension, CS = declination, SA = *Vikshepa*, SB = latitude. (Diagram: B.S. Shylaja and R. Venketeswara Pai)

The conversions of the coordinates can be done using the trigonometric relations (Abhyankar 2002; Hari 2006; Saha and Lahiri 1954) to compare the coordinates as derived from the current ephemerides. The ambiguity in the identification of stars arises because the east-west coordinates are influenced by the shift of the reference point, the First Point of Aries, owing to precession.

We examined the identifications of 27 stars named *Yogataras* (junction stars) and compared these with the ones that are conventionally known to us now. The methods of comparison are demonstrated for *Asvini* (β Ari) in Venketeswara Pai and Shylaja (2016). The texts by Nityananda, Padmanabha and Malayendu provide direct measurements; therefore comparisons are easy and reliable. Malayendu lists another quantity named *Paramonnatamsa*, which is a measured parameter. He explains how to get the declination from this reading given that the latitude of the place is 27° 38′; therefore we can conclude that it was a measured quantity. It is the maximum altitude, obviously corresponding to the meridian passage. *Karanapaddhathi* and many other texts provide formulae for calculating declination from the longitude and latitude measures.

We have converted the given coordinates to right ascension and declination, so that comparison becomes easy.

Nityananda provides the brightness as a scale called *pramana,* which is equivalent to the magnitude scale used today. The first, termed *prathamapramana or aadyamana*, is the brightest; the second brightest is termed *dvimiti*; the third is *trimiti*; and even a fourth one is mentioned, known as *chaturtha pramana*. These scales are specifically described in the middle of the text after the description of stars in Leo. It states that there are thousands of stars fainter than magnitude 4. This value of the magnitude helps us in the identifications. For example, if there are two stars very close to each other, the correct one can be identified on the basis of the brightness scale.

The star list based on the coordinates points to a small region in the sky. Within the observational errors and errors in fixing the epoch, the best possible identifications are listed. Some discrepancies with earlier identifications (e.g. see Pingree and Morissey 1989) also were noticed.

2 Discussion

We have a list of 84 stars from Nityananda, including the 27 stars of the zodiac. We have 22 more stars from Malayendu, 8 from Padmanabha and 10 from Chandrashekhara Samantha.

Not all of the names are necessarily of Indian origin, although *Matsyodara* (belly of a fish) does appear to be an original Indian name. While there are frequent references to a fish in the sky, its dimensions are not defined (Sarma, pers. comm, 2016).

Some of the names are of Arabic origin. Malayendu's list gives the original names as "*pharasi nama*", meaning the name from Persia.

Almost all the texts provide the coordinates for *Lubdhaka* (Sirius) and *Agasthya* (Canopus). It is puzzling that the values of *Vikshepa* are more or less the same in all cases irrespective of the epoch, while in the case of *Dhruvaka* there is a variation. The *Surya Siddhanta* list has five more stars: *Brihma Hridaya, Hutabhuk, Apa, Apavatsa and Agni. Brihma Hridaya* usually is identified with Capella. Chandrashekhara Samanta identifies it as β Aur although the coordinates do not lead us to Capella. All texts based on the *Surya Siddhantha* (copies or commentaries) give the same coordinates irrespective of the epoch.

The list provided by Chandrashekhara Samanta shows confusion with the name *Prajapathi*. He declares that *Mriga Vyadha* is sometimes called *Prajapathi.* His coordinates actually match those of Procyon, α CMi. He lists *Lubdhaka*, α CMa, separately.

The seven stars of the *Saptarishi* are very popular all over India. However there always has been confusion about the names of the individual stars. The catalogs used in our study do away with this confusion by stating the first *Muni*, the second *Muni*, and so on. The doublet is identified as *Vasishta*, and the last one as *Marichi.* However, there is no mention of the companion of *Vasishta*, which is known to all Indians as *Arundhati*.

2.1 Stars of the Navigators

Navigators along the Indian coast used the stars to determine the time and fix their direction, and there are many written accounts of this (e.g., see Ballard 1928;

Tibbetts 1969). Some star charts and indirect references in travelogues also provide clues on this subject. Recently, systematic studies have been made on all aspects of Indian marine navigation and ship building, but traditional navigation techniques using celestial objects were not covered exhaustively.

The main goal of the navigators was to determine the time at night with the help of the stars. Owing to the better visibility of the southern constellations they used the bright stars Fomalhaut, Achernar and Canopus for reckoning the time. With no special names, these stars were simply called '*Munnakshatram*', which means 'the three stars'. Names of asterisms, like the boat, the kite and the whale, were transmitted orally and no written documents exist, apart from the results of the survey conducted by Arunachalam (Arunachalam 1988, 1996). Canopus is known as *Yesu nakshatram*, after Jesus Christ, since it is on the meridian on Christmas midnight. This is a clear indication of European influence.

The islanders of Lakshadweep used the idea that the latitude of an island was determined by when a particular star reached the zenith. Therefore each island was associated with a different star. Quite obviously, the islanders did not utilise the altitude of the Pole Star for this purpose. This may be understood by the fact that at these latitudes (7–10° N) the Pole Star is barely visible.

The names of the stars of the navigators have to be inferred only by the descriptions of their patterns and times of visibility. No specific names were used by the navigators, except for the couple of examples mentioned above. For a detailed discussion on this topic see Shylaja (2016).

3 The Catalogue

The *Siddhantha Raja* by Nityananda provides coordinates of stars based on observations. Ohashi (1994) has studied the *Yantra Kiranavali* by Padmanabha and he provides the *Dhruvaka* and *Vikshepa* of stars, also based on observations.

The *Karanapaddhathi* lists the longitudes as double the actual values (Pai et al. 2017). One of the reasons may be because the angles were measured with a device that had to be viewed using reflection from a water surface. Such a technique was described in the *Siddhantha Sekhara* by Sripathi in the eleventh century (Bhat, pers. comm., 2015) and in the *Grahalaaghav*a by Ganesh Daivajnya in the fourteenth century (Venugopal et al. 2009).

All the 106 stars listed in the catalog are indicated in the star charts shown here as Figs. 2, 3, 4 and 5. It is planned to prepare a complete catalog of all of the coordinates and the corresponding charts for the area justifying our choice for each star. Here we give the example of Matsyodara as derived from various catalogs. The *bhuta sankhya* system used in the text by Nityananda is quite interesting and the technique

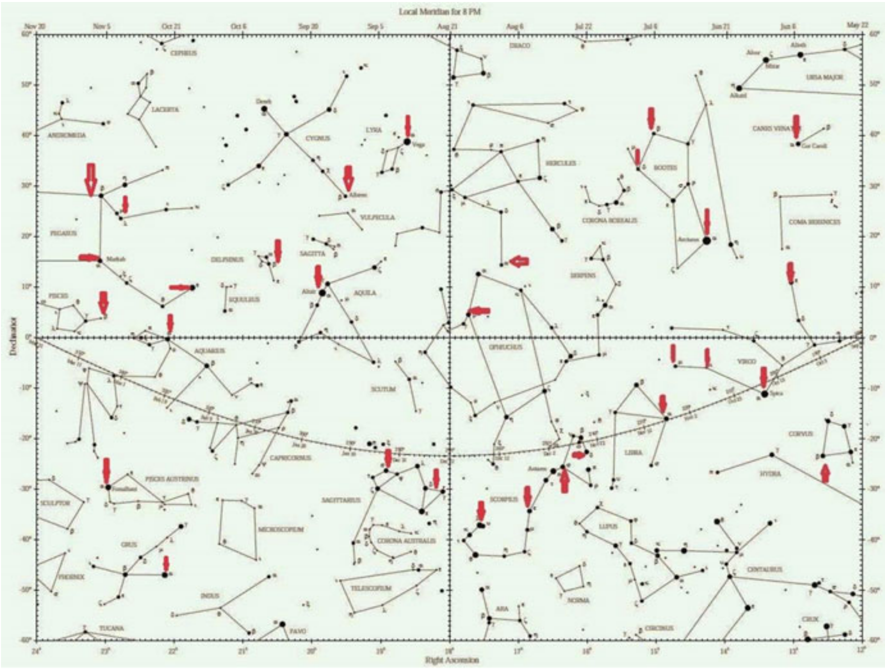

Fig. 2 A star chart from 0 h to 12 h right ascension. Identified stars are indicated by red arrows

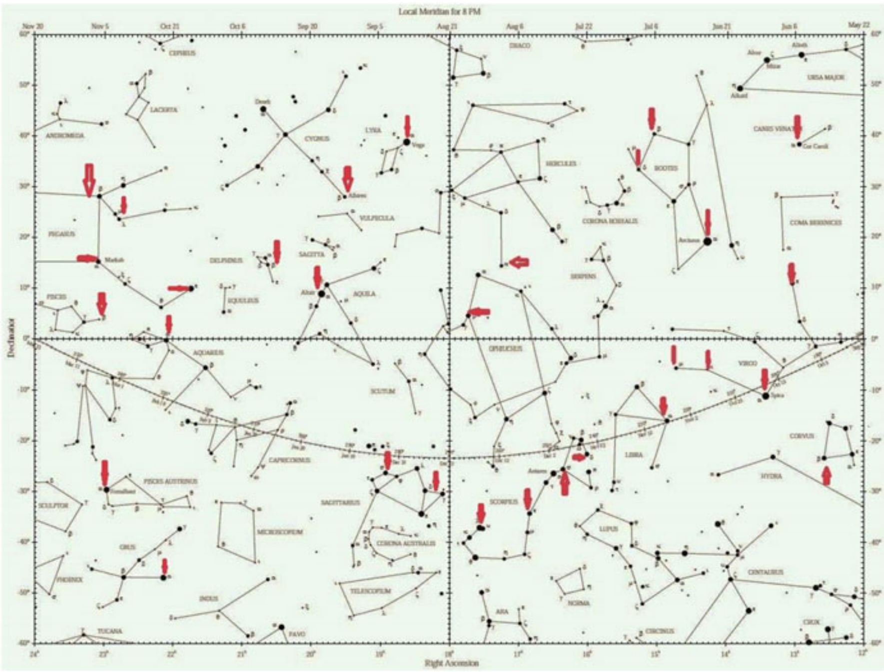

Fig. 3 A star chart from 12 h to 24 h right ascension. Identified stars are indicated by red arrows

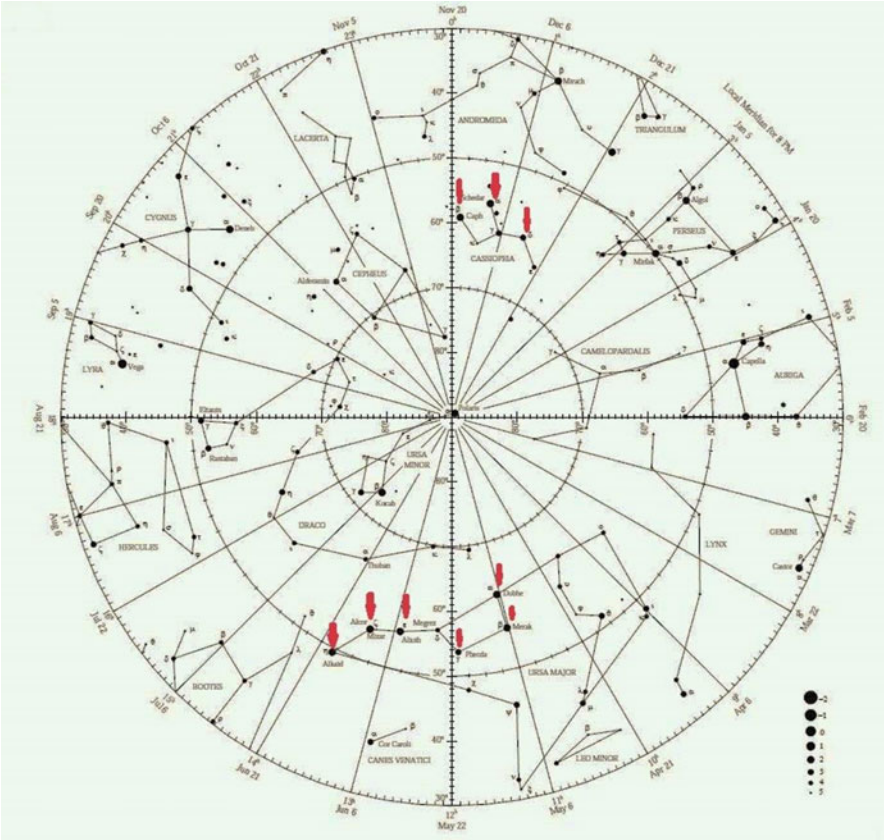

Fig. 4 The northern circumpolar star chart. Identified stars are indicated by red arrows

used for representing fractions of a degree is indigenous. We are preparing a separate note on this aspect.

The process of star identification and justification of each choice needs to be discussed in detail, and we plan to present the results in a series of papers. The first paper in this series (Venketeswara Pai and Shylaja 2016) has already been published, and the second paper (Shylaja and Venketeswara Pai 2018).

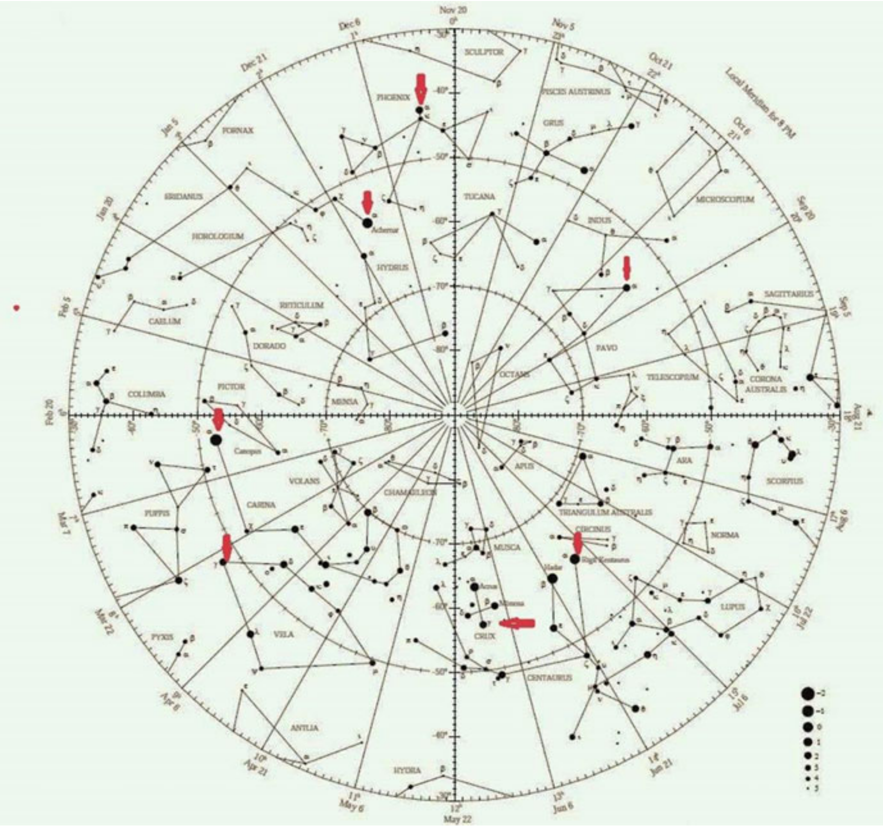

Fig. 5 The southern circumpolar star chart. Identified stars are indicated by red arrows

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The Identification of Nakshatra Junction Stars from Precession Calculations

Upasana Neogi and Mayank Vahia

Abstract The names of the nakshatras along with the longitudes of their junction stars are found in various ancient Indian texts on astronomy. But identification of the appropriate junction stars associated with the nakshatras has been a problem for a long time. Various suggestions have been made to reconcile modern catalogue stars with nakshatras, but they have not been universally accepted. Moreover, the longitudes of the junction stars change due to precession of the Earth's equinox, which is 50.3 arcseconds/year. There is a list of 27 nakshatras along with the longitudes of their junction stars given in the *Maha Bhaskariya*. By comparing those longitudes of the junction stars with their present longitudes and considering a precession of nearly 20°, the appropriate junction star for each nakshatras can be identified. Most of the junction star names proposed by Abhyankar in fit perfectly according to our calculations, except for a few nakshatras: Asvini, Adra, Visakha, Satabhisak and Purva-Bhadrapada.

1 Introduction

Nakshatras or lunar mansions have been a backbone of Indian astronomy, with several records based on their associations. The ecliptic, the apparent path of the Sun, is divided into twelve 30° divisions. These divisions form the twelve signs of zodiac. The zodiac is further subdivided into 27 nakshatras (lunar mansions) or asterisms (sub-constellation). Each nakshatra covers 13° 20′ of the zodiac and is traditionally identified by a marker star called a yogatar*a* or 'union star' or 'junction star'. The yogatara determines the ending and starting points of the nakshatras, which may have been chosen because the star was most clearly visible to naked eye or it had some feature that attracted the eyes. Some researchers will disagree with which specific stars correspond to the yogataras associated with the nakshatras

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(cf. Iyengar, 2013: 30). Abhyankar (1999) had proposed some changes in the associated yogataras based on his readings and calculations.

The longitudes of the junction stars change with course of time due to the precession of the Earth's equinox. The rate of precession is 50.3 arc seconds/year. Hence, the Earth regresses a full 360° cycle through all twelve zodiacal signs in 25,772 years (1° every 71.6 years).

2 The Present Work

Subbarayappa and Sarma (1985: 112) have listed the 27 nakshatras, and the longitudes and latitudes of their yogataras as mentioned in the *Maha Bhaskariya* (written by Bhaskara I). The nakshatras are listed in reference to the 12 zodiac signs assigning them numbers, in the format *mSnn*, where *m* corresponds to the zodiac signs 0–11, *S* denotes sign and *nn* defines the longitude (in degrees) of the junction stars of the nakshatras. The period of Bhaskara I was from AD 600 to 680, and the *Maha Bhaskariya* was written around AD 629 (Subbarayappa and Sarma, 1985: 313). Hence, the longitudes of the junction stars are not the same in the twenty-first century AD and must show a precession of approximately 20° in nearly 1400 years. Hence, it is possible to check the present longitudes of the junction stars and confirm if they show the same amount of precession as expected for the passage of 1400 years.

In this paper, the ecliptic longitudes and latitudes of the junction stars have been compared with those given in the *Maha Bhaskariya*, because Subbarayappa and Sarma (1985: 112) mention the coordinates as longitudes and latitudes. The Dhruvaka-Vikṣepa system has not been used in this paper, since the system re-presents the polar longitudes and latitudes (Abhyankar, 2006).

In Table 1 below, we list the junction proposed by Abhyankar (1999) for each nakshatra, along with their coordinates shown in the *Maha Bhaskariya* and their present coordinates. In column 3 we give the magnitudes of the junction stars, and their coordinates (as derived from the *Maha Bhaskariya*) are listed in columns 4–6. In columns 7 and 8 we give the coordinates of the junction stars for the year AD 2000, taken from the software Stellarium (J2000). In column 4, the signs 0 s, 1 s, 2 s, etc. represent the zodiacal signs in which the junction stars of the nakshatras are found, followed by the longitudes (in degrees). 12 s denotes 0° longitude and latitude which corresponds to the Revati nakshatra. The first point of Aries (i.e. the vernal equinox) was in Revati during AD 600.

The difference in longitudes of the junction stars should be nearly equal to 20° over a period of 1400 years. As per Table 1, the average difference in longitudes is 21.611 ± 5.492°, which accounts for a time nearly equal to 1547 years before AD 2000, with a deviation of ±400 years.

Thus, using the junction star names proposed by Abhyankar (1999), we have calculated the era when Bhaskara I mentioned the longitudes of the junction stars in the *Maha Bhaskariya*, which relates to AD 453 ± 393.

Table 1 Conventional junction stars (After Abhyankar, 1999) associated with the nakshatras, and their present coordinates

Nakshatra	Junction star by Abhyankar (1999)	Apparent Mag	*Maha Bhaskariya*			Stellarium J2000		Difference in longitude
			Lat (°)	Long	Calculated longitude (°)	Lat	Long	
Asvini	β Arietis	2.6	10 N	0s 8°	8	+8°29′13.2″	33.970	25.970
Bharani	41 Arietis	3.6	12 N	0s 27°	27	+10°26′56.8″	48.204	21.204
Krittika	η Tauri	2.85	5 N	1s 6°	36	+4°03′3.1″	59.992	23.992
Rohini	α Tauri	0.85	5 S	1s 19°	49	−5°28′05.6″	69.789	20.789
Mrigsira	λ Orionis	3.5	10 S	2s 2°	62	−13°22′10.1″	83.707	21.707
Adra	γ Geminorum	1.9	11 S	2s 10°	70	−6°44′34.1″	99.105	29.105
Punarvasu	β Geminorum	1.15	6 N	3s 2^0	92	+6°40′58.8″	113.213	21.213
Pusya	δ Cancri	3.9	0	3s 15°	105	+0°04′34.1″	128.722	23.722
Aslesa	ζ Hydrae	3.1	7 S	3s 24°	114	−10°58′10.8″	134.575	20.575
Magha	α Leonis	1.35	0	4s 8°30′	128.5	+0°27′52.8″	149.828	21.328
Purva Phalguni	δ Leonis	2.55	12 N	4s 21°	141	+14°20′0.7″	169.317	28.317
Uttara Phalguni	β Leonis	2.1	13 N	5s 4°	154	+12°15′55.8″	171.616	17.616
Hasta	δ Corvi	2.9	7 S	5s 23°	173	−12°11′48.3″	193.452	20.452
Chitra	α Virginis	0.95	2 S	6s 5°	185	−2°03′17″	203.258	18.258
Svati	α Bootis	0.15	37 N	6s 17°	197	+30°43′32.9″	204.233	7.233
Visakha	α Librae	5.15	1.5 S	7s 2°	212	+0°21′43.1″	225.025	13.025
Anuradha	δ Scorpii	2.35	3 S	7s 12°	222	−1°59′10.6″	242.571	20.571
Jyestha	α Scorpii	1.05	4 S	7s 18°	228	−4°34′12.2″	249.762	21.762
Mula	λ Scorpii	1.6	8.5 S	8s 1°	241	−30°47′18.9″	264.586	23.586
Purvasadha	δ Sagittarii	2.7	7 S	8s 14°	254	−6°28′20.5″	274.581	20.581
Uttarasadha	σ Sagittarii	2.05	7 S	9s 27°	267	−3°26′59.2″	282.385	15.385
Sravana	α Aquilae	0.75	30 N	9s 15°	285	+29°18′16.6″	301.780	16.780

(continued)

Table 1 (continued)

Nakshatra	Junction star by Abhyankar (1999)	Apparent Mag	*Maha Bhaskariya* Lat (°)	*Maha Bhaskariya* Long	*Maha Bhaskariya* Calculated longitude (°)	Stellarium J2000 Lat	Stellarium J2000 Long	Difference in longitude
Dhanistha	β Delphini	4.01	36 N	10s 26°	296	+31°55′3.3″	316.342	20.342
Satabhisak	λ Aquarii	3.7	18 S	10s 7°	307	+0°23′11.7″	341.576	34.576
Purva-Bhadrapada	β Pegasi	2.4	24 N	11s 28°	328	+31^{0}08′26.8″	359.375	31.375
Uttara-Bhadrapada	γ Pegasi	2.8	26 N	11s 15°	345	+12°35′59.7″	9.156	24.156
Revati	ζ Piscium	5.2	0	12s	360	−0°12′50.3″	19.878	19.878

We therefore used the Stellarium (J2000) software (www.stellarium.org) to identify the junction stars for the nakshatras that show a significant deviation in the difference in longitudes. We have replaced the junction stars for the nakshatras Asvini, Adra, Svati, Visakha, Uttarasadha, Satabhisak and Purva-Bhadrapada with stars brighter than visual magnitude 3 within the boundaries of the nakshatras and show a precession of 20° over a period of nearly 1400 years. Table 2 lists the junction stars, with newly proposed names for some of the nakshatras. The columns in this table are the same as in Table 1.

From Table 2, it can be calculated that the average difference in longitude is 20.877 ± 2.348°, which accounts for a time nearly 1497 ± 168 years before AD 2000. Hence, the calculated era of the composition of the *Maha Bhaskariya* is AD 506 ± 168, the original era being AD 629 (Sub-barayappa and Sarma, 1985: 313). In Table 2, the value of maximum precession is 24.885° and that of the minimum is 16.643°.

We have used the Stellarium software to confirm the longitudes of the newly proposed junction stars in AD 600. The longitudes of the stars change due to precession but the obliquity of the ecliptic remains constant, hence the latitudes remain unaffected. So, there should not be any difference in latitudes for the junction stars given by Abhyankar (1999) or identified in this paper with that given in the *Maha Bhaskariya*. Yet a significant difference in latitudes is found for some of the junction stars. For example:

1. The latitude of Uttara-Bhadrapada, as mentioned in the *Maha Bhaskariya,* is 26° N. But considering γ Peg as the conventional junction star (Abhyankar, 1999) to match the longitude, the latitude (+12° 38′ 09.8″) shows a significant mismatch. The Uttara-Bhadrapada nakshatra contains two bright stars, γ Peg and α And. If we consider α And as the junction star, the latitude +25° 46′ 41.4″ nearly matches with the given data but produces a big difference in longitude.
2. Another is the Satabhisak nakshatra. According to the *Maha Bhaskariya*, the latitude is 18° S and the longitude is 307°. As mentioned by Abhyankar, the junction star of Satabhisak is λ Aqr. In AD 600 its latitude was −0° 17′ 03.4″ and its longitude was 322° 00′ 52.8″ (according to Stellarium). Hence there is a mismatch in latitude as well as longitude with that given in the *Maha Bhaskariya*. So we proposed ε Peg, to reduce the difference in longitude. But that results in a huge difference in latitude. Again, if we consider α Piscis Austrini as the junction star, which is a much brighter star, the latitude difference is reduced, with a little increase in the longitude difference. The longitude and latitude of α Piscis Austrini were 314° 10′ 44.3″ and −20° 53′ 08.8″ respectively in AD 600.
3. The most mismatched conventional junction star is α Boo in the Svati nakshatra. Its latitude and longitude are 37N and 197 °, as mentioned in the *Maha Bhaskariya.* It does not even lie between 30N and 30S, which are the latitude limits for all of the junction stars. But the latitude and longitude of α Boo were +31° 41′ 30.0″ and 184° 35′ 52.0″ respectively in AD 600. So we propose 109 Virginis as the junction star of Svati. The longitude nearly matches that given by Bhaskara I, but the latitude shows a difference of nearly 20^0. The latitude and longitude of 109 Virginis were +17° 11′ 01.1″ and 198° 57′ 44.6″ respectively in AD 600.

Table 2 Proposed junction stars associated with nakshatras and their present coordinates

Nakshatra	Proposed junction star	App Mag	*Maha Bhaskariya*			Stellarium J2000		Difference in longitude
			Lat (°)	Long	Calculated Long (°)	Lat	Long (°)	
Asvini	η Piscium	3.8	10 N	0s 8°	8	+5°23′02.8″	26.807	18.807
Bharani	41 Arietis	3.6	12 N	0s 27°	27	+10°26′56.8″	48.204	21.204
Krittika	η Tauri	2.85	5 N	1s 6°	36	+4°03′3.1″	59.992	23.992
Rohini	α Tauri	0.85	5 S	1s 19°	49	−5°28′05.6″	69.789	20.789
Mrigsira	λ Orionis	3.5	10 S	2s 2°	62	−13°22′10.1″	83.707	21.707
Adra	α Orionis	0.45	11 S	2s 10°	70	−16°01′37.1″	88.755	18.755
Punarvasu	β Geminorum	1.15	6 N	3s 2°	92	+6°40′58.8″	113.213	21.213
Pusya	δ Cancri	3.9	0	3s 15°	105	+0°04′34.1″	128.722	23.722
Aslesa	ζ Hydrae	3.1	7 S	3s 24°	114	−10°58′10.8″	134.575	20.575
Magha	α Leonis	1.35	0	4s 8°30′	128.5	+0°27′52.8″	149.828	21.328
Purva Phalguni	δ Leonis	2.55	12 N	4s 21°	141	+14°20′0.7″	161.317	20.317
Uttara Phalguni	β Leonis	2.1	13 N	5s 4°	154	+12°15′55.8″	171.616	17.616
Hasta	δ Corvi	2.9	7 S	5s 23°	173	−12°11′48.3″	193.452	20.452
Chitra	α Virginis	0.95	2 S	6s 5°	185	−2°03′17″	203.258	18.258
Svati	109 Virginis	0.62	37 N	6s 17°	197	+17°07′29.5″	218.564	21.564
Visakha	σ Librae	3.25	1.5 S	7s 2°	212	−7°37′12.3″	230.709	18.709
Anuradha	δ Scorpii	2.35	3 S	7s 12°	222	−1°59′10.6″	242.571	20.571
Jyestha	α Scorpii	1.05	4 S	7s 18°	228	−4°34′12.2″	249.762	21.762
Mula	λ Scorpii	1.6	8.5 S	8s 1°	241	−30°47′18.9″	264.586	23.586
Purvasadha	δ Sagittarii	2.7	7 S	8s 14°	254	−6°28′20.5″	274.581	20.581
Uttarasadha	ζ Sagittarii	2.05	7 S	9s 27°	267	−7°10′57.2″	283.643	16.643
Sravana	α Aquilae	0.75	30 N	9s 15°	285	+29°18′16.6″	301.780	16.780
Dhanistha	β Delphini	4.01	36 N	10s 26°	296	+31°55′3.3″	316.342	20.342
Satabhisak	ε Pegasi	2.35	18 S	10s 7°	307	+22°05′59.5″	331.885	24.885
Purva-Bhadrapada	α Pegasi	2.45	24 N	11s 28°	328	+19°24′21.3″	353.486	25.486
Uttara-Bhadrapada	γ Pegasi	2.8	26 N	11s 15°	345	+12° 35′59.7″	9.156	24.156
Revati	ζ Piscium	5.2	0	12s	360	−0°12′50.3″	19.878	19.878

3 Conclusion

In this paper, we have recreated the sky of AD 600 using Stellarium (J2000) software to find the latitudes and longitudes of the junction stars associated with the different nakshatras. Then we.

have compared those values with the latitudes and longitudes of the junction stars calculated using precession of the Earth's equinox from the data given in the *Maha Bhaskariya.* We have shown that some of the junction stars are different from those proposed by Abhyankar (1999). Hence, we have proposed new junction stars for the following nakshatras: Asvini, Adra, Svati, Visakha, Uttarasadha, Satabhisak and Purva-Bhadrpada.

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The Effect of Modern Sky Chart Software on Star Names

Hani Muhammad Dalee

Abstract New star names recently have been introduced in modern astronomy mobile applications, and in this paper we collect names that have appeared in the last 10 years in ten different applications. We search for the origins of these names, and find that some belong to Arabic, English, Latin, Chinese, Indian, Spanish, Italian, Greek, Roman and Turkish cultures, but many are of unknown origin. In this paper, we examine ten different astronomical software packages, and collect all new star names that have been entered on these since 2005. We then assemble a list of star names, and (where possible) include information on their language of origin and the associated software. We end this paper by trying to answer the question: "Who invented these new names?"

1 Introduction

According to Paul Kunitzsch; a German expert in star names and their origins, known star charts are thought to have been transferred to Greece by the Babylonians and Sumerians. Ptolemy wrote his *Almagest* around AD 150, which was then translated into Arabic many times (e.g. see Dalee, 2008).

Many scholars, including Al-Biruni, Ibn Al-Ajdabi and Al-Qazwini, made celestial spheres and sky charts and added stars names taken from the *Almagest*, but Abdul-Rahman al-Sufi (AD 903–986), found Arabic sky charts in disarray, so he decided to assemble *The Book of the Fixed Stars* or *Sowar Al-Kawakib* صور الكواكب الثمانية والأربعين (see Hafez et al., 2011), where he redrew Ptolemy's 48 star charts (e.g. see Fig. 1), and also mentioned the Arabic names of the stars, many of which (Betelgeuse, Rigel, Aldebaran Fomalhaut, etc.) are still used in modern star charts (Hafez et al., 2015b). Al-Sufi assigned an Arabic name to the brightest star in each constellation (Table 1), and he devised a new three-step magnitude system to record the brightness of each star (see Hafez et al., 2015a).

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Fig. 1 Al-Sufi's depiction of the constellation of Scorpius (The Scorpion) as seen in the sky

Monitoring earlier sky charts allows us to see that many changes have occurred in star names over time, even though these are supposed to be sacrosanct.

In their book *A Dictionary of Modern Star Names*, Kunitzsch and Smart (2011), identified 250 named stars in sky charts and they then traced the origins of these names. In Table 2 we include some of the non-Arabic star names they mention.

Meanwhile, in *Star Names—Their Lore and Meaning*, Allen (1961) has collected names from many different civilizations, so the total number of the stars listed is triple of that mentioned by Kunitzsch and Smart.

After the twelfth century, translation of Arabic works by Latin writers and scholars (often based in Andalusia and Spain) accelerated. However, many of scholars were not familiar with Arabic and other languages, which led to errors in the names they assigned to different stars. We still face this problem today, where some modern sky charts list incorrect star names (see Fig. 2). Here are some examples: Yed Al-Jawzaa = Betelguese (α Ori), Tarazu = Tarazed (γ Aql), Yildiz = Yildum (δ UMi) and Alredif = Arided (α Cyg).

Before the appearance of modern computers and touchscreen astronomical software on cell phones, star naming was more-or-less controlled. But any interested person could quickly notice that new names were continuously appearing, and that these derived from many different languages. We, therefore, ask: How could many of these new names appear without the recognition of the International Astronomical Union?

Table1 A list of the forty-two constellations where the first star (α) in each has an Arabic name

#	Constellation	Star Name	Arabic name
1	α And	Sirrah/Alpheratz	سرة/ الفرس
2	α Aqr	Sadalmelik	سعد الملك
3	α Aql	Altair	النسر الطائر
4	α Ari	Hamal	الحمل
5	α Can	Acubens/Sertan	الزبانى/ الشرطان
6	α Car	Suhel/Tureis	سهيل/ تريس
7	α Cas	Schedir/Shedar	الصدر
8	α Cen	Rigil Kentaurus/Toliman	رجل قنطورس/ الظلمان
9	α Cep	Alderamin	مقدم الذراعين/ الذراع اليمين
10	α Cet	Menkar	منقار
11	α Col	Phact/Pheat	الفختية
12	α CrB	Alphecca/Alphekka	الفكة
13	α Crv	Alchiba/Alkiba	الخباء
14	α Crt	Alkes	الكأس
15	α Cyg	Deneb/Arided	ذنب/ الردف
16	α Del	Al Deneb Al Dulfim/Deneb/Thuban/ Adib	ذنب الدلفين/ ذنب/ الثعبان/ الذيب
17	α Dra	Thuban	الثعبان
18	α Equ	Kitalpha	قطعة الفرس
19	α Eri	Achernar	آخر النهر
20	α Gru	Alnair	النير
21	α Her	Ras Algethi	رأس الجاثي
22	α Hya	Alphard	الفرد
23	α Lep	Arneb	الأرنب
24	α Lib	Zubenel Genubi	الزباني الجنوبي
25	α Lyr	Vega	النسر الواقع
26	α Oph	Ras lhague	رأس الحواء
27	α Ori	Betelgeuse	يد الجوزاء
28	α Peg	Markab	المركب
29	α Per	Mirphak/Algenib	المرفق/ الجنب
30	α Pho	Ankaa/Nair Alzaurak	العنقاء/ نير الزورق
31	α Psc	Alreacha/Okda/Kaitain	الفكة/ العقدة/ الخيطين
32	α PscA	Fomalhaut	فم الحوت
33	α Pup	Tureis	التريس
34	α Sge	Sham/Alsahm	السهم
35	α Sgr	Rukbat/Alrami	الركبة/ الرامي
36	α Ser	Unuk Alhai	عنق الحية
37	α Tri	Muthallah/Ras al Muthallah	المثلث/ رأس المثلث
38	α Tau	Aldebaran	الدبران
39	α UMa	Dubhe	الدب
40	α UMi	Alruccabah	الركبة
41	α Vir	Azimech	السماك
42	α Vul	Anser	النسر

Table 2 Some Latin and Greek star names, and star names from other civilizations

Stars of Latin and Greek origin			
Alkalurops	μ Boo	Muscida	o UMa
Ancha	θ Aqu	Polaris	α UMi
Antares	α Sco	Pollux	β Gem
Arcturus	α Boo	Porrima	γ Vir
Asellus Australis	δ Can	Procyon	α CMi
Asellus Borealis	γ Can	Propus	μ Gem
Bellatrix	γ Ori	Pulcherrima	ε Boo
Canopus	α Car	Regulus	α Leo
Capella	α Aur	Rotanev	β Del
Castor	α Gem	Seginus	γ Boo
Cujam	ω Her	Shualocin	α Del
Gemma/Alphecca	α CrB	Sirius	α CMa
Graffias	β Sco	Spica	α Vir
Grumium/Juza	ξ Dra	Syrma	ι Vir
Kornephoros/Retilius	β Her	Vindemiatrix	ε Vir
Stars of Chinese origin			
Choo or Tchou	α Ara	Raz/Tso Hea	β Crv
Tsih or Cih	γ Cas	Han	ζ Oph
Ma Wei	δ Cen		
Stars of Persian origin			
Alshain	β Aql	Tarazed	γ Aql
Giausar	λ Dra		
Stars of Turkish origin			
Yildum	δ UMi		
Stars of Sumerian origin			
Sargas	δ UMi	Girtab	θ Sco

Fig. 2 New star names assigned between the twelfth century and the present day

Have these new names had an effect on star charts, and what were the sources of these names? We believe that Allen's book (1961) has had the greatest impact on these changes because of its lists of stars written in English.

2 A Research Problem

Since modern astronomical software applications include new star names that previously were unknown to astronomers, we need to research the origins of these names and why they have been added, compare the names with those recognized by the International Astronomical Union (IAU), and count the final number of new names. In 2016, the IAU formed a Working Group on Star Names, specifically to catalogue and standardize approved names for stars, and their work is on-going.[1]

2.1 Hypothesis

Our previous knowledge of star names and their origins will help greatly in solving a large part of how the new star names were added.

2.2 Rationale

More than 140 new star names were found in different mobile phone astronomical applications, and it is very important that amateur astronomers (at very least) are not confused when using different sky charts, even though more than 80% of the stars appearing recently are dim, with magnitudes fainter than +4.

2.3 Objectives

Our main goal is to find out the sources of new star names, and make these results available to professional and amateur astronomers.

[1]The IAU WG lists these new stars on the following web site: http://www.pas.rochester.edu/~emamajek/WGSN/IAU-CSN.txt

2.4 Methodology

We surveyed ten selected astronomy-sky chart applications noted for their fame and popularity, and found that only four of them included significant numbers of new star names. The six remaining applications contained relatively few star names. Some only mentioned the basic and very popular star names, while others merely repeated or copied the first four applications.

We downloaded all ten applications, then surveyed them one-by-one, searching for new star names. Upon encountering a new star name we screen-shot it in order to retain relevant details of the star. This procedure was followed for many new stars that we studied.

We then used Wikipedia and Allen's book to search for the meanings of the names attached to the stars. We found that many of them have been derived from ancient mythologies, but many others had no known meanings. Because of my own background, I was able to easily recognize stars of Arabic origin. In addition, I contacted a number professional astronomers of different nationalities, and they were able to report the meanings of a few star names of Indian and Chinese origin.

2.5 Research Results

Ten software programs (Fig. 3) were adopted for this study. Four of them (Sky Guide, Stellarium, Sky Portal and Sky Chart) included new star names, while the other six (Sky Rover, Sky View, Stars, Star Tracker, Starlight and Star Walk) simply copied the names of the most famous stars. All new star names repeated in more than one application were only mentioned once.

Details of these various astronomical applications are presented individually below.

2.5.1 Stellarium

In Stellarium we found 40 new star names: 11 Arabic, 19 Latin, 2 Chinese, 1 Babylonian, 1 English, 1 German, 1 Greek, 1 Indian, 1 Italian and 2 of unknown origin (see Table 3).

One of the new names is Miram for η Persei (see Fig. 4a). This appears to be an incorrect copy of the name Misam (Arabic = the arm), which was assigned to κ Persei and is shown in the book *Fixed Stars and Constellations in Astrology* (Robson, 1923; see Fig. 4b).

But the strangest new Arabic-like name is Al'dzhabkhakh for μ Leo (Fig. 4c). This name is composed of an Arabic prefix, Al'dzhab, and the suffix khakh, which has no meaning whatsoever.

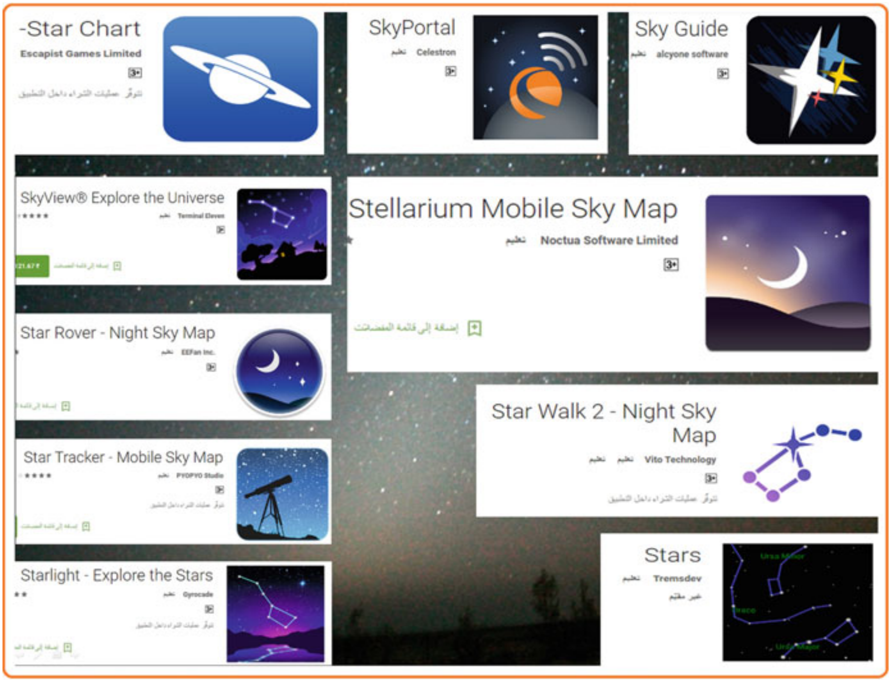

Fig. 3 The software programs used in this study

There were only two new stars that were found in Stellarium and on the IAU list; Miaplacidus (β Car) and Tegmine (ζ1 Cnc).

2.5.2 Sky Guide

In Sky Guide we found 10 new star names: 6 Arabic, 3 Latin and 1 unknown (see Table 4).

Al Minliar (miswritten from Minkhar) al Asad (Arabic = the nose of the Lion) is a name that seems to be given to different stars in the sky by different applications, and it is now the star κ Leo. Arabic mythology says that the Lion has a nose represented by what is now known as the Beehive open cluster in Cancer (Fig. 5, left).

Miaplacidus (β Car) is found in the list of IAU star names.

Terebellum, a Latin word meaning borer or auger, is the name given to two adjacent stars (see Fig. 5, right).

Table 3 Stars found in Stellarium

No	Star name	Bayer designation	Magn	Origin & Meaning
1	Achird	η Cas	3.5	German/? The back of the camel ظهر الناقة
2	Al'dzhabkhakh	μ Leo	3.45	Arabic/? μ Leo (Ras Elased Borealis)
3	Aldhibah	ζ Dra	3.1	Arabic/The plural of Hyena
4	Alphekka (Alfecca) Meridiana	α CrA	4.1	Arabic-Latin/The central jaw (CrA)
5	Armus	η Cap	5	Latin/Alien life
6	Asellus Primus	θ Boo	4	Latin/The first donkey
7	Asmidiske	ξ Pup	3.3	Arabic/Azemich --Spica
8	Brachium	σ Lib	3.25	Latin/The forearm (of the balance)
9	Castra/Kastra	ε Cap	4.5	Latin/A building, or a plot of land (single = Castrum)
10	Cleeia (Kleeia)	δ3 Tau	4.3	Greek/One of the Hyades
11	Deneb Dulfim	ε Del	4	Arabic/The tail of the dolphin
12	Gorgonea Quatra	ω Per	4.6	Latin/The fourth Gorgon -- a female creature
13	Gorgonea Secunda	π Per	4.7	Latin/The second Gorgon -- a female creature
14	Gorgonea Tertia	ρ Per	3.3	Latin/The third Gorgon -- a female creature
15	Haedus 1	ζ Aur	3.65	Latin/The first kid
16	Haedus 2/Haedi	η Aur	3.7	Latin/The second kid
17	Hatsya	ι Ori – 44 Ori	2.75	Latin/?
18	Hyadum 1	γ Tau	3.75	Latin/The first of the Hyades
19	Hyadum 2	δ1 Tau	3.65	Latin/The second of the Hyades
20	Hydrobius	ζ Hya	3.1	Latin/Hydrobius -- some kind of insects
21	Kraz/Raz	β Crv	2.65	Arabic/The sack الخرج
22	Kullat Nunu	η Psc	3.8	Babylonian/The cord that connects the fishes
23	Labr	δ Crt	3.55	?
24	Lucida, Lukida (Anser)	α Vul	4.4	Italian/A light-weight goose
25	Marsik	κ Her	5	Arabic/The forearm
26	Merga (Maraa)	38 Boo	5.75	Arabic/The woman
27	Miaplacidus	β Car	1.65	Latin/The keel of the ship *Argo*
28	Minchir	σ Hya	4.45	Arabic/The nose
29	Miram/Misam	η Per	3.8	Arabic/The wrist
30	Nembus	51 And	3.5	?
31	Peannae Caudalis	π2 Cyg	4.4	Latin-Indian/The tail of Peannae Nee Arivai'
32	Praecipua	46 LMi	3.75	Latin/To give an order
33	Printseps	δ Boo	3.45	English
34	Ruby Star	119 Tau	4.3	English

(continued)

Table 3 (continued)

No	Star name	Bayer designation	Magn	Origin & Meaning
35	Rukh	δ Cyg	2.9	Arabic/A huge legendary bird
36	Sarin	δ Her	3.1	Latin/? Toxic gas
37	Sinistra	ν Oph	3.3	Italian/The left
38	Tegmine/Tegmen	ζ1 Cnc	4.67	Latin/The shell (of the crab)
39	Torcularis Septentrionalis	ο Psc	4.3	Latin/North press
40	Tseen Kee	φ Vel	3.5	Chinese/天紀 'Heavenly order'

2.5.3 Celestron Sky Portal

In Celestron Sky Portal we found 75 new star names: 31 Arabic, 16 Latin, 10 Greek, 4 English, 2 Italian, 1 Albanian, 1 Egyptian, 1 French, 1 Indian, 1 Persian, 1 Spanish, 1 Thai and 5 unknown names (Table 5).

Some star names were derived mainly from recognizable words. ζ Cancri bore the traditional name Tegmine (Tegmen, 'the shell (of the crab)'—see Fig. 6) and the IAU Working Group on Star Names approved the name Tegmine for ζ Cancri A on 12 September 2016.

Musica (18 Del), Libertas (ξ Aql), and Titawin (ε Cas) are three names that also are found on the IAU list.

2.5.4 Star Chart

In Star Chart we found 21 new star names: 7 Arabic, 5 Latin, 1 Chinese, 1 Indian and 7 of unknown origin (Table 6).

One of the most interesting is the Indian star name Bharani which means Aries, the Ram (see Fig. 7 left).

Many star names in Star Chart are completely new (e.g. Sadira, Bunda, Sinistra, Kastra, Jih, Kijam and Neshmel), but not all of their meanings are clear (see Fig. 7 right). None of the names in Table 6 was found on the IAU list.

3 Recommendations

We all should recognize the IAU resolutions and accept the IAU's list of star names. It is not our right to add or omit specific names, and more collaboration is needed between researchers from different cultures and languages in order to further this important topic.

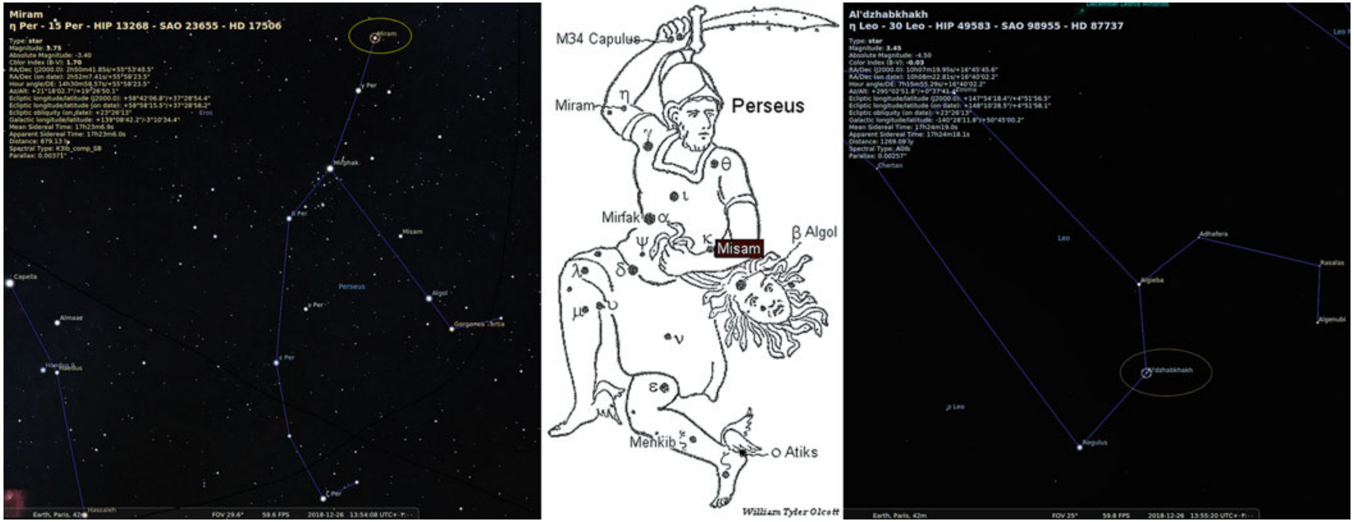

Fig. 4 Miram (left and centre) and Al'dzhabkhakh (right) are two examples of new star names in Stellarium. Miram is believed to have been adopted from the book *Fixed Stars and Constellations in Astrology* (Robson, 1923)

Table 4 Stars found in Sky Guide

No	Star name	Bayer designation	Magn	Origin & Meaning
1	Al Minliar al Asad	κ Leo	4.3	Arabic/The nose of the lion, Alminhar Alasad
2	Ain al Rami	ν1 Sgr	5	Arabic/The eye of Sagittarius
3	Anser	α Vul	4.44	Arabic/The eagle
4	Menchir	δ Hya/σ Hya	4.5	Arabic/The nose
5	Miaplacidus	β Car	1.67	Latin/Miaplacidus is apparently a bilingual combination of the Arabic مياه miyāh for ‘waters’ and Latin placidus for ‘placid’
6	Nodus Secundus	δ Dra	3.1	Latin/The second node
7	Ras al Muthallah	α Tri	3.42	Arabic/The vertex of the triangle
8	Rigil al Awwa	μ Vir	3.9	Arabic/The leg of Al-Awwa
9	Opic	SAO 24615	6.2	?
10	Terebellum	59 Sgr	4.53	Latin/A borer or auger; in English, a genus of sea snails

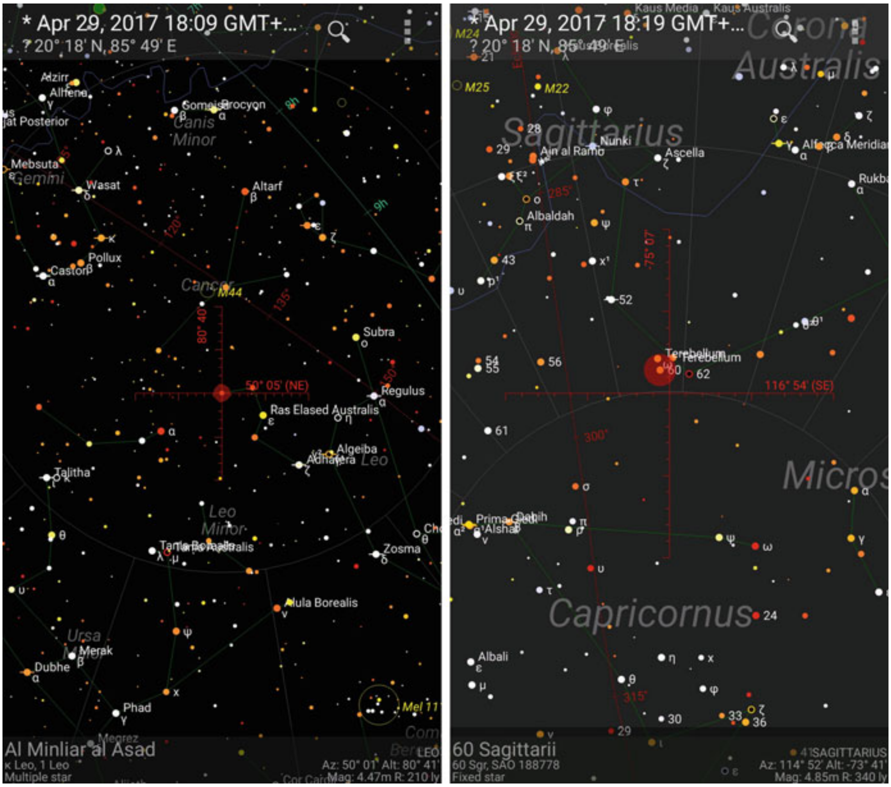

Fig. 5 Al Minliar al Asad (left) and Treballum (right), two examples of new star names in Star Guide

Table 5 Stars found in Celestron Sky Portal

No.	Star name	Beyer designation	Magn	Origin & Meaning
1	Alherem	μ Vel	2.7	Arabic/The cover الحرام
2	Peregrini			Latin/The stranger
3	Adid Australis	ε Per	2.9	Arabic/عضد الثريا The southern humerus
4	Adid Borealis	δ Per	3	Arabic/The northern humerus
5	Ahadi	π Pup	2.7	Arabic/One of أحد ال-
6	Al dhanab	γ Gru	3.0	Arabic/The tail
7	Ras Alkurki			Arabic/The head of the Crane (a bird)
8	Al Fakhbir (Alphecher)	γ Per	2.9	Arabic/“The Excellent One” الفاخر
9	Al fawaris	δ Cyg	2.9	Arabic/The knights
10	Urakhga			Arabic/Rukh, the Roc of Sindbad
11	Al Kab/Alkalb	ι Aur	2.7	Arabic/The dog
12	Al Kafza Borealis	λ UMa	3.4	Arabic/The (second) northern leap
13	Al Kirduh (Alkurha)	χ Cep	4.4	Arabic/A small circular shape on the face of the horse
14	Al Kirkab	κ Gem	3.6	Arabic/?
15	Al Minliar al Ghurab	α Cor	4.0	Arabic/The crow’s beak
16	Algedi Prima	α1 Cap	4.2	Arabic/The first Capricorn
17	Algedi Secunda	α2 Cap	3.6	Arabic/The second Capricorn
18	Agena (Hadar)	B Cen	0.6	Latin/?
19	Alkibash	λ Gem	3.6	Arabic/?
20	Annika (Procyon)	α CMi	0.4	Indian/A name of the goddess Durg (from Sanskrit)
21	Brachium	δ Lib	3.25	Latin/The forearm (of the balance)
22	Cauda Hydrae	γ Hya	3.0	Latin/The head of the snake
23	Castula	υ Cas	4.6	Greek/Pure
24	Celaeno	16 Tau	5.5	Greek/The harpy
25	Cerberus	η Lup	3.4	Greek/A monstrous multi-headed dog
26	Cervantes	μ Ara	5.1	Spanish/A servant
27	Chalawan	47 UMa	5.0	Thai/(ชาละวัน) named after a cave
28	Copernicus	ρ1 Cnc	5.9	English/Copernicus
29	Cornu	σ Lib	3.3	Latin/The horn
30	Coronis/	ε Tau	3.5	Greek/Mother of Aesculapius
31	Oculus Borealis (Ain)			Latin/The eye
32	Dabih Major	β1 Cap	3.1	Arabic/The major slaughterer
33	Dabih Minor	β2 Cap	6.1	Arabic/The minor slaughterer
34	Danab al Shuja	γ Hya	3.0	Arabic/The tail of the male snake
35	Difda al Auwel	α PsA	1.2	Arabic/The first^{t} frog
36	Os Pisces Meridiani			Latin/The central Pisces
37	Donces (Talitha)	ι UMa	3.1	?
38	Double Double	ε Lyr	6.0	English
39	Eudora (Hyadum)	δ Tau	3.8	Greek/Name of five minor goddesses

(continued)

Table 5 (continued)

No.	Star name	Beyer designation	Magn	Origin & Meaning
40	Fafnir	42 Dra	4.8	Greek/The name of the great dragon in Nordic mythology
41	Gruid	β Gru	2.1	Latin/Belonging to Grus
42	Hatya (Meissa) (Heka)	λ Ori	5.6	Arabic/A miswritten version of Heka
43	Helvetios	51 Peg	5.4	Latin/A Celtic tribe that lived in Switzerland during antiquity
44	Heze	ξ Vir	3.4	?
45	Hydor	λ Aqr	3.8	Greek/Water
46	Iclarclau (Dschubba)	δ Sco	2.3	?
47	Juba (Aljeba)	γ1 Leo	2.2	Arabic/The forehead
48	Kakkab	α Lup	2.3	Arabic /The star
49	Kalb (Regulas)	α Leo	1.4	Arabic/The dog
50	Lalande 27,173	Kx Lib	5.8	French/Lalande's star
51	Libertas	ξ Aql	4.7	Latin/Roman Goddess of Liberty
52	Melucta (Mebsuta)	ε Gem	3.0	Arabic/Miswritten from Mebsuta (the stretched arm of the lion)
53	Metallah/ Muthallah	α Tri	3.4	Arabic/A triangle
54	Minbar	χ Dra	3.6	Latin/?
55	Batentaban Borealis			Arabic/The belly of the snake
56	Musica	18 Del	5.5	Italian/Music
57	Myla	α Mus	2.7	Persian/The stork اللقلق
58	Navi	γ Cas	2.2	Italian/The ships or the reverse letters of the name (Ivan)
59	Nehushtan/ Nusakan (Beta CrB)	ξ Ser	3.5	Arabic/The two fences
60	Persian	α Ind	3.1	English/?
61	Polis	μ Sgr	3.8	Coptic-Egypt/The foal المهرة
62	Pulcherrima (Izar)	ε Boo	2.5	Latin/Beautiful
63	Ruticulus (Kornephoros)	β Her	2.8	Latin/Golden red
64	Samoht	α Mon	3.9	Albanian/?
65	Sephdar	η Sgr	3.1	English/Shepard/(Namalwarid النعام الوارد)
66	Suhail al Muhlif/ Suhail	γ Vel	3.4	Arabic/Canopus
67	Talitha Australis	κ UMa	4	Arabic/The southern third leap
68	Titawin	υ And	3.3	Arabic/A city in Morocco تطوان
69	Taygeta	q Tau	4.3	Greek/The mythical King of Laconia
70	Urodelus	ε UMi	4.2	Latin/Urodele or salamander
71	Vathroz Prior	υ Car	6.0	Greek/?
72	Vathorz Posterior	θ Car	2.7	Greek/?
73	Venator (Ratanev)	β Del	5.0	Latin/Stellar
74	Veritate	14 And	5.2	?
75	Vulcan (Keid)	o2 Eri	4.4	Latin/God of fire

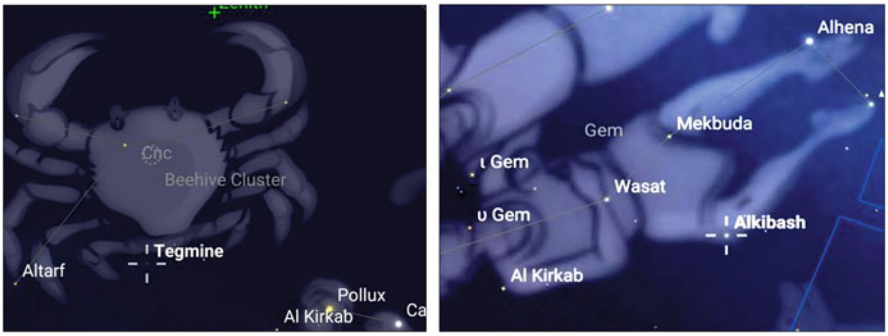

Fig. 6 Tegmine (left) and Alkibash (right), two new star names in Celestron Sky Portal

Table 6 Stars found in Star Chart

No	Star name	Beyer designation	Magn	Origin & Meaning
1	Alwaid	β Dra	2.8	Arabic/The protectors
2	Al Kurud (≡ ζ CMa Alfurud)	θ Col	5	Arabic/The only ones
3	Arm/Armus	η Cap	4.8	Latin/Skin of Evil
4	Ashlesha/Açleshã	P Hya	4.3	?/Embracer (according to Allen's book)
5	Bharani	41 Ari	3.6	Indian/Aries (the ram)
6	Birdun	ε Cen	2.3	Arabic/Non-Arabic horses البرذون
7	Birhan Last	5 Tau	4.1	?
8	Bunda	ξ Aur	4.7	?
9	Chow	β Ser	3.6	Chinese/One of the Chinese imperial dynasties
10	Jih	κ Peg	4.1	?/ The Sun
11	Kajam/Cujam	ω Her	4.6	Latin/(Club)
12	Ksora	δ Cas	2.7	Arabic/A chair (miswritten version of Korsa= Korsi)
13	Lanx Australis (≡ Zubeneschamali)	β Lib	2.6	Latin/A dish
14	Mahasim	θ Aur	2.6	Arabic/Plural of wrist
15	Neshmet	μ Lep	3.3	?
16	Okul	π Cap	5.1	Arabic/Plural of (circular rope) العقال
17	Sadira	ε Eri	3.7	Latin/Mysterious female assassin
18	Salm	τ Peg	4.6	Arabic/The bucket السلم وهو الدلو
19	Sceptrum	53 Eri	3.9	Latin/A sceptre الصولجان
20	Shurnarkabithashutu	τ Tau	3	?
21	Ushakaron?	ξ Tau	3.7	?

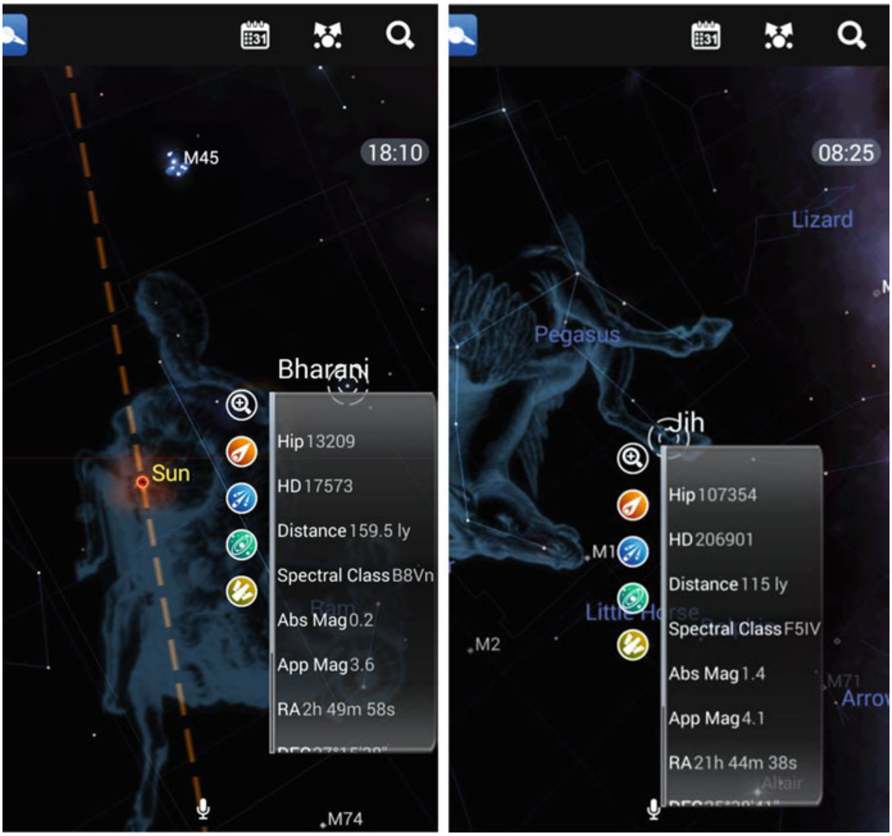

Fig. 7 Bharani (left) and Jih (right), two new star names in Star Chart

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Part III
Eclipses, Transits and Occultations

Transits and Occultations in Indian Astronomy

S. Balachandra Rao, Padmaja Venugopal, and K. Rupa

Abstract In the present paper the procedures for transits and occultations as per the Indian texts are discussed. The algorithms used during various periods are compared with the Improved *Siddhantic* procedures (*ISP)* devised by the authors in the light of modern formulae.

1 Introduction

The procedures for transits and occultations are similar to that of solar eclipse. The participating bodies in the case of transits will be Sun and the planets (Mercury or Venus), while for occultations the Moon and the planet or the star will be under consideration. Transits of Mercury and Venus occur when either of them is in conjunction with the Sun as observed from the Earth, subject to prescribed limits.

The transit of Venus is a less frequent phenomenon as compared to that of Mercury. For example, after the transit of Venus on June 2004 the next occurrence was on 6 June 2012. After that, the subsequent Venus transit will be about 105.5 years later, i.e. in December 2117.

While the detailed working of planetary conjunctions is discussed in all traditional Indian astronomical texts in the chapter *Grahayuti*, it has to be noted that the transits of Mercury and Venus are not explicitly mentioned. This is mainly because when either of these inferior planets is close to Sun it is said to be 'combust' (*asta*) and hence not visible to the naked eye. A transit (of Mercury or Venus) is called *sankramaṇa* (of the concerned planet) or *Gāḍhāsta'*. In a transit of Mercury or Venus the tiny planet passes across the bright disc of Sun as a small black dot.

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2 Computation of a Transit According to The *Ketakī Grahagaṇita*

The following example discusses the transit of Venus of 8 June 2004 according to the *Ketakī Grahagaṇitam* of Venkatesha Ketkar (1930).

2.1 An Example

The transit of Venus on 8 June 2004 corresponds to *Śālivāhana śaka* year (elapsed) 1926, *Jyeṣṭhamāsa-Kṛṣṇapakṣa-Ṣaṣṭhī*, Tuesday. Note that here a *cakra* is a cycle of 19 solar years, and the remnant days are called *ahar-gaṇa* from Ketkar's epoch.

The *cakra* and *ahargaṇa* cycles and the remnant civil days since Ketkar's epoch are: *Cakra*: $C = 6$, *Ahargaṇa*: $A = 4447$.

The mean positions of the Sun and Venus are given by

(i)

$$\text{Mean Sun} = \frac{A \times 69^{\circ}}{70} - \frac{\dot{A}''}{158} - +(C + D) + K$$

where *Dhruvaka*, $D = 0^{\circ}\ 7'\ 38''$ and *Kṣepaka*, $\mathrm{K} = 349^{\circ}\ 05'$.

(ii)

$$\text{Mean Venus} = \frac{A \times 8^{\circ}}{5} + \frac{A'}{8} + \frac{A''}{6} + (C + D) + K$$

where *Dhruvaka*, $D = 318^{\circ}\ 47'\ 10''$ and *Kṣepaka*, $\mathrm{K} = 195^{\circ}\ 28'$.

In the example, $C = 6$ and $A = 4447$. For the mean sunrise at Ujjayinī this yields:

Mean sidereal Sun: $52^{\circ}\ 50'\ 56''$
Mean sidereal Venus: $232^{\circ}\ 51'\ 13''$

2.1.1 True Longitudes and Daily Motions of the Sun and Venus

(1) The Sun's corrected *mandocca* (apogee) $= 79^{\circ}\ 03'\ 30''$.
The Sun's *mandakendra* (anomaly from Apogee)

$$\begin{aligned} &= \text{Mean Sun} - \text{cor.}\textit{Mandocca} \\ &= 52^{\circ}\ 50'56'' - 79^{\circ}\ 03'30'' = 333^{\circ}\ 47'26''. \end{aligned}$$

From this, by adding the *mandaphala*, we get

(i) True (*manda* corrected) Sun $= 53^{\circ}\ 41'\ 06''$

(ii) True daily motion of the Sun = 57′ 21″
(iii) Mean Venus = 232° 51′ 13″

cor. *mandocca* of Venus = 287° 42′ 51″
Mandakendra (Anomaly) = 305° 08′ 22″
Mandaphala (Equation of centre) = 0° 38′ 55″
Manda corrected Venus = 233° 30′ 08″
Śīghrakendra of Venus = Manda corrected Venus – Manda corrected Sun = 233° 30′ 08″ − 53° 41′ 06″ = 179° 49′ 02″
Śīghraphala = 0° 25′ 53″
Adding the *śīghraphala* to the true Sun: True Venus = 54° 06′ 59″

(iv) True daily motion of Venus = −37′ 28″

The negative sign indicates that Venus is *retro-grade* (*vakra*).

(v) Thus, at the mean sunrise on 8 June 2004, we have:

Mean Sun = 52° 50′ 56″, True Sun = 53° 41′ 06″
Mean Venus = 232° 51′ 13″, True Venus = 54° 06′ 59″
True daily motion of Sun, *SDM* = 57′ 21″
True daily motion of Venus, *VDM* = − 37″ 28″

Therefore, the instant of *conjunction* of Sun and Venus is $12^h\ 33^m\ 5^s.7$ (Ujjayini).

(vi) At the instant of conjunction: True Sun = True Venus = 53° 56′ 45″.
(vii) *Śīghrakaraṇa* of Venus:

We have *mandakaraṇa* of Venus (mean heliocentric distance × 100) = 72.

$$\therefore \acute{S}\bar{\imath}ghrakara\d{n}a = 72 + 100 - 144 = 28.$$

(viii) Angular diameter (biṃbam) of Venus, d1 = 59″ 19‴.
(ix) Parama lambanam (horizontal parallax) = 32′
(x) Spaṣṭa Ravimadhya śara (true heliocentric latitude of Venus) = 1′ 54″
Spaṣṭa Bhūmadhya śara (true geocentric latitude of Venus), $\beta = 4'\ 53''.43$
(xi) Angular diameter (*biṃbam*) of the Sun,

$$d_2 = \frac{Sun\text{'}s\ true\ daily\ motion - 57'}{4} + 31'.5 = 31'35''$$

(xii)
$$M\bar{a}naikya\ Kha\d{n}\d{d}a = \frac{Dia.of\ Sun + Dia.of\ Venus}{2} = \frac{d_2 + d_1}{2} = \frac{(31'\ 35'' + 59''\ 19''')}{2} \approx 16'17''$$

$$\text{Mānāntara } Khaṇḍa = \frac{d_2\, d_1}{2} = \frac{\left(31'\,35'' + 59''19'''\right)}{2} \approx 15'18''$$

(xiii) The difference between śaras of the Sun and Venus $\approx 4^{'}53^{''}$(note: the Sun's śara = 0).

(xiv) Sthiti (Half – duration) =

$$\sqrt{\frac{(\text{Mānaikya } Khaṇḍa)^2 - \beta^2}{(SDM - VDM}} \times 60\ Gh$$

$$= \sqrt{\frac{(16'17'')^2 - (4'53'')^2}{57'\,21'' - (-37'28'')}} \times 60\ Gh = 9^{gh}49^{vig}47.31^{pvig}.$$

(xv) Marda (half-duration of totality)

$$\sqrt{\frac{(\text{Mānaikya } Khaṇḍa)^2 - \beta^2}{(SDM - VDM}} \times 60\ Gh$$

$$= \sqrt{\frac{(15'17'')^2 - (4'\,53'')^2}{57'\,21'' - (-37'\,28'')}} \times 60\ Gh = 9^{gh}9^{vig}51^{pvig}$$

Details of the transit are summarized below in Table 1.

Meanwhile, in his *Jyotirgaṇitam* Ketkar (1930) worked out details of the transit of Mercury of 14 November 1907 and the transit of Venus of 9 December 1874 (see Fig. 1). Both transits were worked for his place, Bagalkote (now in Karnataka), which shared almost the same longitude as Ujjayini.

Table 1 Summary of the transit of Venus on 8 June 2004[a]

Name	Contact	Gh.	Vig.
Sparśa (beginning)	First	6	32
Sparsa Marda (beginning of totality)	Second	7	12
Madhya (Middle)	—	16	22
Moksa Marda (end of totality)	Third	25	32
Moksa (end of the transit)	Fourth	26	12

[a]The timings listed here are after the mean sunrise at Ujjayini

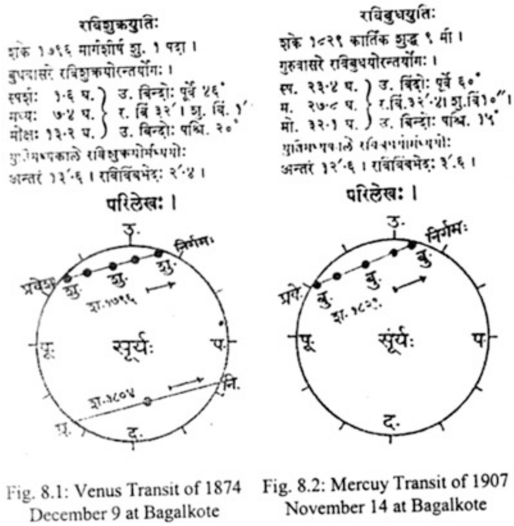

Fig. 1 Details of the transit of Venus of 9 December 1874 and the transit of Mercury of 14 November 1907. (After Ketkar 1930)

3 Improved *Siddhāntic* Procedure (ISP) for Transit Computations

We provide below a procedure inspired by the papers of Professor T.S. Kuppanna Sastry on eclipses within the framework of *Siddhāntic* astronomy, which has been evolved by us to compute transits. This procedure is different from the modern one.

It is important to note that for a transit the inferior planet (Mercury or Venus) is in inferior conjunction with the Sun and always retrograde (*vakra*).

In what follows, the parameters are represented by convenient-to-remember multi-lettered notations like SDIA, PAR, HDUR etc. for the convenience of easy identification as also for the advantage of computer programming.

(i) The instant of conjunction in longitude of the true Sun and the true planet (Mercury or Venus) is determined.
(ii) At the instant of conjunction the following parameters are determined:

1. True positions of the Sun and the planet
2. (a) True daily rates of motion of the two bodies (*SDM* and *PDM*)
   (b) $\dot{m} = \dfrac{(SDM - PDM)}{60}$
3. The geocentric latitude (śara) of the planet β
4. The horizontal parallaxes of the two bodies (PAR1 and PAR2)
5. The ascending node (pāta) of the planet
6. The angular diameters (biṃbam) of the bodies (SDIA) and (PDIA)
7. Note that items (2), (3), (4) and (6) are in minutes of arc (kalās).
8. VRKNG $\equiv \frac{(PDM - SDM)}{60}$, difference of rates of motion per *nāḍi.*

Note: (a) 1 day = 60 *nāḍi*s or *ghatīs* ≡24 hours
$\therefore 1$ *nādī* $= \frac{2}{5}$ hour = 24 minutes and 1 *vināḍī*
= 24 seconds
VRKNG: Vyarka Graha Nāḍī Gati
(b) Corrected Vyarka- Graha- Nāḍīgati,

$$\dot{m} = \frac{206}{205} \times VRKNG$$

2. Let $PAR = PAR_1 - PAR_2$, difference of the parallaxes in min of arc
3. $D = PAR + \frac{(SDIA+PDIA)}{2}$, sum of the semi-diameter with the difference of parallaxes
4. $D' = PAR + \frac{(SDIA-PDIA)}{2}$, sum of the difference of parallaxes with the difference of the semi diameters.
5. The corrected latitude (*śara*) of the planet:

   $\beta' = \beta \times \frac{204}{205}$ in minutes of arc.

6. The condition for the occurrence of the transit and its totality:

   (a) If, $|\beta'| < D$, the transit occurs
   (b) If, $|\beta'| < D'$, the transit is total

7. The middle of the transit is obtained by applying a small correction to the instant of conjunction.

   This correction is given by

$$\frac{-\beta' P}{(\dot{m})^2 + p^2} \textit{nādī},$$

   where P = Difference in rates of change in the planets' latitude per *nāḍī.*

8. The half-duration of the transit is given by

$$HDUR = \frac{\sqrt{D^2 - (\beta')^2}}{\dot{m}} \text{in } \textit{nāḍīs},$$

9. The half-duration of the totality is given by

$$THDUR = \frac{\sqrt{(D')^2 - (\beta')^2}}{\dot{m}} \text{ in nāḍīs},$$

10. The beginning of the transit (first contact, external ingress): BEGG = MIDDLE – HDUR
11. The beginning of the totality (second contact, internal ingress): BEGGT = MIDDLE – THDUR

12. The middle of the transit is the instant of greatest obscuration.
13. The end of the totality (third contact, internal egress): ENDT = MIDDLE + THDUR
14. The end of the transit (fourth contact, external egress): END = MIDDLE + HDUR

3.1 The Transit of Venus of 8 June 2004

We illustrate the above procedure by applying it to the famous 2004 Venus transit (geocentric). According to the *Indian Ephemeris* we have:

1. Instant of conjunction (in longitude) of the Sun and Venus: $14^h\ 08^m$ (IST).
   At the instant of conjunction we have:
2. True Sun = True Venus = $77^\circ\ 53'\ 32''$ (*Sāyana*, tropical)
3. True daily motion: $SDM = 0^\circ\ 57'\ 23''$, $PDM = -37'\ 36''$
4. Latitude of Venus, $\beta = -11'$
5. Parallax of the Sun, $PAR_1 = 8''.659262$
6. Parallax of Venus $PAR_2 = 30''.44077$
7. Difference of parallaxes, $PAR = PAR_2 - PAR_1 = 21''.781508$
8. Node of *Śukra* = $76^\circ\ 43'\ 12''$ (*Sāyana*)
9. Angular semi-diameters:

$$\frac{SDIA}{2} \equiv 946''.8672, \frac{PDIA}{2} = 28''.86874,$$

10. VRKGN $= \frac{(57'23''+37'36'')}{60} = 1'.5830556$
11. $\dot{m} = \dfrac{206}{205} \times 1'.5830556 = 1'.590778$
12. $D = PAR + \frac{SDIA+PDIA}{2} = 16'.769612$
13. $D' = PAR + \frac{SDIA-PDIA}{2} = 15'.807321$
14. $\beta' = \beta \times \frac{204}{205} = -10'.946341$
15. Since $|\beta'| < D$ the transit is possible, and if $|\beta| < D$ the transit is total
16. Correction to instant of conjunction for middle of the transit:

$$\frac{-\beta' P}{(\dot{m})^2 + p^2} = -16^m.35.$$

17. Middle = $14^h\ 08^m - 16^m.35 = 13^h\ 51^m.65$ (IST)

Table 2 Transit of Venus of 8 June 2004

Contacts	ISP (IST)	Meeus (IST)
Beginning of transit (first contact)	$10^h\ 41^m$	$10^h\ 45^m$
Internal ingress (second contact)	$11^h\ 01^m$	$11^h\ 04^m$
Middle of transit	$13^h\ 52^m$	$13^h\ 51^m$
Internal egress (third contact)	$16^h\ 43^m$	$16^h\ 38^m$
End of transit (fourth contact)	$17^h\ 02^m$	$16^h\ 58^m$

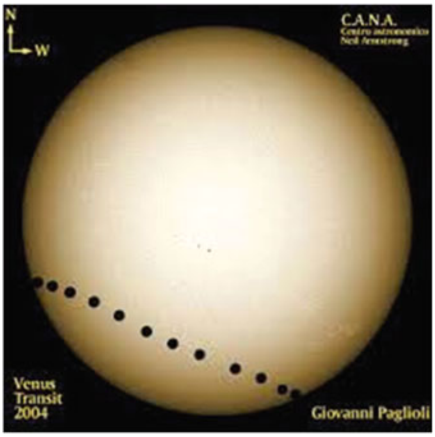

Fig. 2 Schematic diagram showing the path followed by Venus across the solar disk during the transit of 8 November 2004

18. HDUR $= \dfrac{\sqrt{D^2 - (\beta')^2}}{\dot{m}} = 3^h 10^m 44^s\ 3^h 10^m.7$

   (a) First contact: $13^h\ 51^m.65 - 3^h\ 10^m.7 \approx 10^h\ 41^m$
   (b) Fourth contact: $13^h\ 51^m.65 + 3^h\ 10^m.7 \approx 17^h\ 02^m$

19. THDUR $= \dfrac{\sqrt{(D')^2 - (\beta')^2}}{\dot{m}} = 2^h 51^m 13^s$

(a) Second contact: $13^h\ 51^m.65 - 2^h\ 51^m \approx 11^h\ 01^m$
(b) Third contact: $13^h\ 51^m.65 + 2^h\ 51^m \approx 16^h\ 43^m$

3.1.1 Summary of the Circumstances of the Transit of Venus

In Table 2, the instants of contact obtained according to our ISP are compared with those in Meeus (1989) (converted to IST). There is a difference of about 4 min in the *HDUR*, which gets reduced by the 'successive approximation' (*asakṛt*). The movement of Venus across the Sun's disc is shown schematically in Fig. 2.

3.2 The Transit of Mercury of 8/9 November 2006

1. Instant of conjunction of the Sun and Mercury: $3^h\ 20^m$ A.M (IST) on 9 November 2006. At the instant of conjunction we have the following:
2. True Sun = True Mercury = $226°\ 21'\ 30''$ (Sāyana)
3. True daily motion: SDM = $60'\ 13''$, PDM = $-79'\ 0''$
4. Latitude of Mercury, $\beta = 7'$ (S)
5. Parallax of the Sun, PAR1 = $8''.8799$
6. Parallax of Mercury, PAR2 = $13''.02111$
7. Node of Mercury = $48°\ 11'\ 57''$ (Sāyana)
8. Angular semi diameters: $\frac{SDIA}{2} = 970''.2929$, $\frac{PDIA}{2} = 4''.975$
9. VRKNG = $\frac{60'13''+79'0''}{60} = 2'.3202778$ per nāḍī
10. $\dot{m} = \frac{206}{205} \times 2'.3202778 = 2'.3315962$ per nāḍī
11. $D = PAR + \left(\frac{SDIA+PDIA}{2}\right) = 979'.4091 = 16''.323485$ where PAR = PAR2 – PAR1 = $13''.0211 – 8''.8799 = 4''.1412$
12. $D' = PAR + \left(\frac{SDIA-PDIA}{2}\right) = 969'.4591 = 16'.157652$
13. $\beta' = \beta \times \frac{204}{205} = -6'.9658537$
14. Since, $|\beta| < D$ the transit is possible and since, $|\beta'| < D'$, the transit is total.
15. Correction to the middle of the transit

$$\frac{-\beta' P}{(\dot{m})^2 + p^2} = -8 \text{ min}$$

$$\text{MIDDLE} = 3^h20^m - 8^m = 3^h12^m(\text{IST})$$

16. $HDUR = \frac{\sqrt{D^2 - \beta'^2}}{\dot{m}} \approx 6^n.331523 \equiv 2^h31^m57^s$
17. THDUR = $\frac{\sqrt{D'^2 - \beta'^2}}{\dot{m}} \approx 6^n.252788\ 2^h30^m04^s$

3.2.1 Summary of the Circumstances of the Transit

Table 3 provides the timings of the contacts and the middle of the transit, and our values are compared with those from Meeus (1989).

Remarks: (1) The half duration according to *ISP* is less by about 3 min. This difference gets reduced by the process of 'successive approximation' (*asakṛt*); (2) The timings of the circumstances here are such that the transit is not visible in India.

We have successfully demonstrated how our Improved Indian classical astronomical procedure (*ISP*) can be adopted to predict correctly the transits of Venus and

Table 3 The transit of Mercury on 8/9 November 2006

Contacts	ISP (IST)	Meeus (IST)
Beginning of transit (first contact)	$00^h\ 40^m$	$00^h\ 43^m\ 09^s$
Internal ingress (second contact)	$00^h\ 42^m$	$00^h\ 45^m\ 02^s$
Middle of transit	$03^h\ 12^m$	$03^h\ 2^m\ 09^s$
Internal egress (third contact)	$05^h\ 42^m$	$05^h\ 39^m\ 21^s$
End of transit (fourth contact)	$05^h\ 44^m$	$05^h\ 41^m 14^s$

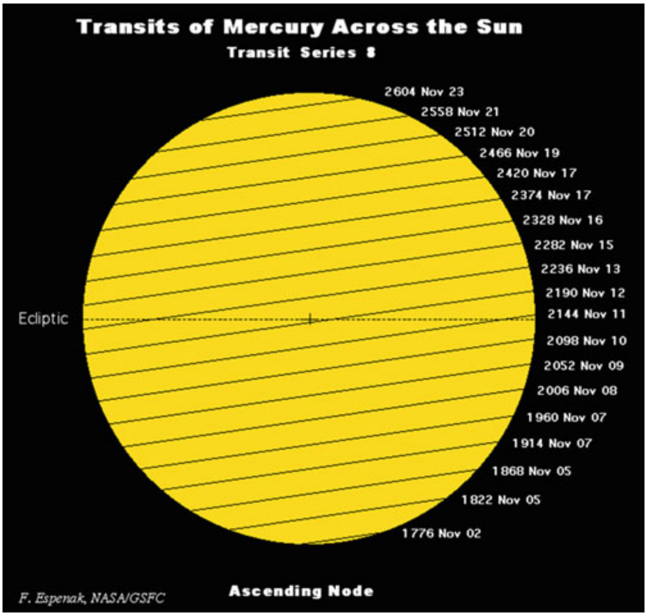

Fig. 3 Transits of Mercury. (After Fred Espenak)

Mercury. The efficacy of our procedure is verified by working out the recorded transits of Mercury and Venus starting from 1631.

Transits of Mercury over a cycle near the ascending node is shown in Fig. 3.

3.3 *The Transit Venus of 6 June 2012*

Following the procedure explained earlier and by 'successive approximations', the timings of the contacts and the mid-event were obtained for the transit of Venus of 6 June 2012, the final such transit in the twenty-first century. The next transit of Venus will be 105.5 years later, on 11 December 2117. The *geocentric* circumstances are listed in Table 4. Here 'geocentric' means the computations are with respect to the Earth's centre.

Table 4 The transit of Venus of 6 June 2012

Contacts	Timings (IST)
Beginning of transit (first contact)	$03^h\ 41^m$
Internal ingress (second contact)	$03^h\ 59^m$
Middle of transit	$07^h\ 01^m$
Internal egress (third contact)	$10^h\ 03^m$
End of transit (fourth contact)	$10^h\ 21^m$

Table 5 Contact timings at six Indian cities during the 6 June 2012 transit of Venus

	Internal Egress (IST)			Internal Egress (IST)		
City	h	m	s	h	m	s
Bangalore	10	04	53.7	10	22	08.6
Chennai	10	04	38.2	10	21	52.8
Delhi	10	05	15	10	22	27.2
Hyderabad	10	04	55.9	10	22	09.7
Kolkota	10	04	05.4	10	21	18.2

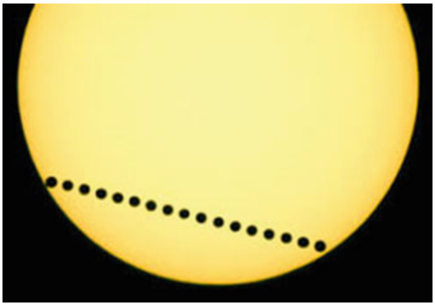

Fig. 4 The transit of Venus of 6 June 2012

The transit was visible in India. But, the first and second contacts (external and internal in-gress) took place long before sunrise and hence could not be seen from anywhere in India. Only the middle (instant of least distance) and the last two (internal and external egress) contacts could be seen at all places in India. Table 5 gives the instants of the middle, internal egress and external egress for six cities in India, while, Fig. 4 shows a schematic diagram of Venus transit on 6 June 2012.

4 Superior Conjunction of an Inferior Planet with The Sun

The transit of the inferior planets, Venus and Mercury discussed in the previous section occur when these planets have an inferior conjunction with the Sun. Of course these are subject to their respective transit limits (like the ecliptic limits).

An interesting situation, rarely discussed, is when an inferior planet has a superior conjuncttion with the Sun. In the case of transit the inferior planet comes in between the Earth and the Sun. This is the case of an *inferior* co-junction of the planet. On the other hand, in the case of a *superior* conjunction Sun hides the inferior planet i.e. the Sun lies between the Earth and the planet.

In Indian classical astronomical texts, the two situations are not explicitly discussed. However, their circumstances can be worked out by the general classical method of planetary conjucttion (*grahayuti*) discussed in this paper later.

In fact, the cases of inferior and superior conjunctions of an inferior planet can be easily determined from the Indian *siddhantic* procedure.

In the case of an inferior conjunction the *śīghrakendra* of the planet (*Budha* and *śukra*) is 180° where as for the superior conjunction the *śīghrakarṇa* of the planet is the difference between the heliocentric distances of the Earth and the planet. Here *śīghrakendra* is the angular distance between Sun and the planet as seen from the Earth. On the other hand, for a superior conjunction the *śīghrakarṇa* is a measure of its geocentric distance. We have considered a modern example of superior conjunction of Venus with the Sun in what follows.

4.1 The Superior Conjunction of Venus with the Sun (**Śukrāditya yuti**) on 9 June 2008

The instant of the superior conjunction in longitude is $9^h\ 7^m.5$ (IST). This is not a transit of Venus since in this case the planet comes behind the Sun and hence the phenomenon is referred to as Venus' occultation by the Sun. The duration of the occultation is quite long and extends to the previous day as well as to the following day of the day of the conjunction.

In what follows, *sāyana* means tropical (longitude) and *nirayaṇa* is the sidereal (longitude). At the instant of conjunction (in longitude) viz., 9 07 .5(IS T), we have

1. (i) Sun's *sāyana* longitude: $78° 41'$
   (ii) Venus' *sāyana* longitude: $78° 41'$
2. (i) Sun's diameter, $SDIA = 2 \times 946''.7826 = 31'.55942$
   (ii) Venus' true diameter, $VDIA = 2 \times 4''.08054 = 0'.16108$
3. (i) Sun's parallax, $PAR_1 = 8''.6584$
   (ii) Venus parallax, $PAR_2 = 5''.671$
4. (i) Difference in parallaxes, $PAR = PAR_2 - PAR_1 = -3''.5913$
5. (ii) Venus' true daily motion, $PDM = 73'.73$
6. $D = PAR + (SDIA + VDIA)/2 = 951''.528145 = 15'.8588$
7. $\dot{m} = 206/205 \times (PDM - SDM) = 16'.40966$ per day
8. Venus' latitude, $\beta \equiv \mathrm{p} = +2'.85$
9. Rate of change in Venus' latitude, $P = 2'.383$ per day
10. Correction to the instant of conjunction for the middle of the occultation
    $COR = -35^m.9$
    MIDDLE $= 9^h\ 07^m.5 - 0^h\ 35^m.9 = 8^h\ 31^m.6$ (IST)
11. Half duration, HDUR $= 21^h\ 58^m.43$
    Inst. of the Beginning: $10^h\ 33^m$ (IST) on 8 June

Inst. of the Middle: $8^h\ 32^m$ (IST) on 9 June
Inst. of the End: $6^h\ 30^m$ (IST) on 10 June

Note: This phenomenon of the superior conjunction of an inferior planet is rarely discussed in conventional texts.

4.2 The Transit of Mercury on 11 November 1861

In his classical nineteenth century tome, *A Manual of Spherical and Practical Astronomy* Chauvenet (1960) worked out the details of this transit. It was not visible in the U.S.A. while in Europe only the egress could be seen.

Chauvenet computed the egress time for Altona (longitude 9° 56′.5 E; latitude 53° 22′.8 N) as $22^h\ 01^m\ 10^s.4$. The time actually observed by astronomers Petersen and Pope (1861) was $22^h\ 01^m\ 08^s.5$. The timings were local mean time of Altona (from noon).

5 Lunar Occultation of Planets

Indian astronomers have classified the different types of conjunctions between two heavenly bodies. If the conjunction is

(i) between two planets it is called *yuddha* (encounter);
(ii) between a planet and the Moon it is called *samāgama*—in modern parlance this phenomenon is referred to as 'lunar occultation';
(iii) between a planet and the Sun, it is called *astamana* or *astańgata* (heliacal setting).

In the *Sūryasiddhānta* the above concepts are described as follows:

tārāgrahaṇāṃ anyónyaṃ syātāṃ yuddhasamāgamau |
samāgamaḥ śaśāńkena sūryeṇāstamanaṃ saha|| – sūrya siddh. (Ch.7 śl.1).

We will illustrate the above procedure with two examples: a lunar occultation of a star and lunar occultation of a planet. We adopt the improved *Siddhāntic* Procedure (*ISP*), explained earlier, to work out these phenomena.

*5.1 Occultation of Regulus (*Makha*) on 18 December 2016*

Instant of conjunction: $23^h\ 23^m$ (IST)

True longitude of Moon = True longitude of Regulus = 150°.0725
Moon's latitude $\beta1 = -31'$

Latitude of Regulus, $\beta_2 = 28'$

$$\beta = -59'(\beta 1 - \beta_2)$$

Horizontal parallax of the Moon = 57′.256
Moon's angular diameter = 31′.20267 = *MDIA*
Note: The parallax and the diameter of the star are negligible compared to those of the Moon.

$$D = 72'.85734 = D'$$

$$\beta' = (\lambda) = -59' = \left(\beta \times \frac{204}{205}\right)$$

$$\dot{m} = MDM \times \frac{204}{205} = 13'.2667$$

Occultation is total ($\because D > \beta'$)
$D\beta = 4140''$ $\dot{m} = 769''.002$

$$\mathrm{COR} = \frac{99|\lambda|}{1000\dot{m}} = 19.79014\ (\mathrm{min})$$

$$\text{Half interval} = 0.4098874\ \text{hrs}$$

The circumstances are summarized in Table 6.

Note that the non-occultation of Regulus (*Makha*) started on 9 June 2008. The last occultation was on 13 May 2008. The next occultation was on 18 December 2016. This meant that there was a long gap of non-occultations of nearly 8 years and 9 months. The next series of occultations ran from 18 December 2016 to 25 April 2018 (i.e. for a period of 1 year 4 months and 7 days).

5.2 *Occultation of Mars on 21 March 2015*

Instant of conjunction = $28^h\ 26^m$ (IST)
Tropical longitude of Sun = Tropical longitude of Mars = 22° 45′ 46″
Moon's latitude $\beta 1 = 1°\ 11'$ (south)

Table 6 Summary of the occultation of Regulus on 18 December 2016

Contacts	ISP(IST)
Beginning	$23^h18^m11^s$
Middle	$23^h42^m47^s$
End of occultation	$24^h07^m23^s$

Table 7 Summary of the occultation of Mars on 21 March 2015

Contacts	ISP(IST)
Beginning	$27^h54^m22^s$
Middle	28^h26^m
End of occultation	$29^h57^m38^s$

Latitude of Mars $\beta_2 = 0° \ 15'$ (south)
Moon's Parallax $= 3635''.324$
Mars' Parallax $= 3''.786$
Moon's semi-diameter $= 990''.559$
Mars' semi-diameter $= 2''.0149$
D = (Sum of semi-diameter) + Moon's Parallax $= 992''.5739 + 3635''.324 = 77'.1316$
$\beta_1 - \beta_2 = -1° \ 11' + 0° \ 15' = 56'$ (south)
Daily motion of Moon (MDM) $= 14° \ 38' \ 35''$
Daily motion of Mars (PDM) $= 44' \ 34''$
$MDM - PDM = 13° \ 54' \ 1'' = 834' \ 1''$

$$\beta' = \beta \times \frac{204}{205} = -55'.7268 \, \dot{m} = VRK \times \frac{206}{205} = 838'5''(\text{day})$$

$$HDUR = \frac{\sqrt{D^2 - (\beta')^2}}{\dot{m}} = \frac{53'.32757}{838'5''} \times 24^h = 1^h31^m38^s$$

The circumstances are summarized above in Table 7.

6 Conclusion

In the preceding sections we have explained in detail the procedures for the computation of (i) transits, (ii) the superior conjunctions of Venus and Mercury and (iii) lunar occultations of planets and stars.

We have made a comparison of the procedures given in classical texts and also by Venkatesh Ketkar (1930) with our own Improved *Siddhāntic* Procedures (*ISP*). The results of our *ISP*, with its simpler procedure and *sans* Besselian elements, compare well with modern results.

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The Reliability of the Records of Observed Solar Eclipses in India and Comparison with Contemporaneous Eclipse Data from Other Countries

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Abstract In this paper, we examine the reliability of the records of solar eclipses observed in southern India taken from recently compiled records of solar eclipses. Observations in AD 938, 1087 and 1268 survived the preliminary examination of reliability. We have carried out a more precise examination utilising the so called 'Sôma Diagram', which determines the ΔT values of the periods with the aid of contemporaneous eclipse data from other countries. Finally, the Indian observations of AD 938, 1087 and 1268 have been incorporated into the determination of a narrower range of ΔT values. We will describe the examination process and give these three ranges.

Period	Observed years	Range of ΔT
938	912, 938, 939, 968	1513 s < ΔT < 2164 s
1087	1061, 1069, 1087	1197 s < ΔT < 1673 s
1268	1245, 1267, 1268, 1275	98 s < ΔT < 806 s

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1 Introduction

We have been determining the range of ΔT using solar eclipses observed in various countries: China, Babylonia, Greece, Rome, Iran, Iraq, Korea and Japan (see, e.g. Tanikawa and Sôma, 2004; Tanikawa, Sôma and Ueda, 2010, 2014), and using occultations of China (Sôma and Tanikawa, 2016). Here

$$\Delta T = \mathrm{TT} - \mathrm{UT}$$

where TT is the terrestrial time, meaning uniform time, and UT is the universal time, meaning the time measured by the spin rate of the Earth.

Recently, Indian data became available. The Indian data of solar eclipses range from the fifth century to the present (Subbarayappa, 2014). In addition, more than 300 solar and lunar eclipses recorded as stone inscriptions in southern India have been tabulated by Shylaja and Geetha (2016).

One of the authors of this paper (BSS) then went back to the original phrases and sentences on the Indian stone inscriptions and interpreted their meanings. As a result, we select five eclipses that may have been observed.

After giving a list of eclipses in Sect. 2.1, we carry out a preliminary check of the reliability of the records in Sect. 2.2. Here we simply plot for each eclipse a totality or annularity band for a reasonable value of ΔT, and compare qualitatively the magnitude of the eclipse mentioned in the record and the actual magnitude. We discard the eclipse of 16 December 1107, which surely was partial at the observation site and therefore is not useful for the determination of ΔT.

The second step is done in Sect. 3 for the data survived the preliminary examination, when we incorporate eclipse data from other countries. We compiled so-called ‘Sôma Diagrams’, which determine the range of ΔT values at the time of the observations using contemporaneous eclipse data from India and other countries. From the Sôma Diagrams, we can check the reliability of the eclipse records, both from India and other countries. We will describe the examination process.

Here we explain the necessity of the examination of reliability. Some records of solar eclipses have exaggerated expressions, even though these were observed records. For example, a record says that the eclipse was total. However, actually it was nearly total. Sometimes it was only partial. In the case of observed records, it is always necessary to examine the reliability of the descriptions, that is, exaggeration or not. In particular, single reports of observation are not reliable since, in general, the impression of unusual phenomena tends to be exaggerated. When there are plural reports from different places or different years, these independent records strengthen the reliability of the contents of the reports. In fact, two independent exaggerated reports may lead us to a contradiction. One realistic and one exaggerated report may also lead us to a contradiction. Two realistic reports give us useful information for ΔT.

In Sect. 3 we obtain the three ranges of ΔT listed in the Abstract.

Table 1 A list of observed solar eclipses, observation sites, and related inscriptions

Y	M	D	Place	Description
819	06	26	Saligrama Hasana	Sakalakalikalusha (almost total)
938	02	03	Ottur, Soraba	Valaya grahana (annular eclipse)
1087	08	01	Soundatti, Raibag	total
			KR Nagara, Mysore	'total' is not mentioned
			Kurtuoti Gadag	'total' is not mentioned
			Hunagund Bijapur	'total' is not mentioned
			Kolhapur Manaharashtra	'total' is not mentioned
			Kalkere, Hanagal	'total' is not mentioned
1107	12	16	Harapanahalli, Hassan	'annular' is not mentioned
			Anduru, Tulajapur Maharashtra	annular
			Bagali	'total' is not mentioned
1268	11	06	Akkalapundi	eclipse
			Mutukuru, Palnad Taluk	
			Ujjini, Kudligi Taluk	

2 Observed Eclipses from the Ninth to the Thirteenth Centuries in India

2.1 List of Eclipses

Subbarayappa (2014) has published a list of 159 solar eclipses dating between AD 900 and 1600 that were recorded on inscribed stones from southern India. One of the authors of this paper (BSS) then independently chose records that strongly suggested that the eclipses were observed, and these are listed in Table 1.

We show the positions of the observation sites in Fig. 1, and list them in Table 2.

2.2 Preliminary Analyses

In this Section, we first plot the equi-magnitude curves including totality or annularity band of eclipses of Table 1 for reasonable values of ΔT and examine whether the inscriptions are reports of observations or predictions, and whether they are realistic or exaggerated.

2.2.1 The Eclipse on 26 June 819

The equi-magnitude curves are shown in Fig. 2 (upper panels). The right panel is the enlargement. The figure shows that the eclipse was deep at Saligrama Hasana (cross), hence we judge that this eclipse was actually observed. Inscriptions say

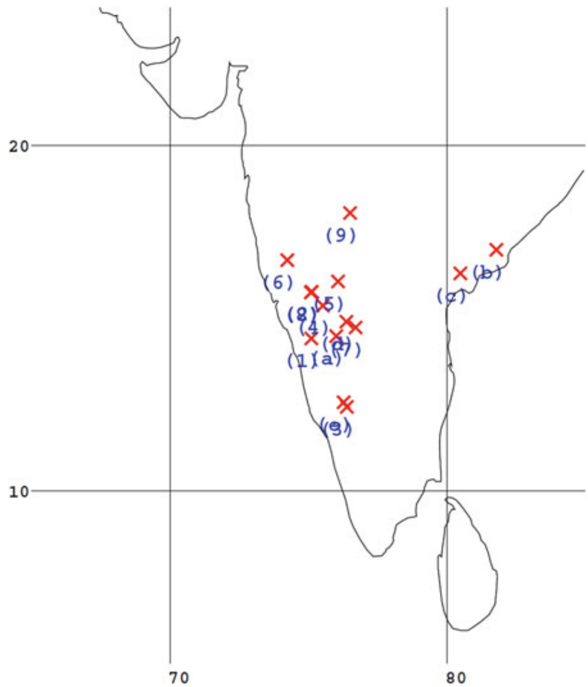

Fig. 1 Positions of cities in southern India

that the eclipse was almost total. However, for $\Delta T = 2848$ sec, the magnitude was around 0.85. Changes of ΔT by ± 1000 sec do not change the magnitude very much.

So, we do not analyse this eclipse more precisely in this paper as it is not useful for the determination of ΔT.

2.2.2 The Eclipse on 3 February 938

The equi-magnitude curves are shown in Fig. 2 (lower panels). The right panel is the enlargement. The figure shows that the eclipse was deep in Ottur and Soraba, hence we judge that this eclipse actually was observed. The inscriptions say that the eclipse was annular. It seems that this is an exaggeration. In order to confirm this, we compare this eclipse with European observations of contemporaneous eclipses in Sect. 3.

2.2.3 The Eclipse on 1 August 1087

The equi-magnitude curves are shown in Fig. 3 (upper panels). The right panel is the enlargement. The figure shows that the annular band passes very close to the following cities in India: Soundatti, KR Nagara, Kurtukoti Gadag, Hungund Bijapur, Kolhapur Maharashtra and Kalkere. We judge that this eclipse was actually observed. In particular, the inscriptions at Soundatti say that the eclipse was total.

Table 2 A list of the positions of the observation sites

City	Latitude ° ′	Longitude ° ′
(0) Saligrama Hasana	76 16	12 34
(1) Ottur, Soraba	75 06	14 25
(2) Soundatti, Raibag	75 07	15 46
(3) KR Nagara, Mysore	76 23	12 26
(4) Kurtuoti Gadag	75 31	15 22
(5) Hunagund Bijapur	76 04	16 04
(6) Kolhapur Manaharashtra	74 14	16 41
(7) Kalkere, Hanagal	76 42	14 44
(8) Harapanahalli, Hassan	75 05	15 45
(9) Anduru, Tulajapur, Maharashtra	76 30	18 03
(a) Bagali, Harapanahalli Taluk, Ballari	76 00	14 29
(b) Akkalapundi Rajamundry Taluk	81 47	16 59
(c) Mutukuru, Palnad Taluk	80 29	16 18
(d) Ujjini, Kudligi Taluk	76 22	14 54
(e) Saligrama Hasana	76 16	12 34
Cordoba	−04 46	37 53
Olmos	−03 59	40 09
Cueva de la Mora	−03 55	40 20
Constantinople	28 59	41 01
Farfa	12 42	42 13
Baghdad	44 26	33 20
Kyoto	135 48	35 00
Kaeson	126 34	37 58
Linan	120 10	30 15

We may determine a very narrow range of values for ΔT. In Sect. 3 we compare this eclipse with contemporaneous eclipses observed at Baghdad and Kyoto.

2.2.4 The Eclipse on 16 December 1107

The equi-magnitude curves shown in Fig. 3 (lower panels). We see the enlargement in the right panel. The figures show that the annularity band is rather distant from the following southern Indian cities: Harapanahalli, Anduru and Bagali. The inscriptions at Anduru, Tulajapur Maharashtra say that the eclipse was annular. We judge that this eclipse was actually observed but the magnitude was exaggerated. Therefore, we do not, in what follows, use this eclipse for the determination of a ΔT value.

2.2.5 The Eclipse on 6 November 1268

The equi-magnitude curves are shown in Fig. 4. The right panel shows the enlargement. The figure shows that the eclipse could have been total in one of the following

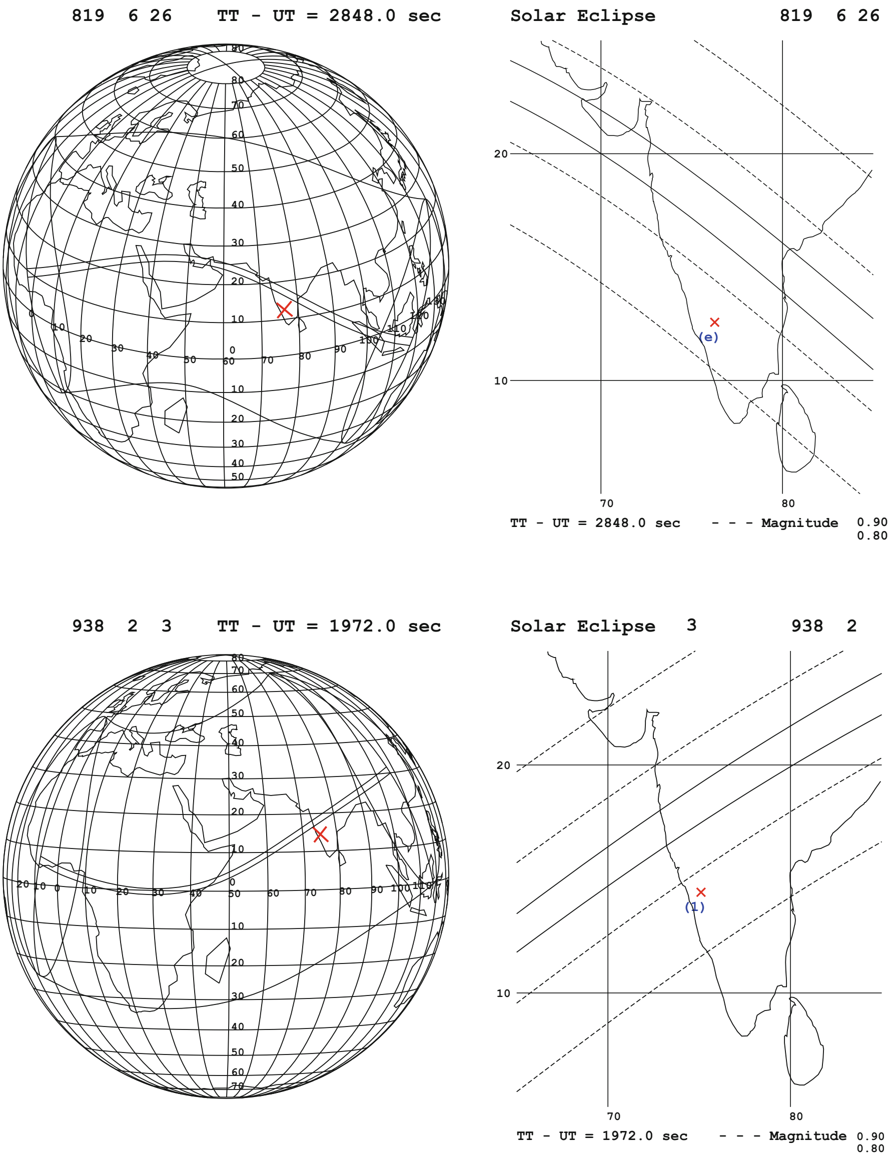

Fig. 2 Upper panels: the eclipse band for the eclipse of 26 June 819 and $\Delta T = 2848$. Lower panels: the eclipse band for the eclipse of 3 February 938 and $\Delta T = 1972$

cities, Ujjini, Mutukuru or Akkalapundi, although inscriptions say nothing about totality.

We judge that this eclipse actually was observed. The exact place of totality is dependent on the value of ΔT, so we need an elaborate analysis. We do this in Sect. 3.

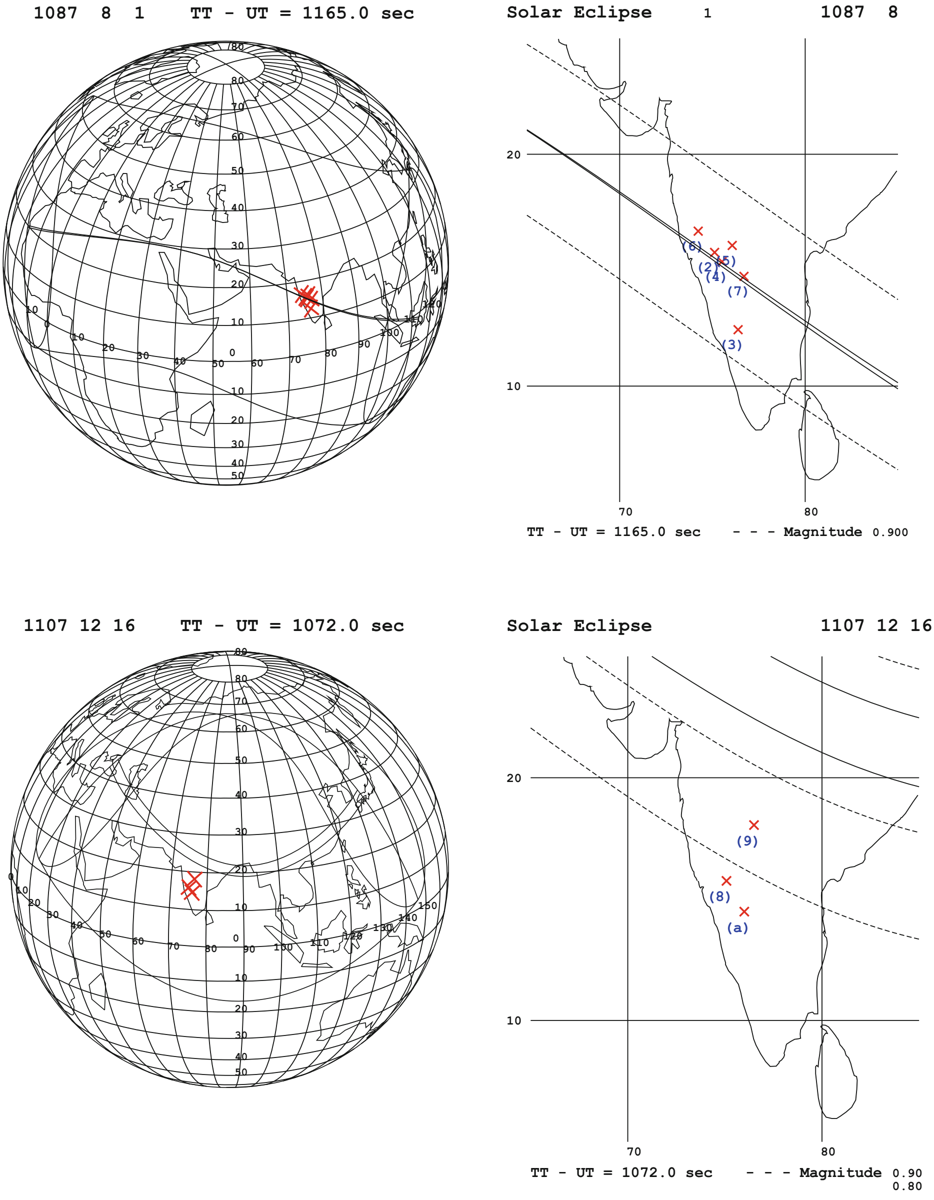

Fig. 3 Upper panels: the eclipse band for the eclipse of 1 August 1087 and $\Delta T = 1165$. Lower panels: the eclipse band for the eclipse of 16 December 1107 and $\Delta T = 1072$

3 Dedailed Analyses of the Indian Eclipses and ΔT

We saw in Sect. 2.2 that eclipses useful for determining ΔT were those of 3 February 938, 1 August 1087 and 6 November 1268. In this Section, we try to obtain the range of ΔT values from these three eclipses with the help of contemporaneous eclipses that were observed in other nations.

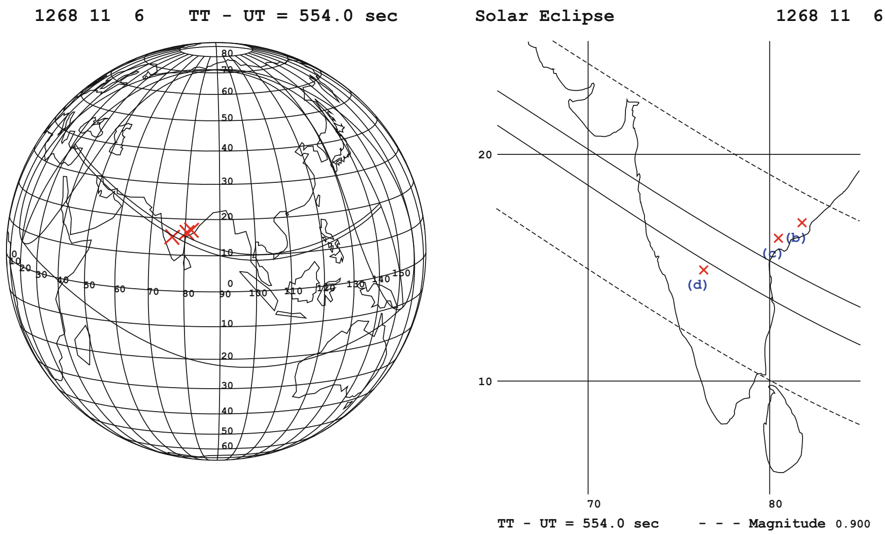

Fig. 4 The eclipse band for the eclipse of 6 November 1268 and ΔT = 554

3.1 The Eclipse of 3 February 938 and Contemporaneous Eclipses

We start the analysis with eclipse of 3 February 938. There were several more-or-less contemporaneous eclipses: on 17 June 912, observed from Cordoba, Spain; on 19 July 939 observed from Olmos, Spain; and on 22 December 968 observed from Constantinople and Farfa (see Table 3). These were claimed to be total or annular by observers. There were other eclipses on 11 November 923 and 18 August 928 both observed from Baghdad, but these were partial (Stephenson, 1997). Therefore, we do not include these two eclipses in our analysis.

We plot the Sôma Diagram in Fig. 5. The abscissa is the coefficient of the lunar tidal term and the ordinate is ΔT. In general, for a given year, the totality or annularity region of this parameter space for the eclipse is bounded by nearly parallel curves.

In Fig. 5, inside the red parallels is the parameter range of the totality of the eclipse at Ottur. The eclipse on 17 June 912 was total between the dashed parallels at Cordoba, while the eclipse on 19 July 939 was total between solid parallels at Cueva de la Mora, and between dotted parallels at Olmos. The eclipse on 22 December 968 was total between green curved parallels at Constantinople, while total between blue curved parallels at Farfa. For the modern value of the coefficient of the lunar tidal term (0.0 of the abscissa), that is, $-12.929''$/century (Sôma and Tanikawa, 2016), we obtain the range of ΔT as shown by a red interval in the figure.

Table 3 A list of solar eclipses that occurred around AD 939

Oppol No.[a]	Year	Month	Day	Site	Remarks	References
5042	912	06	17	Cordoba (Spain)	Total	Stephenson (1997: 438)
5099	938	02	03	Ottur, Soraba	'Annular'	
5102	939	07	19	Olmos (Spain)	Total	Stephenson (1997: 443)
				Cueva de la Mora	Total	
5169	968	12	22	Constantinople	Total	Stephenson (1997: 390)
				Farfa (Italy)	Total	Stephenson (1997: 391)

[a]This refers to the eclipse number listed in Oppolzer (1887)

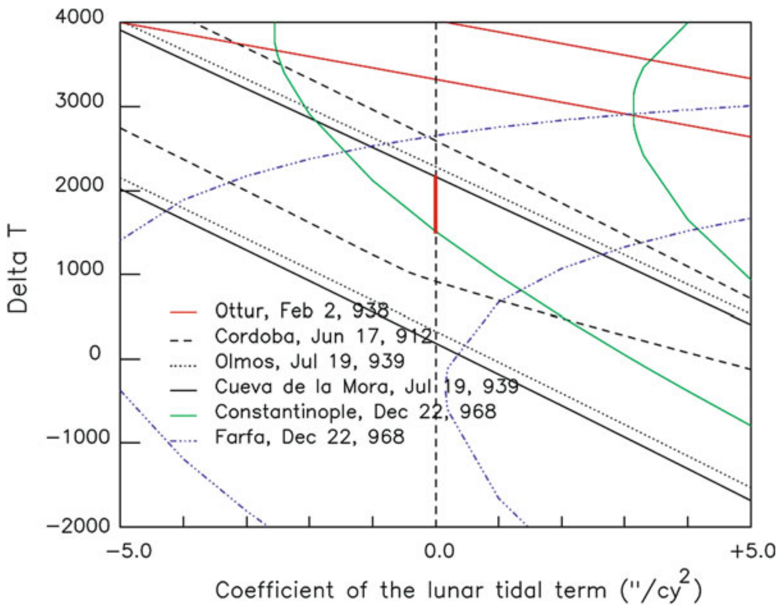

Fig. 5 The Sôma Diagram for around AD 938

$$1513 \text{ s} < \Delta T < 2164 \text{ s}.$$

Adopting the nearest value ΔT = 2164, the magnitude of the eclipse on 3 February 938 at Ottur was 0.885. The above range of ΔT is for 30 years from AD 938 to 968.

3.2 *The Eclipse of 1 August 1087 and Contemporaneous Eclipses*

There are six inscriptions in India for the eclipse on 1 August 1087 as mentioned in Sect. 2.2.3. Among them, inscriptions at Soundatti, Raibag, say that the eclipse was

Table 4 A list of solar eclipses that occurred around AD 1087

Oppol No.[a]	Year	Month	Day	Site	Remarks	References
5385	1061	06	20	Baghdad	Total	Stephenson (1997: 439)
5405	1069	07	21	Kyoto	Deep partial	Kanda (1935)
5449	1087	08	01	Soundatti	Total	
				KR Nagara, Mysore		
				Kurtukoti Gabag		
				Hunagund, Bijapur		
				Kolhapur, Maharashtra		
				Kalkere, Hanagal		

[a]This refers to the eclipse number listed in Oppolzer (1887)

total. The eclipse threw a very narrow annularity shadow on the Earth. If the inscriptions at Soundatti are reliable, a very narrow range of ΔT values can be obtained. There are two observations of contemporaneous eclipses (see Table 4).

We plot five annularity parallels in Fig. 6 to avoid over-crowdedness of the lines. These parallels, except those for KR Nagara, are all included in the totality band of eclipse on 20 June 1061 observed at Baghdad. From this coincidence, we conclude that five records of observation in India and one record at Baghdad are reliable. For the modern value of the coefficient of the lunar tidal term (0.0 of the abscissa), we obtained the following range of ΔT values, as shown by the red interval in the figure:

$$1197 \text{ s} < \Delta T < 1673 \text{ s}.$$

This comes from the lower-most and upper-most boundaries of the five annularity parallels for Indian cities. If we dare to adopt the range of ΔT from the parallels of Soundatti, Raibag, we obtain 1267 s < ΔT < 1323 s. We give this range for reference. We now add the report from Kyoto of the eclipse of 21 July 1069, which was partial in Kyoto. The curved narrow solid parallels show the annularity band at Kyoto. Two curves to the right are equi-magnitude curves of 0.98 and 0.96. The report says that it was like a dark night. We consider that the magnitude of the eclipse should have been large, and from Fig. 6 we obtain a magnitude ~0.97 at Kyoto.

3.3 The Eclipse of 6 November 1268 and Contemporaneous Eclipses

The eclipse of 6 November 1268 was inscribed at three place in southern India: Ujjini, Kudligi Taluk; Mutukuru, Palnad Taluk; and Akkalapundi Rajahmundry Taluk. There is no mention of totality. There are three contemporaneous eclipse observations made elsewhere that are useful for the determination of ΔT. These

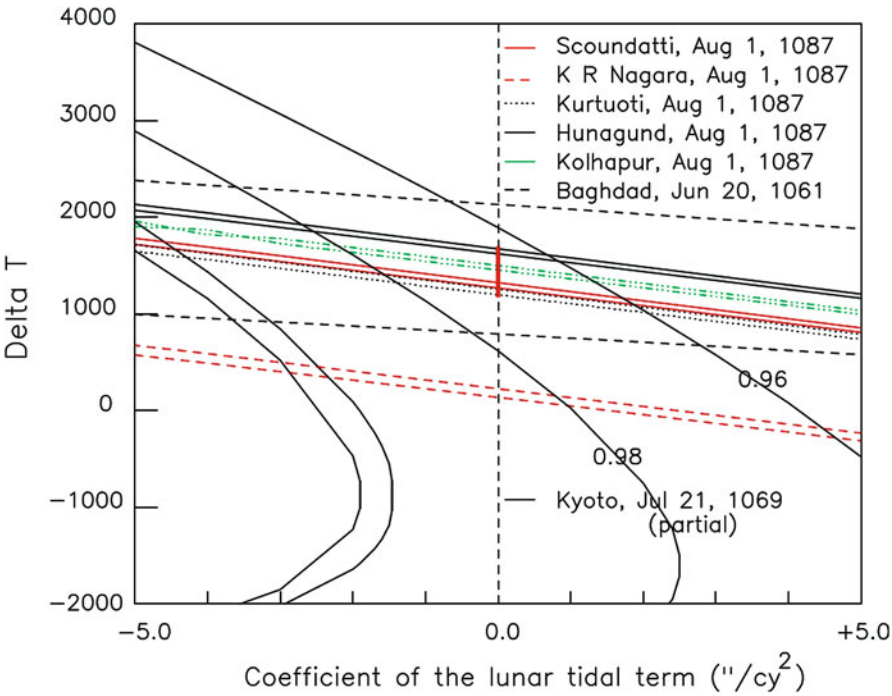

Fig. 6 The Sôma Diagram for around AD 1087

occurred on 25 July 1245, observed from Kaesong; on 25 May 1267, observed from Constantinople; and on 25 June 1275, observed from Linan (Table 5).

Three parallels of totality from Indian observations do not overlap (see Fig. 7). Thus, totality was observed not more than one place. The record of Kyoto is expressed by the dashed parallels and the record of Kaesong is expressed by the solid parallels. These do not overlap. These are consistent, because the eclipse was total at Kaesong, while partial at Kyoto. The totality of the eclipse of 25 May 1267 at Constantinople is expressed by green curved parallels. The totality of the eclipse on 25 June 1275 at Linan is indicated by the blue parallels. Now, for the modern value of the coefficient of the lunar tidal term (0.0 of the abscissa), we obtain the range of values of ΔT as shown by a red interval in the figure:

$$98 \text{ s} < \Delta T < 806 \text{ s}.$$

The lower limit is obtained from the lower limit of Kaesong, while the upper limit is obtained from the upper limit of Constantinople. This determination is reasonable in the sense that the range is contained in the totality bands for Linan (1275), Constantinople (1267) and Kaesong (1245). It is out of the totality band of Kyoto (1245). Our result shows that Ujjini may have witnessed totality or close to totality during the eclipse of 6 November 1268. Also, at Mutukuru people witnessed almost totality, with the magnitude at 0.98 for ΔT = 806 s.

Table 5 A list of solar eclipses that occurred around AD 1087

Oppol No.[a]	Year	Month	Day	Site	Remarks	References
5848	1245	07	25	Kaesong	Total	Kim and Chong (1451)
				Kyoto	'Sun was thin'	Kanda (1935: 87)
5902	1267	05	25	Constantinople	Total	Stephenson (1997, 404–405)
5905	1268	11	06	Ujjini, Kudligi Taluk		
				Mutukuru, Palnad Taluk		
				Akkalapundi Rajamundry		
5922	1275	06	25	Linan	Total	

[a]This refers to the eclipse number listed in Oppolzer (1887)

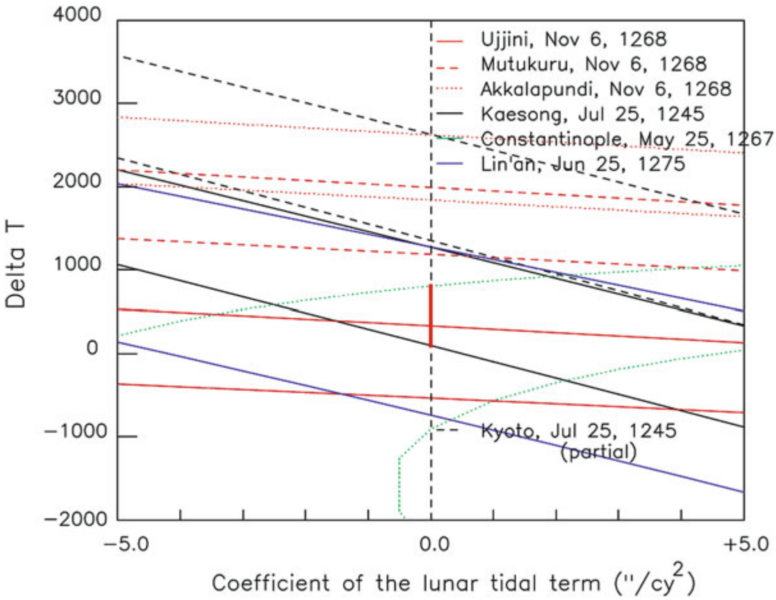

Fig. 7 The Sôma Diagram for around AD 1268

4 Concluding Remarks

We have obtained three ranges of ΔT for the years AD 938, 1087 and 1268. In each determination, the addition of Indian records played an important role. In particular, for the eclipse of 1087, the Indian records were crucial in obtaining a narrow range of ΔT values.

One important consequence of our research was that given plural contemporaneous records of eclipses, we were able to judge the reliability of some records and assign them actual magnitudes instead of using terms like ‘nearly total’, ‘like a three-day moon’, ‘dark like night’, etc.

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On Stone Inscriptions from Bāgalakoṭe and Śivamogga Districts of Karnāṭaka

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Abstract Stone inscriptions have been found to provide useful, astronomically significant data. New epigraphical volumes have been published in recent years, with revisions on previous interpretations of inscriptions along with unpublished ones. The first of the two cases presented here is of an inscription mentioning a total solar eclipse. The second case is of an inscription describing a 'planetary conjunction', which also is a rare find.

1 Introduction

Inscriptions offer an unconventional source of astronomical data, although the priority is given to the details of the deed or the cultural event (Shylaja and Ganesha, 2012), for example: grants given to a person or temple, or to commemorate the death of a war hero. Hence the date or details regarding an astronomical event assumes lesser importance. However, eclipses, planetary conjunctions and solstices are considered auspicious for making grants (Dāna Śāsana), and therefore gain importance. Such occasions include equinoxes (autumn and vernal) and a special occasion termed Vyatīpāta (an instant corresponding to the equality of the magnitudes of the declinations of the Sun and the Moon, i.e., $|\delta_S| = |\delta_M|$ (Shylaja and Ganesha, 2016a).

Here we discuss two cases which are astronomically useful and significant; they have been made available recently, and are inscriptions of grants.

2 A Total Solar Eclipse

The group of temples in Paṭṭadakallu village, is one of many famous UNESCO heritage sites in the state of Karnāṭaka. In the premises of Mallikārjuna Temple lies an octagonal pillar with a distinctive temple inscription (Fig. 1). It describes a grant

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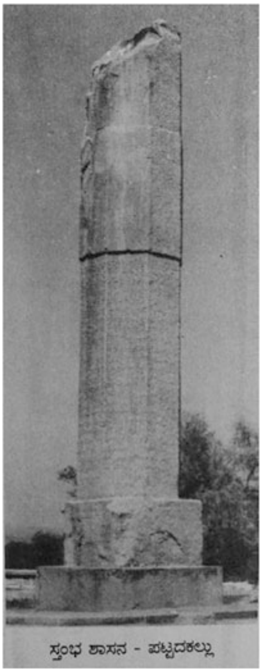

Fig. 1 The octagonal pillar with a square base at the Mallikārjuna Temple, Pattadakallu village. The inscription has been carved on the sides of the pillar and on the base

made during the time of Kīrtivarma – II (eighth century) during a total solar eclipse. As we have already reported on our earlier work (Shylaja and Geetha, 2016b), it is rare to find words describing the details of eclipses in inscriptions. The Inscription mentions the phrase "... Śrāvaṇamāsē Amāvāsyāyām Sarvvagrāsē Sūryyagrahaṇē ...", which clearly means ". . . the month of Śrāvaṇa, new moon day, on the occasion of total solar eclipse . . ."(Bhat Suri et al. 2006).

Considering that a solar eclipse is clearly mentioned, the epigraphers give the date as AD 25 June 754, as follows:

> As regards the date of the inscription refers itself to the reign of Kirtivarman II, by speaking of him with the paramount titles. And further though it does not quote the year of the Saka era or the regnal year, it gives details, which enable us to place it exactly. The grants were made, or one of them was made, on the occasion of a total eclipse of the sun on the new-moon tithi of the month Śrāvaṇa; and the English date is the 26th June 754 AD, on this day, which corresponds to the new-moon day of the first pūrṇimānta Śrāvaṇa of Śaka-Samvat 677 current, there was a total eclipse of the sun, which was visible right across India. (Hultzsch, 1979: 1).

The same eclipse has been cited in several epigraphical studies of the region of Bāgalakōṭe District and its surrounding regions (Annigeri, 1960: 24; Burgess, 1874: 32; 1878: 126; Hultzsch, 1979: 1; *The Indian Antiquary*, 1984: 168), with the Śaka year given as 677 (which convert to AD 755). This leads to a debate on the current or elapsed Śaka. In these discussions, the description of the eclipse as 'total' is lost. There are very few inscriptions which directly mention the type of eclipse, let alone totality. Therefore this record is of great significance.

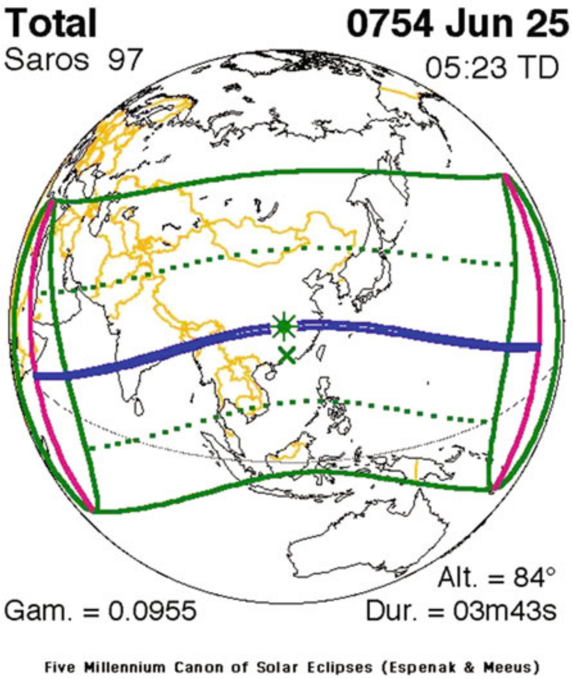

Fig. 2 The path of totality covering the region of the inscription. (After Espenak and Meeus 2006)

The path of totality crossed the coordinates of the temple premises (15.950 N, 75.820 E) as per the NASA eclipse canon (see Fig. 2). The Occult software gives the magnitude as 0.98. We have matched the coordinates of the place with the path derived from the software developed by Dr. Mitsuru Sôma for the theoretical prediction of eclipses (Sôma and Tanikawa, personal communication), as shown in Figs. 3 and 4. This eclipse can be used to calculate the value of ΔT for that year.

The eclipse date of AD 25 June 754 sets the limits on the value of ΔT, to about 2900 s and 3300 s. Hence this date becomes invaluable to the study of variations in ΔT (Tanikawa et al. 2018).

3 Panchagrahayōgapuṇyakāla: A Conjunction of Five Planets

An inscription from Hosanagara Tāluk, Śivamogga, dated Śaka 1474, Virōdhikrit, Māgha, Bahuaḷa 30, has been converted to AD 24 February 1552 AD by epigraphical experts (Shariff 2009: 98). This is a special inscription because, it refers to a time of 'Panchagrahayōgapuṇyakāla', which means an occasion when five planets are grouped together in the sky.

The inscription does not mention the names of the planets, but we have verified that on 24 February the five 'planets' in the group were the Sun, the Moon, Mercury,

Fig. 3 The path of totality based on predictions by Mitsuru Sôma. (Courtesy: Mitsuru Sôma)

Saturn and Mars (Fig. 5). Here one needs to bear in mind that the Sun and the Moon were given the status of planets. As per the software, Stellarium, on 24 February 1552 Saturn and Mars appear to have been in positions of near conjunction, while the Sun and the Moon were close to each other since it was a New Moon day.

However, there is a possibility that the date in question was 23 February, the previous day. On that day, at dawn, the Moon was closer to Saturn and Mars (see Fig. 6).

The date of 25 January in the previous month gives another possibility for the description of 'Panchagrahayōgapuṇyakāla'. One needs to remember that the nodes of the Moon also were given the status of 'planets'. For this date (see Fig. 7), the ascending node of the Moon was the fifth planet. This can be inferred from the fact that there was a solar eclipse on that day (although it was not visible from India). As Fig. 7 shows, this date presents us with a closer grouping of planets than on 24 February.

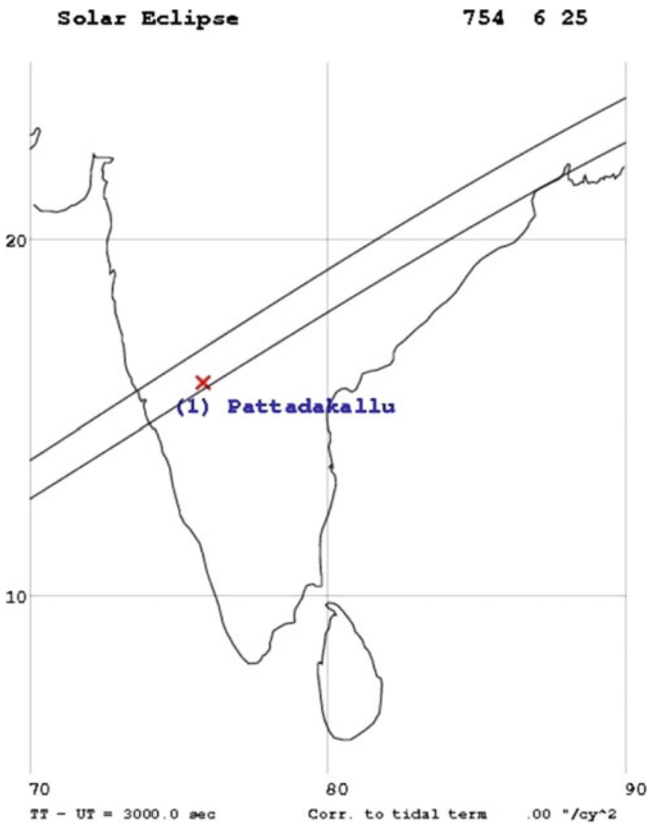

Fig. 4 An enlargement of path of totality showing the position of the village of Pattadakallu

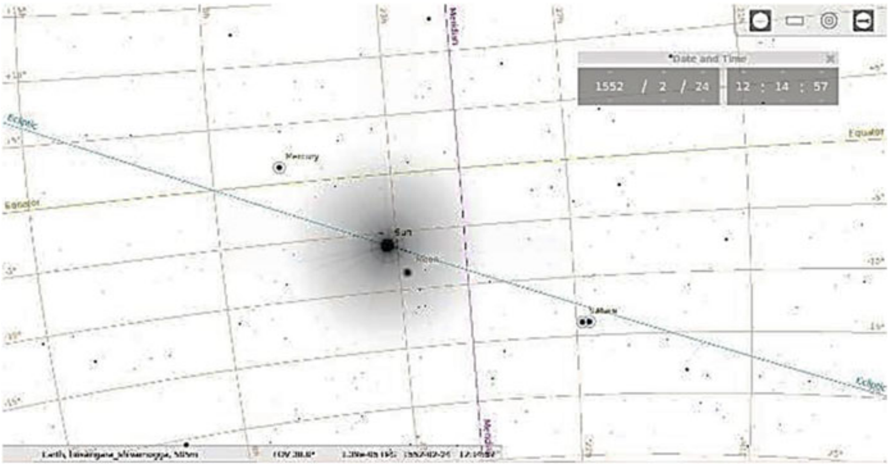

Fig. 5 Planetary positions on 24 February 1552. 'Planets' from left to right are: Mercury, the Sun, the Moon, Saturn and Mars. (From Stellarium)

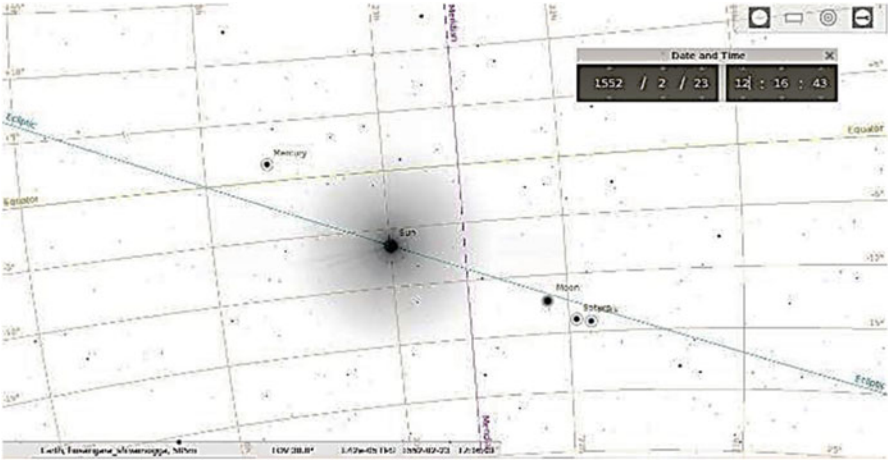

Fig. 6 Planetary positions on 23 February 1552. Planets in the same order as above. (From Stellarium)

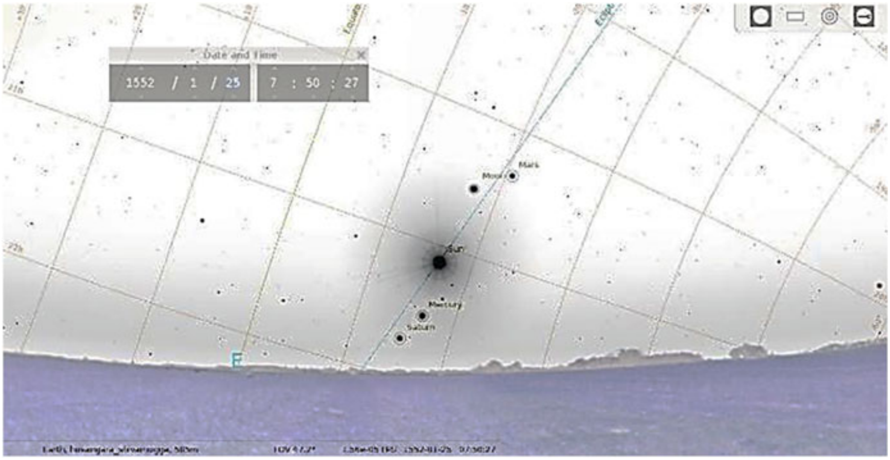

Fig. 7 Planetary positions on 25 January 1552. 'Planets' from left to right are: Saturn, Mercury, the Sun, the Moon, and Mars. (From Stellarium)

The date can be fixed decisively when another inscription of the same year becomes available. This date has to have details on the name of the year, the month and the possible inclusion of an intercalary month.

4 Conclusion

It is a great challenge to extract useful astronomical information from the vast number of inscriptions scattered all over India. The present study throws light on the significance of such research, which involves rigorous hard work. The two dates presented in this paper are from two different regions (~330 km apart) in Karnāṭaka. The difference between the dates spans nearly 800 years. This shows that throughout this interval astronomers in these regions maintained a tradition of thorough and accurate observation. The records discussed in this paper give hope of finding further detailed texts with meticulous observations.

This study also provided an opportunity for us to test the validity of different available softwares for predicting solar eclipse paths of totality.

Acknowledgements Espenak and Meeus (2006) and Stellarium software have been used to verify and visually present the data. The authors gratefully acknowledge Professors Mitsuru Sôma and Kiyotaka Tanikawa for their insight and invaluable discussions regarding dates of historical solar eclipses.

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An Historical Perspective on Lunar Occultations of Stars: Periodicity and Circumstances

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Abstract In Indian astronomical texts, generally the lunar occultation of particular stars, like Makhā (Regulus), Citrā (Spica), Rohiṇi (Aldebaran) and Jyesṭhā (Antares), are considered important. In this paper, a study of the phenomenon of a lunar occultation and the periodicity of this phenomenon are discussed. Actual circumstances of some occultations of stars cited by earlier authors and also recordings inscribed on stone are worked out.

1 Introduction

In Indian Astronomy, the Siddhāntic texts discuss the phenomena of conjunctions of the Sun, the Moon and the planets, between any two of them, and also with some important stars. If the conjunction is

1. Between two planets it is called yuddha (war or encounter).
2. Between a planet and the Moon, then it is called samagama. In modern parlance we call it a lunar occultation.
3. Between a planet and the Sun, it is called astamana or astangata (heliacal setting).

The transits of the inferior planets viz. Mercury and Venus are special cases of this third category. In the case of Mercury or Venus, an inferior conjunction can result in a transit. In addition, these two planets can have a superior conjunction with the Sun, in which case these bodies will be covered by the Sun.

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For superior planets (Mars, Jupiter and Saturn) the conjunction results in a planet going behind the Sun as observed from the Earth. This is also a case of a helical setting.

An occultation occurs when one object passes in front of another as seen by the observer. In the course of the sidereal period of 27.32 days the Moon has conjunctions with all stars that have identical longitudes with that of the Moon. A lunar conjunction with every star turns out to be an occultation only when their latitudes are sufficiently close. Since a lunar orbit has a mean inclination of about 5° 8′ to the ecliptic, stars whose latitudes are less than 5° 8′ are eligible for occultation. However since the Moon's orbital plane oscillates, its inclination to the ecliptic rises to a maximum of about 6° 21′, hence stars with latitudes up to 6° 21′ also are eligible for occultation. Thus stars that are eligible for lunar occultation include Makhā (Regulus), Citrā (Spica), Rohiṇi (Aldebaran) and Jyesthā (Antares).

2 The Procedure for an Occultation

The procedure for an occultation is similar to that of a solar eclipse. The participating bodies in the case of a lunar occultation are the Moon and the star. At the instant of conjunction (in longitude) of the Moon with the star, the angular semi-diameter d, the horizontal parallax π and the latitude (śara) β_1 of the Moon are determined. The semi-diameter and the horizontal parallax of the star can be ignored since these are too small compared to those of the Moon. If β_2 is the latitude of the star, then the half duration of the Moon is given by.

$t = \sqrt{[(d+\pi)^2 - (\beta_1 - \beta_2)^2]}$/(True Daily Motion of the Moon)

Then the beginning and the end of the occulation are given by instant of conjunction $\pm\ t$. However, for greater accuracy the semi-diameter of the star may be considered, and an iterative procedure may be performed.

2.1 Conditions for the Lunar Occultation of a Star

Suppose β_1 and β_2 are the latitudes respectively of the Moon and star, π is the Moon's horizontal parallax and d is the Moon's semi-diameter. The condition for occultation is that the absolute difference in latitudes should be less than the sum of the Moon's semi-diameter and parallax:

i.e. $|\beta_1 - \beta_2| < \pi + d$

The minimum values of π and d are about 3223″.5 and 878″.5 and the maximum values are 3672″.3 and 1000″.7, respectively. Accordingly, the minimum and the maximum values of ($\pi + d$) are respectively 4102″.0 and 4673″.0 (i.e. 1° 8′ 22″ and 1° 17′ 53″). Thus, we have:

1. The lunar occultation of a star of latitude β_2 is *certain* if $|\beta_1 - \beta_2| < 1° 8' 22''$;
2. An occultation is not possible when $|\beta_1 - \beta_2| > 1° 17' 53''$; and
3. The phenomenon is *doubtful* if $1° 8' 22'' < |\beta_1 - \beta_2| < 1° 17' 53''$.

2.2 *Periodicity of Occultation Cycles of Stars*

It is estimated that

1. A star whose latitude is less than 3° 56′ has *two* series of lunar occultation during the sidereal period of the Moon's node;
2. A star whose latitude lies between 3° 56′ and 6° 21′ has only one series of lunar occultations; and
3. A star whose latitude is greater than about 6° 21′ is never occulted by the Moon.

2.2.1 For Stars Latitude <3° 56′

Important stars that lie within this latitude limit are Makhā (Regulus), Citrā (Spica), Anurādhā (δ Scorpii), Uttarāṣādhā (δ Sagittarii). In Table 1 we compare the lengths of each series of occultations, and the intervals between two successive beginnings of the series for these four stars whose latitudes are numerically less than 3° 56′.

From Table 1 we observe that as the latitude numerically increases from 0° to 3° 56′ the length of each series goes on increasing with a minimum of about 1.4 years for Makhā (Regulus) and a maximum of about 2.02 years for Uttarāṣādhā (δ Sagittarii).

On the other hand, the interval between two successive series decreases from a maximum of about 9.854 years for Makhā (Regulus) to a minimum of 4.614 years for Uttarāsādhā (δ Sagittarii).

Table 1 Length of series and interval between successive series, for stars with latitudes <3° 56′

Star	Mag	Latitude	Series length	Interval between successive beginnings
Makhā (Regulus)	1.34	0° 27′ 53″	1.412	9.854
Citrā (Spica)	1.21	−2° 03′ 15″	1.546	6.778
Anurādhā (δ Scorpii)	2.54	−1° 59′ 08″	1.536	6.868
Uttarāṣādhā (δ Sagittarii)	2.14	−3° 26′ 56″	2.02	4.614

Table 2 Length of series, for stars latitude between 3° 56′ to 6° 21′

Star	Mag	Latitude	Series length
Kṛittikā (Alcyone, η Tauri)	2.96	4° 03′ 02″	5.839
Jyeṣṭhsā (Antares, α Scorpii)	1.2	−4° 34′ 09″	5.0880
Rohinī (Aldebaran)	1.06	−5° 28′ 04″	3.529

2.2.2 For Stars with Latitudes Between 3° 56′ to 6° 21′

Important stars that appear in this latitude belt are Kṛittikā (Alcyone, η Tauri), Jyeṣṭsā (Antares, α Scorpii) and Rohinī (Aldebaran). Stars in this range of latitude have only one series of occultations in the node's period of about 18.6 years. In Table 2, we compare the series length for different stars. From Table 2, we note that as the latitude of a star increases numerically from 4° 03′ 02″ for Kṛittikā (Alcyone, η Tauri) to a maximum of 5° 28′ 04″ for Rohinī (Aldebaran) the series length decreases from 5.838 to 3.529 years.

3 Historical References Worked Out

In the famous text of Ptolemy's *Almagest* and Copernicus' *De Revolutionibus* there are some interesting references to the occultation of some bright stars observed by the two great astronomers or their predecessors. We provide some of these references in Table 3.

We work out the circumstances using the *Improved Siddhāntic Procedure* (*ISP*) for a few among the examples given in Table 3.

1. Timocharis (320–260 BCE) recorded his observation of the occultation of Spica (Citrā) on 9 March −293 at Alexandria for about 4 seasonal hours before midnight. The instant of lunar conjunction of Spica: about 27 h (IST); the true tropical longitude of the Moon and the star, $\lambda = 171°.36$; the Moon's latitude, $\beta_1 = -93'$; the star's latitude, $\beta_2 = -123'.25$; the difference in latitude $= 30'.25$; the Moon's horizontal parallax, $\pi = 55'.1438$; and the Moon's angular semi-diameter, $d = 15'.0257$. The circumstances of the occultation are as follows:

   External Ingress = 25 h 1 m.2
   Middle = 26 h 56 m
   External egress = 28 h 50 m.7

2. The astronomer Agrippa (ca. first century CE) recorded his observation of the lunar occultation in Bithynia of the Pleiades, which took place on the night of 29/30 November 92 CE. The brightest star in that group corresponds to Alcyone. The instant of the lunar conjunction with the star was about $22^h\ 19^m$ (IST); the true tropical longitudes of the star and the Moon, $\lambda = 33°.4736$; the star's latitude, $\beta_2 = 243'.0334$; the Moon's latitude, $\beta_1 = 294'$ and difference in

Table 3 Recorded occultations in Ptolemy's *Almagest*

Star	Date	Reference
β Scorpii	259 BCE Dec. 21	Timocharis, Alexandria
α Virginis	294 BCE Mar. 9	Timocharis, Alexandria
Pleiades	283 BCE Jan. 29	Timocharis, Alexandria
Spica	283 BCE Nov. 9	Timocharis, Alexandria
β Scorpii	272 BCE Jan. 18	Alexandria
Conjunction of η Virginis and Venus	272 BCE Oct. 12	Timocharis, Alexandria
δ Cancri by Jupiter	241 BCE Sept. 4	
Pleiades	92 Nov. 29	Agrippa, Bithynia
α Virginis	98 Jan. 11	Menelaus, Rome
β Scorpii	98 Jan. 14	Menelaus, Rome
Regulus	139 Feb. 23	Ptolemy, Alexandria
Aldebaran	1497 Mar. 9	De Revolutionibus

latitude $= 50'.967$; the Moon's parallax, $\pi = 54'.4349$; and the Moon's angular semi diameter, $d = 14'.8326$. Now, by the *ISP* we have the following circumstances of the occultation of Alcyone:

External Ingress = 20 h 37 m.6
Middle = 22 h 20 m.9
External egress = 24 h 4 m.2

3. Copernicus recorded in his *De Revolutionibus* his observation of the occultation of Aldebaran on 9 March 1497 at Bologna an hour before midnight. The instant of the lunar conjunction of Aldebaran = $26^h 15^m$ (IST); the true topical longitude of the Moon and the star, $\lambda = 62°.833$; the Moon's latitude, $\beta_1 = -288'$; the star's latitude, $\beta_2 = -310'$; the difference in latitude $= -22'$; the Moon's horizontal parallax, $\pi = 56'.852$; and the Moon's angular semi-diameter, $d = 15'.49$. The following are the circumstances of the occultation obtained by using the *ISP*:

   External Ingress = 24 h 7 m.8,
   Middle = 26 h 15 m
   External egress = 28 h 22 m.2

4. Menelaus (CE 70–140) records his observation of Spica on 11 January 98 at Rome. By the *ISP* we get the following: the instant of the lunar conjunction of Spica = 10^h (IST); the true tropical longitude of the Moon and the star, $\lambda = 177°\ 23'\ 21''$; the Moon's latitude, $\beta_1 = 1°\ 22'$ (S); the difference in latitude $= 1°\ 8'$; the Moon's horizontal parallax, $\pi = 57'.14993$; and the Moon's angular semidiameter, $d = 15'.572293$. The circumstances of the occultation are as follows:

   External Ingress = 7 h 49 m 31 s
   Middle = 9 h 51 m 54 s
   External egress = 11 h 54 m 16 s

4 Planetary Conjunctions and Occultations Recorded on Stone Inscriptions in India

1. 17 October 1129 (SII X (7.53)). This record cites Jyeṣṭhsā (Antares), Guru (Jupiter) and the Moon together. According to the computations using our *ISP* we find that there was a close conjunction of Antares but an actual occultation did not happen on this date.
2. 1 April 1142 (EKU Appendix vol. III no 133 Gutti). This record cites an occultation of Rohiṇī (Aldebaran). The date is given as Dundubhi, Chaitra, Shu 3.
3. 24 June 1158 (EC XII no 1 Kunigilu). Jupiter, the Moon and Rohiṇī were together. But according to the *ISP* it was only a conjunction, not an occultation.
4. 9 April 1207 (EC X no 319 Hiriyuru). Mars and Regulus were occulted by the Moon. When worked out we found that star Regulus was close to the Moon, but the actual occultation series of Regulus started in May 1207.
5. 13 April 1233 (EC XII no 31 Kadaba). The Moon, Mercury, Venus and Rohiṇī were in a group. This date corresponds to an occultation of Rohiṇī. The actual series of Rohiṇī occultations started on 11 January 1233. The date is given Saka 1156 Vijaya, Vaishakha Shu 2, Rohiṇī, Ekaadashasta Navagraha.
6. 3 April 1234 (EC VII 29(121) Basaralu). An occultation of Rohiṇī. On this day an actual occultation of Rohiṇī happened. This was verified using the ISP, with difference in latitude of the two bodies 0.76°. The date is mentioned as Saka 1157, Vaishakha, Shu 2, Sarohini, Pritiyoga.
7. 7 April 1300 (EC vol. IX no 423 Bastihalli). This record cites an Antares occultation. When verified we find that the difference in latitude of Antares and the Moon was 0.52°.
8. 6 March 1310 (EC V no 11 K R Pete). This record cites an occultation of Rohiṇī.
9. 12 September 1310 (EC XIV (152). A Rohiṇī occultation. But from our computation it occurred later, on 15 September, with a difference in latitude of 0.38°.
10. 21 November 1515 (EC VII 7 Mandya). The record dated Saka 1438, Dhatu, KarthikaPurnima mentions an occultation of Rohiṇī, and according to our computation there was occultation, with a difference in latitude of 0.96°.
11. 6 August 1531 (EKU Appendix vol. III no 19 and 41 Lepakshi). An occultation of Rohiṇī happened, with a difference in latitude of 0.98′. The record dated Saka 1453, Khara, Sravana ba 8, also mentions Krishna Jayanthi.
12. 3 November 1533 (EKU vol. I no 219 Hara). An occultation of Rohiṇī. According to our computation the difference in latitude was 0.59°.
13. 1 August 1534 (EKU Appendix vol. III no 12 Gurrepalli). There was an occultation of Rohiṇī.
14. 9 August 1543 (EKU vol. I no 16 Balla). There was an occultation of Antares during the day.

15. 9 May 1560 (EKU V part III no 305 Buburu). An occultation of Antares. According to our computation the actual occultation occurred on 10 May, with a latitudinal difference of 0.31°.
16. 25 November 1662 (EC vol. X no 43 Jamburu). An occultation of Rohiṇī at about 21 h. The record is dated Saka 1584, Plava, Margashira shu 15, Uttara, Karkaṭaka lagna.
17. 14 February 1710 (EKU vol. I no 123 Hara). An occultation of Regulus.
18. 9 November 1717 (EKU vol. no 36 Siriguppa). An occultation of Rohiṇī. The record is dated Saka 1639, Hevilambi, Karthika ba 2, but according to our computation the occultation occurred on 19 November 1717, with the latitudinal difference between the Moon and Rohiṇī of 0.93°.
19. 12 February 1848 (EC VI 9 Pandavapura). An occultation of Rohiṇī. According to our computation the actual occultation took place at 4.30 a.m. on 13 February.

5 Conclusion

In the preceding section we discussed the conditions required for a lunar conjunction of some bright stars to become occultations. We noted that in the case of stars whose celestial latitudes are less than about 3° 56′ there will be two series of occultations in a cycle of about 18.6 years, the sidereal period of the Moon's node (Rāhu). Those stars whose latitudes, south or north, lie between 3° 56′ and 6° 21′, will have only one cycle of occultation in a period of almost 18.6 years. On the other hand, if the star's latitude exceeds about 6° 21′ its conjunction with the Moon will never be accompanied by an occultation.

Finally, we presented a list of historically important references to lunar occultations of some bright stars recorded by Ptolemy, Copernicus and others, and we also verified occultation recordings found on Indian stone inscriptions.

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The Role of Eclipses and European Observers in the Development of 'Modern Astronomy' in Thailand

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Abstract 'Modern astronomy' was introduced to Siam (present-day Thailand) (Siam officially changed its name to Thailand in 1939) when the Belgian Jesuit missionary-astronomer Father Antoine Thomas carried out stellar and lunar eclipse observations during 1681 and 1682 in order to determine the latitude and longitude of Ayutthaya. Three years later a contingent of French Jesuit missionary astronomers observed a total lunar eclipse from Lop Buri, which marked the start of an intensive two-and-a-half year period of observational activity at Lop Buri under the sponsorship of King Narai. During this interval, a partial solar eclipse and two further lunar eclipses were observed from a number of different observing sites. Although a substantial astronomical observatory was constructed in Lop Buri and this was used by French Jesuit missionary-astronomers, 'modern astronomy' ended suddenly in 1688 when King Narai died and most Western missionary-astronomers were expelled from Siam.

'Modern astronomy' only re-emerged in Siam after a hiatus of almost 200 years when another royal supporter of astronomy, King Rama IV, invited French astronomers to observe the total solar eclipse of 18 August 1868 from Siam, and his son, King Rama V, hosted British astronomers during the 6 April 1875 total solar eclipse.

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Thailand's romance with total solar eclipses continued during the 9 May 1929 solar eclipse when King Rama VII visited British and German astronomers based near Siam's southern border, and this was the catalyst required for the birth of home-grown 'modern astronomy'. Soon after, Siam's first astronomy classes began at Chulalongkorn University, and in 1944 this university hosted Siam's first professional astronomer when Rawee Bhavilai, a solar specialist, joined the Physics Department. The latest phase in the professionalisation of astronomy occurred in 2009 when the Government approval the formation of the National Astronomical Research Institute of Thailand (NARIT).

In this paper we trace the critical roles that solar and lunar eclipses played in the emergence and final adoption of 'modern astronomy' in Thailand from 1682 through to the present day.

1 Introduction

This paper deals with the development of modern astronomy in Siam (which is now known as Thailand). By 'modern astronomy' we refer to Western astronomy, as it was practised by trained astronomers in Europe during the seventeenth to twentieth centuries, and the emergence of solar physics and astrophysics in Thailand and other Asian nations in the eighteenth and nineteenth centuries (see Nakamura and Orchiston 2017).

An underlying theme throughout the past 400 years has been the key role that solar and lunar eclipses played in the birth and ultimate adoption of Western astronomy in Asian countries. Initially, eclipse observations were used to determine the longitudes of the observing sites. For example,

> In the 17th and partly also in the 18th century Hipparchos's old method for the determination of longitudes was renovated using the transits of craters on the edge of the shadow ... Though the accuracy of this method could not exceed more than some tenth of a minute of time, its utility was great in those times. For instance the eclipse of 1634 observed in Cairo, Aleppo and the western part of Europe, enabled the astronomers to shorten the Mediterranean Sea by 1000 km in respect to its assumed length before that time ... (Link 1969: 10)

Then, during the second half of the nineteenth century, solar eclipse observations led to major breakthroughs in solar physics, and especially our knowledge of the solar corona (e.g. see Clerke 1893; Meadows 1970; Nath 2013).

In this paper we review lunar and solar eclipses observed from Siam in 1682, 1685, 1686 and 1888, and Siamese observations of the total solar eclipses of 18 August 1868, 6 April 1875 and 9 May 1929. For each eclipse we describe the astronomers involved, their scientific instruments and their observations. We end this paper by briefly noting the development of professional astronomy at a Thai university in the 1930s, and the founding of the National Astronomical Research Institute of Thailand in the early years of the twenty-first century.

2 The Eclipses

2.1 Introduction

The appearance of ‘modern astronomy’ in Siam was made possible only because of the personal interest of King Narai. One of the most revered of Thailand’s historic rulers, King Narai the Great (Fig. 1; see Orchiston et al. 2016) was born in 1633 and died prematurely in July 1688. Narai was the fourth king to rule during the Prasat Dynasty, which was the fourth of the five dynasties of the Ayutthaya Kingdom (see Table 1). He was just 23 years of age when he became the King of Ayutthaya, in 1656, and ruled until his death.

Fig. 1 King Narai. (en. wikipedia.org)

Table 1 Thai kingdoms and dynasties. King Narai ruled during the Prasat Dynasty

Kingdom	Duration (years AD)	Dynasty
Sukhothai	1238–1438	
Ayutthaya	1350–1767	Uthong
		Suphannaphum
		Sukhothai
		Prasat
		Ban Phlu Luang
Thonburi	1767–1782	
Rattanakosin/Thailand	1782–	

Two years before his death, King Narai was described by a visiting Westerner:

> [He is] . . . about 55 years old, handsome, lovely, dark, has good behaviour, and is brave. He is also intelligent, a good ruler . . . [and is] kind-hearted . . . (Chaumont 1686)

Unfortunately there are no other descriptions of King Narai and we cannot be sure that the likeness shown in Fig. 1 is realistic, as not long before the visit that prompted this portrait he had entertained a Persian delegation, and he liked their attire so much that he decided to adopt it for his own court appearances (Smithies and Bressan 2001).

When he became king, Narai

> . . . inherited a large and powerful kingdom in the centre of mainland South-East Asia. His realm reached south to the kingdoms of Pattani, Ligor, Phattalung and Songkhla; in the east Cambodia had acknowledged Ayuttaya's suzerainty, and in the west the port of Tenasserim on the Bay of Bengal was under Thai control. (Hodges 1999: 36)

For Thai localities mentioned in this paper see Fig. 2.

King Narai had an enlightened foreign policy. He believed that exposure to Eastern and Western civilizations was a good way of developing Siam, so during his reign he signed treaties with England, France, Holland and Persia, and he expanded trade with India, Indonesia, China and Japan. Soon Ayutthaya, the Siamese capital, gained a "... reputation as an 'emporium of the East' ..." due to its role "... as a focus for the transshipment of goods between Europe/India and China/ Japan ..." (Sternstein 1965: 108).

Fig. 2 A map showing Thailand localities mentioned in the text. (Map: Wayne Orchiston)

Because of King Narai's

> . . . enlightened policy of promoting increasing contact with Eastern and Western nations, both Lop Buri and Ayutthaya quickly acquired a cosmopolitan flavour, with Armenian, Chinese, Dutch, English, French, Indian, Japanese, Javanese, Malay, Persian, Portuguese and Turkish communities. Many of these people worked for the state or had their own businesses, but there was always a transient population of visiting Europeans, Arabs, Indians and Asians. Because of this, there is a wealth of published material on seventeenth century Siam, as book after book appeared describing—and often singing the praises of—Ayutthaya and Lop Buri. It must be remembered that by international standards both were large cosmopolitan cities. (Orchiston et al. 2016: 28)

One of King Narai's personal interests was astronomy. As a prince, he received a thorough Buddhist education from the monks, but he also was taught astrology and astronomy by lay teachers. Once he was king, Narai's contact with foreigners also contributed to his education, for as Hodges (1999: 36) has pointed out,

> His reign coincided with European advances in the sciences associated with navigation, astronomy and horology. He lived in an age when humans were first beginning to grasp the nature and extent of the cosmos . . .

At this time there was a constant stream of Jesuits and other Europeans passing through Siam *en route* to China or returning to Europe (e.g. see Love 1999; Vande Walle and Golvers 2003), and through them King Narai continued to learn about astronomy, telescopes, other scientific instruments and the newly constructed Paris Observatory. Furthermore, instead of favouring gifts of cloth, spices and jewellery typically presented by visiting dignitaries, King Narai made it known that he also liked to receive telescopes, clocks and military equipment (Hodges 1999).

This was the scientific-cultural milieu in Siam when it gained its first exposure to 'modern' Western astronomy in 1681.

2.2 The Lunar Eclipse of 22 February 1682

In Table 2 we list the start, middle and end times of the total phase of the lunar eclipse in local time,[1] along with the positions of the Moon and Sun, as observed from Ayutthaya. As the table illustrates, this eclipse was visible in the morning just

[1]All of the times listed in Tables 2, 3, 5, 7 and 9 were calculated using Herald's OCCULT v3.6 and the NASA Catalog, which agreed to within 1 min in all instances. 'Local Time' was defined as UT + 7 h. The Jesuits in Siam in the seventeenth century used local apparent solar time for their eclipse timings. This means that for instance the times given in the table for the 1685 lunar eclipse, for comparison with the timings of the Jesuits should be corrected by −18 min to account for the time difference between the 7 h meridian (105° E) and the meridian of Lop Buri (100.65° E). Additionally, they should be corrected by +6 min by the equation of time to get apparent solar time. The start of the totality, 4:37, will then be corrected to 4:25 local apparent solar time and the time of the end of the totality, 6:21, will be corrected to 6:09, both of which are very close to the times actually reported by the Jesuits.

Table 2 Details of the lunar eclipse 22 February 1682

Totality	Local time	Moon		Sun	
		Altitude	Azimuth	Altitude	Azimuth
Start	05 h 25 m	+17°	267°	–19°	96°
Middle	06 h 13 m	+06°	279°	−07°	99°
End	07 h 01 m	−05°	282°	+05°	102°

Table 3 Details of the lunar eclipse of 11 December 1685

Totality	Local time	Moon		Sun	
		Altitude	Azimuth	Altitude	Azimuth
Start	04 h 37 m	+26°	288°	−27°	109°
Middle	05 h 29 m	+15°	290°	−15°	110°
End	06 h 21 m	+03°	293°	−04°	113°

before the beginning of astronomical twilight, and the Moon was low in the western sky. Sunrise occurred at 06 h 39 m local time, before the eclipse had ended, so only the very early parts of totality were visible in a completely dark sky. Mid-totality occurred just before the beginning of civil twilight. By this time, the sky would have had an obvious blue hue, with only the brighter stars still visible.

2.2.1 Father Antoine Thomas: The Observer of the Eclipse

The Jesuits were an order of Roman Catholics with particular interest in astronomy and mathematics (see Udias 2003) and during the sixteenth century the Spaniard Francis Xavier founded Jesuit missions throughout Asia. Thus, when King Narai assumed the throne in 1656 "... there were Jesuits as well as Dominicans [already] established in the Portuguese colony at Ayŭt'ĭa." (Hutchinson 1933: 6).

Despite this early Jesuit presence in Siam during King Naria's reign it was only in 1681 that the missionary-astronomer Father Antoine Thomas took up temporary residence in Ayutthaya, and as far as we have been able to ascertain he was the first to introduce Siam to Western astronomy (Orchiston et al. 2018a).

Antoine Thomas was born in Namur (Belgium) on 25 January 1644, and joined the Jesuit Order in 1660. While training for the priesthood he studied in various towns in Belgium and in France (Lefebvre, 1930), and by the time he was ordained, in 1678, he had developed an interest in mathematics and astronomy. Subsequently he studied mathematics in Portugal and published a short research paper (Thomas 1679) about a lunar eclipse that he observed.

Thomas planned to carry out missionary work in Japan, and while trying to arrange this he had to spend nearly a year in Siam. By good fortune, the 22 February 1682 lunar eclipse occurred during this sojourn.

2.2.2 Father Thomas' Observations of the Eclipse

Soon after he settled in the Portuguese sector of Ayutthaya Father Thomas carried out solar observations in order to determine the latitude of the city. These observations were made from "... the House of the Society of Jesus in the suburbs, to the south of Juthia [i.e. Ayutthaya]." (Thomas 1692; our English translation).

Father Thomas records (1692) that he observed the 22 February 1682 eclipse, but Bhumadhon (2000) suggests that his observations were made in collaboration with Father Gouye. However, Gouye's account (1692: 693) clearly documents that it was only Thomas who made the observations. As we suggested earlier,

> The confusion appears to have arisen because even though Gouye was tasked with publishing the astronomical observations of the Jesuit missionary-astronomers who were based in Siam, he also liked to add his own comments and corrections. However, Gouye's biography (see Thomas Gouye n.d.) clearly indicates that he spent his whole life in France and never visited Siam. (Orchiston et al. 2016: 42)

Unfortunately, we do not know from exactly where Father Thomas observed the eclipse. It would have been from the Jesuit church in the Portuguese district of Ayutthaya or from the veranda or courtyard of the Jesuit residence which was located near the church. The location of the Jesuit church is shown on several old maps of Ayutthaya, and one of these is reproduced here as Fig. 3.

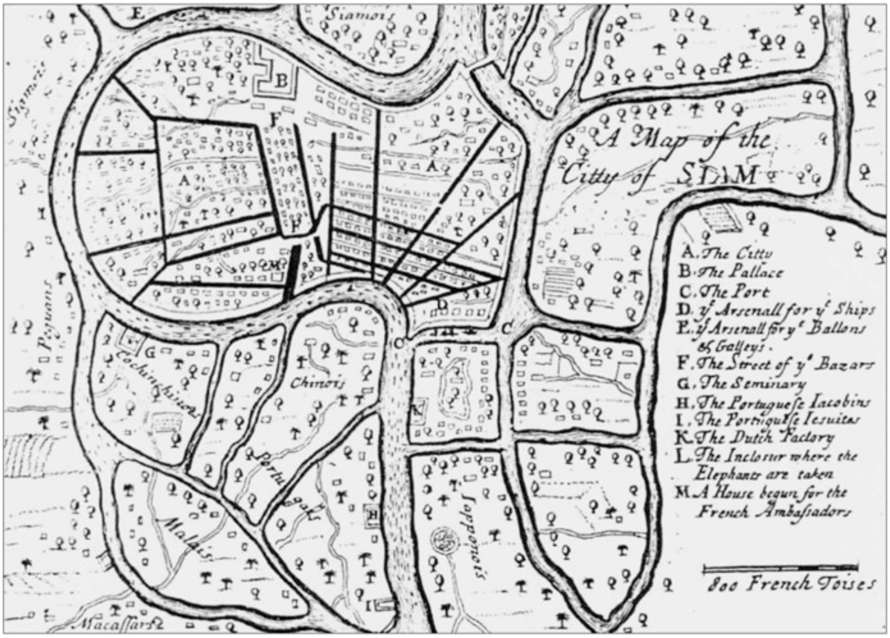

Fig. 3 A map of Ayutthaya in the 1680s showing the location of the Portuguese residential precinct (marked 'Portugals' to the south of the river on the left), and above the Malayan precinct. The Portuguese Jesuit church was on the western bank of the river close to the bottom of the map, and is marked by the 'I'. (After Loubère 1693)

Father Thomas (1692) makes no mention of having access to a telescope, so we can presume that he observed the eclipse with the naked eye, but to record the contact times we know that he used a simple pendulum clock (ibid.).

For further information about Father Antoine Thomas and his observation of the 1682 lunar eclipse see Orchiston et al. (2018a).

2.3 The Lunar Eclipse of 11 December 1685

In Table 3 we list the start, middle and end times of the total phase of this lunar eclipse in local time based upon modern calculations, along with the positions of the Moon and Sun, as observed from Lop Buri. As the table illustrates, the eclipse of 10–11 December 1685 was visible from Siam on the morning of 11 December, with the start of totality occurring before the beginning of astronomical twilight. At this time, the Moon was about 20° north of due west and was low in the sky. Astronomical twilight would have just begun when the eclipse reached the mid-totality phase, and there would have been a minor twilight glow on the horizon about 20° south of east.

2.3.1 The French Jesuit Contingent to Siam: Observers of the Eclipse

This eclipse was observed by a group of French Jesuit missionary-astronomers that had arrived in Siam on 24 September 1685 as part of a French diplomatic mission. This mission resulted from efforts by King Narai and his principal adviser Constantine Phaulkon (1647–1688; Sioris 1988) to build closer diplomatic relations between Siam and France. This initiative was seen as a counter to the growing economic presence of the Dutch in Siam (see Cruysse 2002; Hutchinson 1933), and fortuitously, at the time Louis XIV (1638–1715) was keen to establish a major trading facility in Siam (Love 1994a, b).

Leading the French mission was the diplomat Alexandre Chevalier de Chaumont (1640–1710; see Chaumont 1686), who was accompanied by the notorious transvestite François-Timoléone Choisy (1644–1724; see Choisy 1687), Father Bénigne Vachet (1641–1720) from la Société des Missions Étrangères de Paris (who had lived in Siam since 1671), and the six Jesuits listed in Table 4. These six missionary-astronomers had been

> . . . sent out by Louis XIV., under a royal patent, to carry out scientific work in the Indies and in China, in order, as the patent puts it, "to establish Security in Navigation and to improve Sciences and Arts." (Giblin 1909: 1)

Leading the missionary-astronomers was Father Jean de Fontaney, and with the exception of Guy Tachard,[2] they were bound for China but had to sojourn in Siam

[2]Guy Tachard (1651–1712) would stay behind and play a key political role in the development of scientific astronomy in Siam (see Orchiston et al. 2016, 2018b).

Table 4 Jesuit missionary-astronomers who came to Siam in 1685 with the French delegation

Name	Birth/death dates	Immediate destination after Siam
Jean de Fontaney	1643–1710	China (1688–1702)
Joachim Bouvet	1656–1730	China (1688–1697; 1699–1730)
Louis le Comte	1655–1728	China (1688–1691)
Jean-François Gerbillon	1654–1707	China (1688–1707
Guy Tachard	1648–1712	Remained in Siam
Claude de Visdelou	1656–1737	China (1688–1709); India (1709–1737)

Professor Michael Smithies (2003: 189), arguably the world's foremost authority on Siam of the 1680s, refers to these Jesuits as ". . . mathematicians [and] . . . astrologers . . ." Today there is a clear distinction between astrologers and astronomers, and we believe that Smithies was misled by the English translation of Tachard's tome, which reads: *Relation of the Voyage to Siam Performed by Six Jesuits sent by the French King, to the Indies and China, in the Year 1685, with their Astrological Observations, and their Remarks on Natural Philosophy, Geography, Hydrography, and History* (Tachard 1688). However, this is a serious mistranslation, because the original French volume refers specifically to '*Astronomical Observations*' and never mentions astrology

until the end of 1687. Consequently, they were able to observe the December 1685 lunar eclipse.

It is significant that before they left France,

> Tachard and the other five Jesuit astronomers were admitted to the Académie Royale des Sciences [in Paris], and supplied with astronomical instruments on the understanding that these would be used—among other things— to determine the latitude and longitude of different geographical features and population centres . . . [They also] were supplied with tables of Jovian satellite phenomena, courtesy of Paris Observatory, and various reference books and charts. (Orchiston et al. 2016: 31)

2.3.2 The Location of the Observing Site

The December 1685 lunar eclipse was observed from Lop Buri, not from Ayutthaya. Although Ayutthaya was the capital of Siam, King Narai developed Lop Buri as an attractive alternative capital (see Thavornthanasan, 1986), and he preferred to spend up to 9 months each year there. When members of the French delegation arrived in Lop Buri (or 'Louvo' as it was usually referred to)[3] they were extremely impressed, finding a ". . . town which is, so to speak, in the Kingdom of Siam what Versailles is in France." (Gervaise 1689).

Although he had a commodious palace in the centre of Lop Buri, King Narai also had a 'country retreat' in the form of a ". . . very roomy Palace . . . surrounded by brick walls fairly high." (Giblin 1904: 11), located at the water reservoir called 'Tale Chup-sawn' about 4 km east of Lop Buri (Giblin 1904: 22). This artificial lake was described by Father Tachard:

[3]In the 1680s Lop Buri was variously referred to as Louvo (Tachard 1686), Louveau (Gervaise 1689), Luvo (see Giblin 1904) and La-wo (ibid.) by the French.

> There is a large stretch of water which makes of it a peninsula [where King Narai's 'country retreat' was located], and on this water the King of Siam has built two frigates with six small pieces of cannon, on which this Prince takes pleasure in going about. Beyond this canal [lake] is a forest, 15–20 leagues in extent and full of Elephants, Rhinoceros, Tigers, Deer and Gazelles. (Giblin 1904: 12)

Figure 4 shows the location of the water reservoir and the 'country retreat' relative to King Narai's palace in Lop Buri and Wat San Paulo, the observatory that was later built for the Jesuit missionary-astronomers.[4]

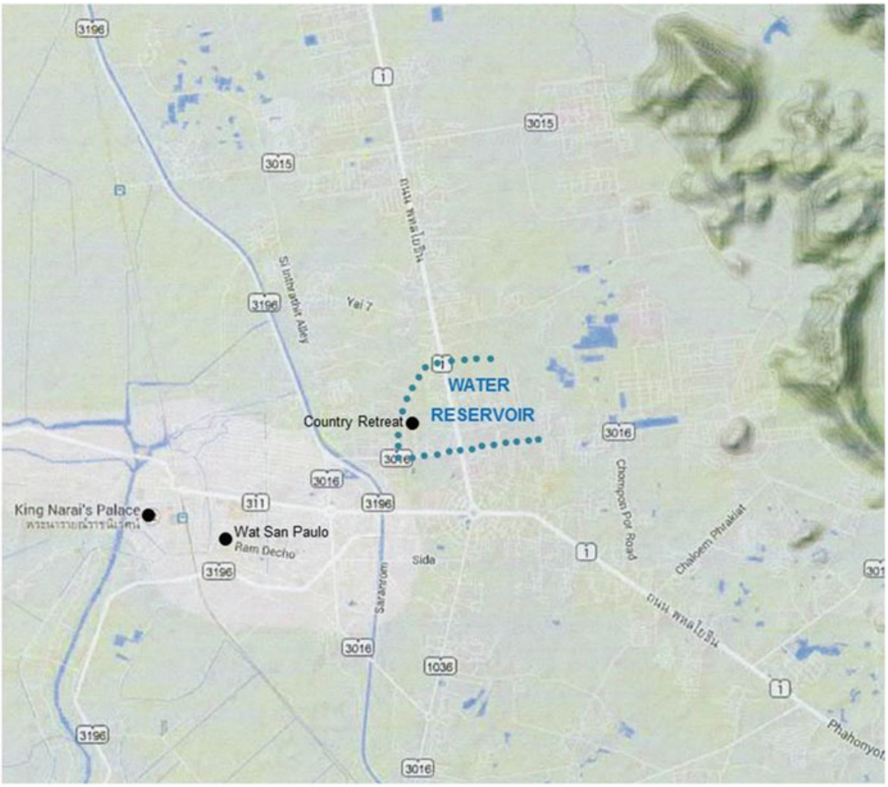

Fig. 4 A map of Lop Buri showing the location of King Narai's water reservoir and his 'country retreat' in relation to his palace and Wat San Paulo. The blue dots mark the position of the 12–13 feet high earth embankment that was erected to stop run-off from the mountains to the east, thereby forming the water reservoir. During his survey, Mr. Irwin noted that terracotta pipes had carried water from the south-western corner of the water reservoir to King Narai's palace. (Map modifications: Wayne Orchiston)

[4]Note that Fig. 4 is an updated version of Fig. 14 that was published in Orchiston et al. 2016: 39. In Fig. 4 the revised boundary of the water reservoir is now based on the cadastral map that was prepared by A.J. Irwin in the 1890s, but was unavailable when the 2016 paper was researched and written.

King Narai used his 'country retreat' palace when he went on hunting and

> . . . pleasure trips to the forests abounding with every variety of trees and to the wild mountain scenery abounding in birds and beasts, and [he] was enchanted with the romantic scenery of the region. (Smith 1880)

There is some confusion in the literature about the location where the French contingent made their observations (e.g. see Soonthornthum 2011), but a careful analysis quickly resolves this issue. When King Narai met the French astronomers in Lop Buri on 22 November 1985 he invited them to join him and observe the eclipse from his 'country retreat'.

2.3.3 Observations of the Eclipse

In preparing for the eclipse, Phaulkon and the Jesuit astronomers visited King Narai's 'country retreat' on 9 December and were impressed:

> A more convenient spot could not be selected. We saw the Heavens on all sides and we had all the space necessary for setting up our instruments. Having settled everything we returned to Louvo. (Tachard, 1686).[5]

On 10 December,

> . . . we had cause to be transported to the Tale-Poussonne our telescopes and a spring clock very trustworthy and regulated by the Sun . . . [so that we could] observe there the Eclipse, according to the orders of the King. (ibid.)

They set up their telescopes and the clock on a terrace beside the water reservoir, and after resting for 3–4 h they went to their observing site. They noted that by this time "It was then nearly three hours after midnight." (ibid.).

By good fortune the night was clear, and

> We prepared for the King a very long telescope of 5 feet [length] in a window of a saloon which opened on the corridor [terrace] in which we were. (ibid.)

It is interesting that although the presents that King Louis XIV gave King Narai included telescopes, the Jesuit astronomers chose to set up one of their own telescopes for King Narai to use. But—as we shall see—they selected the wrong telescope.

Once the eclipse had begun,

> . . . the King was informed and came at once to the window. We were seated on Persian mats, some with telescopes, others with the clock, others ready to write the time of the observation. We saluted His Majesty with a profound bow, after which the observations were begun. (Tachard 1686)

[5]This quotation and subsequent ones listed as 'Tachard (1686)' are actually taken directly from Giblin (1909) and are Giblin's English translations of the astronomical excerpts contained in Tachard's two-volume work *Voyage de Siam des Pères Jésuites Envoyés par le Roi aux Indes & à la Chine* (1686).

Subsequently, King Narai

> . . . wished to look through a telescope 12 feet long, which Father de Fontaney was using, and we immediately carried it to him. He allowed us to rise and stand up in his presence, and he was quite willing to look through the Telescope after we had done so, for it was necessary to put it in position to show it to him.
>
> Those who know the respectful attitude which Siamese Kings expect from those who may be in their presence have spoken to us of this favour as of something very unique. (ibid.)

Figure 5 is a drawing that was published later, and purportedly shows the Jesuit astronomers and King Narai observing the eclipse.[6] Elsewhere (Orchiston et al. 2016) we have shown that this drawing contains considerable artistic licence and should not be regarded as a realistic representation of the eclipse observations.

Be that as it may, King Narai apparently enjoyed observing the eclipse, and he

> . . . expressed a special satisfaction seeing all the spots [craters, etc.] of the Moon in the Telescope, and in seeing that the plan [map] which had been drawn of it at the Paris

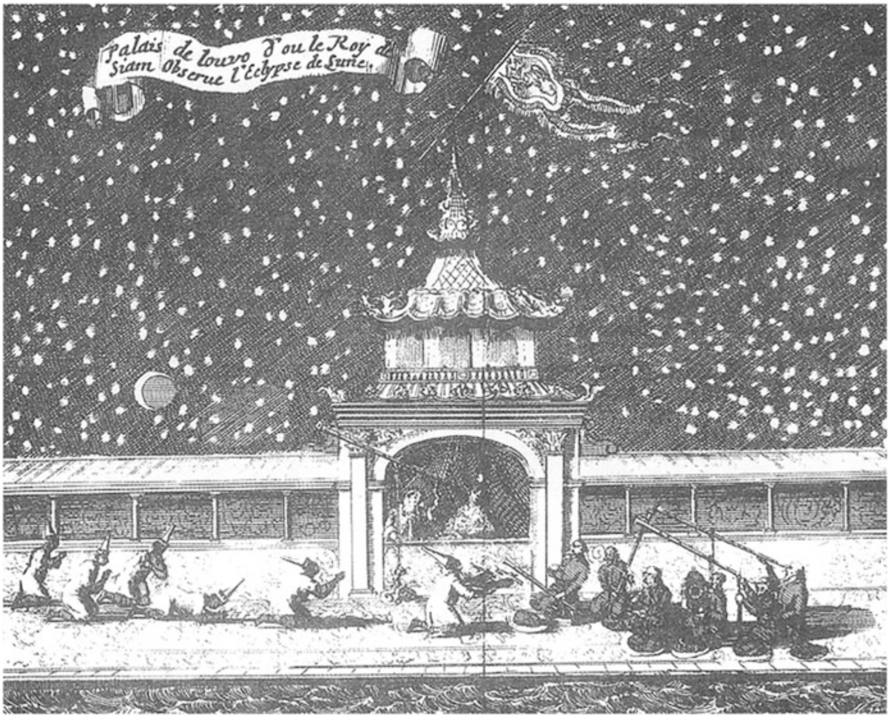

Fig. 5 A drawing showing King Narai and the Jesuit astronomers observing the 11 December 1685 total lunar eclipse from the King's country retreat which was on an island in the water reservoir that was located to the northeast of his palace in Lop Buri. (en.wikipedia.com)

[6]The prostrated individuals in this drawing are King Narai's court astrologers.

> Observatory agreed with it so well. He put several questions to us during the Eclipse. For example: Why the Moon appeared upside down in the Telescope? Why one could still see the part of the Moon which was eclipsed? What time was it at Paris? What could be the utility of such observations made at the same time at two places at such a distance apart? &c. (Tachard 1686)

The map of the Moon to which Tachard refers was prepared in 1678 and on 18 February 1679 was presented to the Academy of Sciences in Paris by Jean Dominique Cassini, the Director of Paris Observatory (Launay 2003).

After the eclipse, the French computed the longitude of Lop Buri as 121° 02′ E of the island of El Hierro. Meanwhile, the latitude of Lop Buri later was reported to be 14° 48′ 17″ N (Tachard 1689). The currently accepted value is 14° 48′ 00″ N, while Lop Buri is now known to be 118° 42′ E of the island of El Hierro.

For further information about the 1685 eclipse and the dynamic socio-political environment in which it was observed see Orchiston et al. (2016), while Gislén et al. (2018) provide a detailed examination of the contact timings for different lunar craters and other features.

2.4 The Lunar Eclipse of 30 November 1686

In Table 5 we list the start, middle and end times of the umbral phase of the partial lunar eclipse in local time, along with the positions of the Moon and Sun to the nearest degree, as observed from Lop Buri. As the table illustrates, this eclipse began in the morning not long before the beginning of astronomical twilight (the Sun was still 25° below the horizon), and the Moon was in the western sky. By mid-eclipse, when 51% of the Moon's diameter was in the Earth's shadow, civil twilight was about to begin; around this time, the sky would have been blue all over and normal daylight activities could have commenced, even though some of the brightest stars would still have been visible. As the twilight continued to increase in brightness, the Moon continued to move even lower in the western sky, setting at sunrise, which occurred at 06 h 27 m local time (before the eclipse had ended). In the period just before sunrise, the Moon would have been far less prominent due to its low altitude and the quite bright twilight.

Table 5 Details of the lunar eclipse of 30 November 1686

		Moon		Sun	
Umbral phase	Local time	Altitude	Azimuth	Altitude	Azimuth
Start	04 h 40 m	+24°	288°	−25°	107°
Middle	06 h 00 m	+06°	291°	−07°	111°
End	07 h 20 m	−11°	297°	+11°	116°

Table 6 Observers of the total lunar eclipse of 30 November 1686 and their instruments

Observing site	Observers	Instruments
Ayutthaya	Father Jean-François Gerbillon	Three telescopes with focal length of 2.5, 6 and 12 feet, respectively. A small pendulum clock.
	Mr. de Lamar (Royal Engineer of Siam)	
	Father Louis le Comte	
	Mr. Verét (Director of the French East India Company in Ayutthaya)	
	Father Claude de Visdelou	
Lop Buri	Father Joachim Bouvet	Two telescopes, one with a focal length of 5 feet. A small pendulum clock.
	Father Jean de Fontaney	
	Father John Baptist Malbonard	
	"Other priests"	

After Bhumadhon (2000: 47–49)

2.4.1 Observations of the Eclipse

It is interesting that not all of the Jesuit astronomers mentioned in Table 4 observed this eclipse, and that they were joined by others. Furthermore, the observations were carried from Ayutthaya *and* Lop Buri. Relevant information is summarised below in Table 6. Of the original contingent of six Jesuit missionary-astronomers only Guy Tachard missed this eclipse, but his absence is excusable for he was in France at the time (see Sect. 2.5.2, below).

According to the information assembled by Bhumadhon (2000), in Ayutthaya the eclipse was observed from the terrace and backyard of an unidentified house (presumably located in the Portuguese sector of the city), while in Lop Buri, Fathers Bouvet, de Fontaney and Malbonard assembled at the house of Louis Laneau (1637–1696), the Patriarch of Metellopolis and Head of the French Foreign Missions in Siam, along with other local priests. Father Malbonard was identified as the leader of the monks at Ayutthaya (Bhumadhon 2000). It is reported that King Narai planned to join Fathers Bouvet and Fontaney and observe the eclipse, but at the appointed time he was too busy to do so (ibid.).

A notable outcome of these eclipse observations was the discovery that Lop Buri was just 12 km east of Ayutthaya (ibid.).

The foregoing is merely an interim report on this eclipse. Records of the observations are housed at Paris Observatory, and have still to be studied in detail.

2.5 The Lunar Eclipse of 16 April 1688

In Table 7 we list the start, middle and end times of the umbral phase of the partial lunar eclipse in local time, along with the positions of the Moon and Sun to the

Table 7 Details of the lunar eclipse of 16 April 1688

Umbral phase	Local time	Moon		Sun	
		Altitude	Azimuth	Altitude	Azimuth
Start	00 h 11 m	+65°	177°	−65°	356°
Middle	01 h 37 m	+58°	220°	−58°	040°
End	03 h 04 m	+42°	241°	−42°	061°

nearest degree, as observed from Lop Buri. As the table illustrates, this eclipse was visible on the evening of 15–16 April in the few hours following midnight in a completely dark sky, ending long before the beginning of astronomical twilight. The event began with the Moon very high in the southern sky. By mid-eclipse, when 59% of the Moon's diameter was in the Earth's shadow, the Moon was still almost as high but in the south west, and at the end of the event it was somewhat farther west, but still almost half way between the horizon and the zenith.

2.5.1 Observers of the Eclipse

This lunar eclipse was observed by a new contingent of French Jesuit missionary-astronomers, whose presence in Siam can be traced back to the unbridled success of the total lunar eclipse of December 1685 and the observations carried out at King Narai's 'water reservoir' palace.

On 15 December 1685, just a few days after the eclipse, Chevalier de Chaumont set sail for France, accompanied by Father Tachard and a Siamese delegation led by Kosa Pan. King Narai was so impressed by the Jesuit observations of the recent eclipse that he sent King Louis XIV a letter inviting him to send a second contingent of Jesuit missionary-astronomers to Siam (see Orchiston et al. 2018b).

Father Tachard (1689) explains how this came about:

> . . . Phaulcon conversed with the King about obtaining 12 Jesuit Mathematicians, with the idea of building an observatory similar to those at Paris and at Peking. He explained to His Majesty the glory and utility which would accrue to him and the advantage which his subjects would draw from these from which they would learn the most beautiful Arts and finest Sciences of Europe. The King consented to this project, and it was decided that Tachard should return to France for the Jesuits. (Tachard 1689)

We can see that in next to no time Father Tachard ". . . had become an astronomical advisor to King Narai and Constantine Phaulkon and a scientific ambassador for King Narai . . ." (Orchiston et al. 2018b; cf. Giblin 1904), but Smithies (1994) and Cruysse (1992) both take a rather jaundiced view of Father Tachard's political acumen (see Orchiston et al. 2016: 31–32).

When he sailed for France in December 1685, Father Tachard carried not only the letter from King Narai to King Louis XIV but also a letter from Constantine Phaulkon to Father François de la Chaise (1624–1709), King Louis' personal confessor in Paris. In part, this letter reveals King Narai's plans to rapidly develop Western astronomy in Siam:

> The King my master having already ordered the Father Superior to select a site at Louvo [Lop Buri], and another at Ayutia, *to build* Churches, *Observatories* and Houses, which may seem to him proper, I undertake at the same time to give orders that all these will be ready to receive the Fathers on their arrival. *If the six Mathematicians (the Fathers and my Brothers), have been able to accomplish so much in two months what will not fifty or more do in the space of twenty years*. (Tachard 1689; our italics)

If nothing else, the above letter assumed that King Louis XIV would accede to King Narai's request for more Jesuit astronomers, and this is precisely what came to pass. Indeed, King Louis XIV was pleased with what the six French astronomers had been able to achieve in the short time they had been in Siam so he obliged by sending not 12, but 16, new Jesuit missionary-astronomers (Tachard 1689), and they are listed in Table 8.[7] They, Father Tachard and the new 'Envoy Extraordinary from Louis XIV to the King of Siam', Simon de la Loubère (1642–1729) arrived in Siam at the end of September 1687 and went straight to Ayutthaya.

But when the contingent of new missionary-astronomers visited Lop Buri they were not only welcomed by the original Jesuit contingent but also discovered Wat San Paulo,[8] one of the new observatories promised by Phaulkon (and mentioned in his letter to Father François de la Chaise). A contemporary drawing of this impressive astronomical facility is reproduced here in Fig. 6.[9]

The plan that the first contingent of French Jesuit missionary-astronomers, except Father Tachard, would go to China eventuated towards the end of 1687, and Wat San Paulo was left in the care of Father Tachard and the newly arrived astronomers. But all this changed in January 1688 when Father Tachard sailed once more for Europe, destined for Paris and the Vatican as King Narai's personal representative (Smithies and Bressan 2001). Father Tachard left Father le Royer in charge of the Observatory (Smithies 2003).

2.5.2 Observations of the Eclipse

King Narai observed the 16 April 1688 lunar eclipse from his palace in Lop Buri together with "... his Brahmin astrologer, and he even sent to the [Jesuit] Fathers a mandarin to ask them some questions." (Le Blanc 1692). Meanwhile, the Jesuits carried out their observations independently from Wat San Paulo (ibid.). As it turned

[7] Although Tachard (1689) states that sixteen Jesuit astronomers went to Siam in 1687, Udias (2003) could track down only fourteen when he researched this topic, and these are individuals listed in Table 6. Smithies (2003: 192) also refers to these astronomers as 'astrologers'.

[8] There is confusion over the correct spelling of Wat San Paulo, with both this (correct) version and 'Wat San Paolo' featuring at different times on different interpretive panels at the site itself! Even Soonthornthum (2011: 181) mistakenly uses Wat San Paolo.

[9] In fact, by this time only one observatory had been built (cf. Hodges, 1999). Moreover, part of the massive building shown in Fig. 6 was still under construction when Constantine Phaulkon and King Narai died in June and July 1688 respectively (Smithies 2003). Because of their passing, the planned Ayutthaya observatory was never built.

Table 8 Jesuit missionary-astronomers who embarked for Siam in 1687 with the second French mission

Name	Birth/death dates	Ultimate fate
Claude de Bèze	1657–1695	Returned to France
Jean Venant Bouchet	1655–1732	Went to Pondicherry, India, and carried out astronomy
Charles de la Breuille	1653–1693	Remained in Siam with Portuguese Jesuits in Ayutthaya; died in a shipwreck in 1693
Jean Colusson	????–1722	????
Patrice Comilh	1658–1721	Returned to France
Charles Dolu	1655–1740	Went to Pondicherry, India
Jacques Duchatz	1652–1693	Died in a shipwreck in 1693
Pierre d'Espagnac	1650–1689	Died en route from Bangkok to India in 1688
Marcel Le Blanc	1653–1693	Died in a shipwreck in 1693
Jean Richaud	1633–1693	Went to Pondicherry, India; carried out astronomy in India; died in a shipwreck in 1693
Louis Rochette	1646–1687	Died en route from France to Siam in 1687
Abraham le Royer	1646–1715	????
Pierre de Saint-Martin	???? –1689	Died en route from Bangkok to India in 1688
Francois Thionville	1650–1691	????

After Udias (2003: 54)

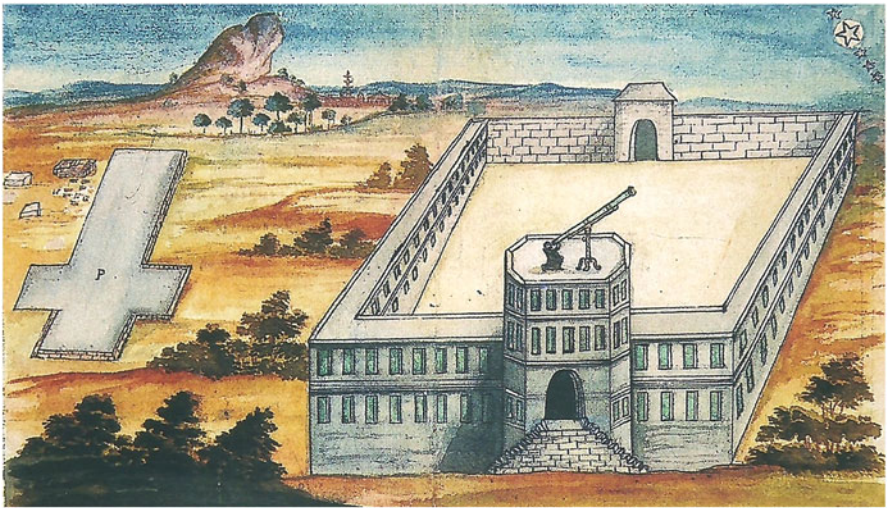

Fig. 6 A contemporary painting of Wat San Paulo, with its distinctive 4-storey observatory. (Wikimedia Commons)

out, this was destined to be the first and the last eclipse observed from Wat San Paulo by the Jesuit missionary-astronomers.

The records of this eclipse are preserved in Paris, and have yet to be studied in detail.

2.6 The Partial Solar Eclipse of 30 April 1688

The final seventeenth century eclipse observed from Siam by the second contingent of French missionary-astronomers was the 30 April 1688 solar eclipse. This occurred just 2 weeks after the 15–16 April lunar eclipse.

As Fig. 7 and Table 9 reveal, this was a partial solar eclipse as viewed from Siam, with the Sun in the eastern morning sky. At mid-eclipse, 73% of the Sun's diameter was covered by the Moon. The eclipse was total along a path beginning in India, passing to the north of Thailand, and ending in present-day Canada.

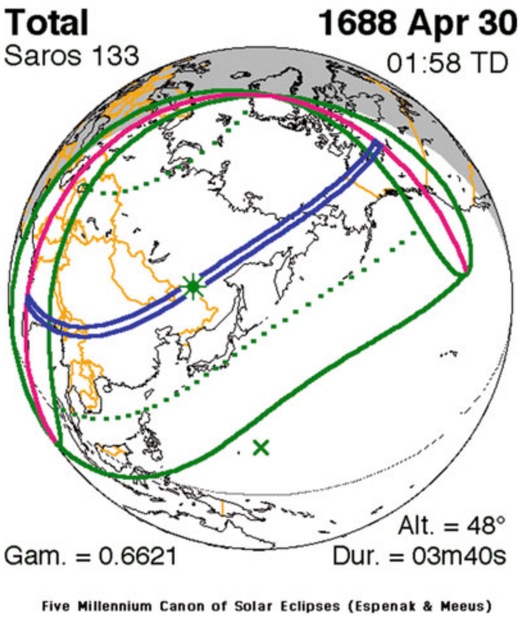

Fig. 7 A map showing the path of totality in blue of the solar eclipse of 30 April 1688. (After Espenak and Meeus 2006)

Table 9 Details of the 30 April 1688 partial solar eclipse

Phase	Local time	Sun Altitude	Sun Azimuth
Start	06 h 40 m	+10°	077°
Middle	07 h 35 m	+23°	080°
End	08 h 35 m	+37°	082°

2.6.1 Observations of the Eclipse

King Narai was ill at the time, but in a manuscript dating to 1688 Major de Beauchamp wrote that

> Mr Constance [Phaulkon] took advantage of this occasion to speak to him [King Narai] about an eclipse of the sun which was to occur in a few days; he asked if his health was strong enough to allow him to witness it, and [if so] the Jesuit Fathers would give him this pleasure. He replied he was, and he should bring them when the eclipse was to occur. *Mr Constance brought the Jesuit Fathers to the palace*; they set up their telescopes before the king who spent at most less than half an hour with them because the weather was not as good as one would have hoped. (cited by Smithies 2003:197; our italics)

Figure 8 is a contemporary painting of this event. This shows the Jesuit astronomers on the roof of one of the palace buildings, using eyepiece projection to view an image of the Sun on a piece of paper or card. Prostrated and surrounding the Jesuit astronomers are King Narai's Court astrologers, while the King is seen at the window on the right, being briefed, probably, by Father le Royer. Constantine Phaulkon is most likely the seated non-Jesuit, directly behind the telescope. Note that Fig. 8 includes a degree of artistic licence, for it shows only one astronomical telescope, not the 'telescopes' reported by Major de Beauchamp.

Fig. 8 A painting showing the observation of the partial solar eclipse of 30 April 1688 by French Jesuit missionary-astronomers from King Narai's palace in Lop Buri, in the company of the King and his prostrated Court astrologers. (en.wikipedia.org)

Further details of the Siamese observations of this eclipse are presented by Gislén et al. (2019).

To our knowledge, the solar eclipse April of 1688 was the last astronomical event that King Narai witnessed. His passion for Western astronomy, reliance on Constance Phaulkon, tolerance of Roman Catholicism and eagerness to foster closer ties between France and Siam created increasing disquiet among some members of the Royal Family, in the Siamese Court and amongst Buddhist monks. This culminated. in the staging of a *coup d'etat* by Phra Phetracha, King Narai's foster brother, and the King and his supporters were arrested. On 5 June 1688 Phaulkon, King Narai's son and other supporters were executed, and an ailing King Narai died soon after, on 11 July (Cruysse 2002; Smithies 2002). It has been suggested that it was poisoning that led to his lingering, and ultimately terminal, illness.

For 'Western astronomy' in Siam the result was disastrous:

> Pra Phetracha then installed himself as the King of Ayutthaya, and upon reversing King Narai's progressive policies closed Siam's borders to the West and expelled most of the foreigners living there … Wat San Paulo was closed, and all but one of the Jesuit astronomers quickly moved to the French fort in Bangkok before sailing to India … This brought a sudden and totally unexpected end to an all-too-short, yet extremely productive, period of scientific astronomical activity in Siam (Orchiston et al. 2018b)

After this, almost 200 years would pass before Western astronomy would return to Siam.

2.7 The Total Solar Eclipse of 18 August 1868

This is a famous eclipse in the annals of astronomy, and we would describe it as a 'watershed event'. Astronomical knowledge expanded enormously during the second half of the nineteenth century (Clerke 1903), when photography and spectroscopy were applied to astronomy (see Hearnshaw 2009; Hughes 2013). The solar corona finally was accepted as a tenuous outer atmosphere of the Sun rather than a mysterious terrestrial or lunar feature, and the basic chemical composition of the chromosphere, prominences and the corona were firmly established.

In fact it was the spectroscopic observations during the 18 August 1868 total solar eclipse that led to major breakthroughs (see Cottam and Orchiston 2015; Nath 2013). The path of totality is shown in Fig. 9, and the eclipse was observed from Aden, India (see Launay 2012; Nath 2014; Orchiston et al. 2017), Siam (Orchiston and Orchiston 2017), and the Dutch East Indies (present-day Indonesia; see Mumpuni et al. 2017), but

> … the most important observations—the ones that led to the aforementioned 'major breakthroughs'—came predominantly from India. (Kochhar and Orchiston 2017: 737–738)

What of the observations made from Siam?

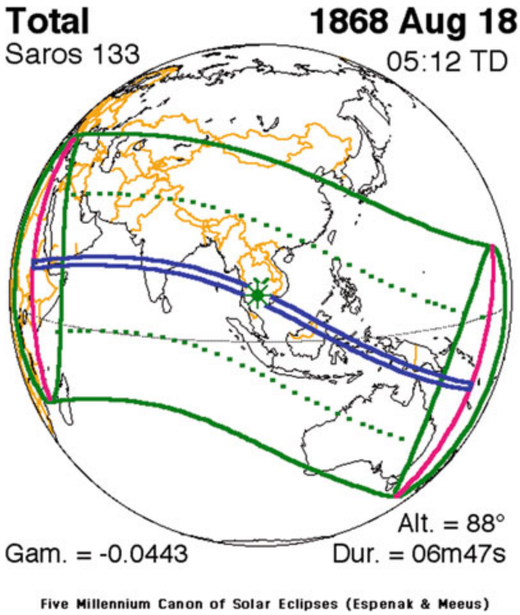

Fig. 9 A map showing the path of totality in blue of the solar eclipse of 18 August 1868. (After Espenak and Meeus 2006)

2.7.1 The French Expedition to Siam: Observers of the Eclipse

The 'Father of Thai Science', King Rama IV (1804–1868; Saibejra 2006) had a keen interest in astronomy (Aubin 2010), just like King Narai, and apart from organising his own observing expedition and attracting local political dignitaries such as Singapore's Sir Harry Ord (see Orchiston and Orchiston 2019), he also invited a team of French professional astronomers to visit Siam and observe the eclipse from Wah-koa on the west coast of the Gulf of Thailand (see Fig. 10).

Leading the French expedition was the Director of Marseilles Observatory Édouard Jean-Marie Stephan (1837−1923; Fig. 11a; Tobin 2014), who was assisted by two Paris Observatory astronomers, Georges-Antoine-Pons Rayet (1839–1906; Fig. 11b; Baum 2014) and François-Félix Tisserand (1845–1896; Fig. 11c; Débarbat 2014).

2.7.2 French Observations of the Eclipse

The French set up their observing camp on ancient sand dunes adjacent to the beach at Wah-Koa (Fig. 12), their principal instruments being 40-cm and 20-cm reflectors with silver-on-glass primary mirrors, a 15-cm refractor, a meridian telescope and an astronomical clock.

When the French expedition reached Wah-koa, Stephan

> . . . was heartened to find that Mr Hatt [a local hydrograpic engineer assisting the expedition] had been far from idle: before leaving Saigon he had arranged for prefabricated observatories

Fig. 10 A map showing Wah-Koa (the red bull's eye) and the path of totality of the 1868 eclipse across Siam. (Map modification: Wayne Orchiston)

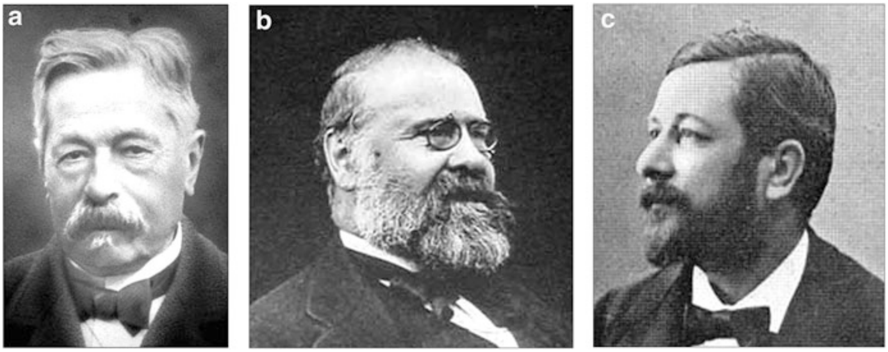

Fig. 11 (**a**) (left): Édouard Stephan. (en.wikipedia.org); (**b**) (centre): Georges Rayet. (adapted from *Astrophysical Journal*, 1907: facing page 53); (**c**) (right): Felix Tisserand. (After *Bulletin de la Société Astronomique de France* 1913)

to be built for the meridian telescope and the Cauche refractor, and these were now on site. Meanwhile, he also had arranged for the local people to build a very large bamboo house parallel to the beach. This was fully 80m in length, and was open towards the sea and flanked by two long galleries which were subdivided into numerous compartments.

A flat area to the south-west of the large bamboo building was reserved for the astronomical instruments, and their installation now became the main priority of the eclipse party. Mr Hatt

Fig. 12 A photograph by Rayet of the French eclipse camp, showing instrument huts and the 40-cm (left) and 20-cm (right) reflecting telescopes set up outdoors. (Courtesy: Archives, Observatoire de Marseille, 132 J 84)

> had successfully erected a large granite column inside the 'meridian house', and the meridian telescope was attached to this, and the astronomical clock was installed on its own column in this same building. (Orchiston and Orchiston 2017: 305)

With totality lasting an exceptionally long 6 minutes and 57 seconds,[10] this eclipse promised exciting research opportunities, but the French team must have been disheartened on the morning of 18 August when the sky was completely covered by clouds and it was raining just a few miles north-east of their observing site. But 10 min before totality most of the clouds disappeared, and the astronomers were able to observe the eclipse.

The French had no photographic equipment at Wah-koa, so they relied on visual and spectroscopic observations, with particular interest in the form of the corona and the locations and nature of prominences. Stephan (1869: 25) concentrated on the prominences (he called them 'protuberances'), ". . . which appeared to me in the big telescope in marvellous clarity . . ." Three of Stephan's drawings showing prominences and the corona are reproduced here in Fig. 13.

Meanwhile, Rayet subjected the chromosphere and the most prominent prominence to spectroscopic scrutiny and recorded a number of emission lines. He tried to correlate these with known lines in the solar spectrum, but mistook one prominent line for the well-known D line of sodium. In fact, this marked a new element, first

[10]This was only 35 s shorter than the longest possible duration of totality of a total solar eclipse, which is 7 min 32 s.

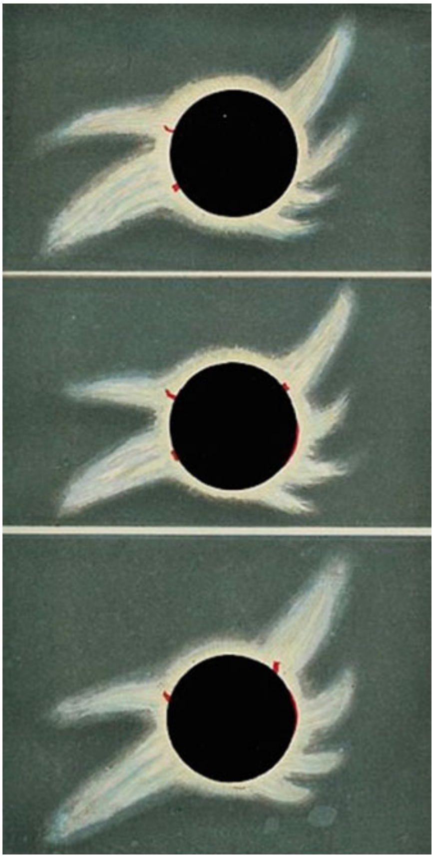

Fig. 13 Three drawings of the 18 August 1868 total solar eclipse by Édouard Stephan. (en.wikipedia.org)

mentioned by Madras Observatory Director Norman Robert Pogson (1829–1891; Snedegar 2014), which would later be named helium (after 'helios', the Greek God of the Sun). So Rayet

> . . . was not party to the discovery . . . Without doubt, this 'missed opportunity' arose from Rayet's familiarity with stellar rather than solar spectra. Had he made the connection, his name would now be much better known as the co-discoverer of helium rather than of Wolf-Rayet stars. (Orchiston and Orchiston 2017: 315)

Nonetheless, the French observations of this eclipse were a success, and

> . . . useful new data on the nature of the prominences were accumulated, even if the overall scientific outcomes paled into insignificance when measured against those published by Jules Janssen on the basis of his observations of this same eclipse made from India. (ibid.)

For further information about the French expedition to Siam in 1868 and their observations of the 18 August total solar eclipse see Orchiston and Orchiston (2017).

Meanwhile, observations of the eclipse by members of King Rama IV's expedition and Sir Harry Ord's party made little contribution to science and so are not discussed here. However, this eclipse was used very astutely by King Rama IV as a political weapon against the British and the French, both of whom had colonial aspirations involving Siam (see Aubin 2010; Orchiston and Orchiston 2019).

2.8 The Total Solar Eclipse of 6 April 1875

As Fig. 14 illustrates, the path of totality of the 6 April 1875 total solar eclipse passed through the Gulf of Thailand (not far north of where the 1868 eclipse was observed from). As well as offering a chance to build on the spectroscopic success of the 1868 eclipse and continue to explore the form of the corona, the 1875 event also invited astronomers to investigate the mysterious green coronal line, K 1471, that American astronomers had discovered during the 7 August 1869 total solar eclipse and named 'coronium' (see Maunder 1899).

2.8.1 The British Expedition to Siam: Observers of the Eclipse

King Rama IV had contracted malaria when he was at Wah-Koa observing the 1868 solar eclipse and he died soon afterwards, so in 1875 it was his son, King Rama V (1853–1910; also known as Chulalongkorn) who invited foreign astronomers to Siam to observe the eclipse, "Inspired by the memory of his father *and his [own] great interest in and knowledge of astronomy* . . ." (Hutawarakorn-Kramer and

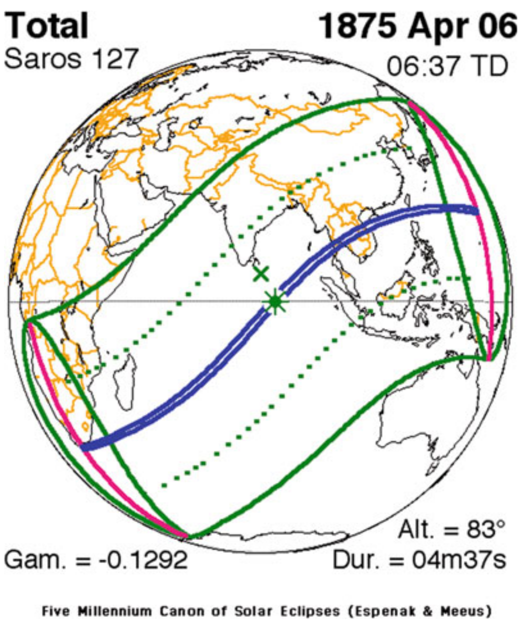

Fig. 14 A map showing the path of totality of the solar eclipse of 6 April 1875. (After Espenak and Meeus 2006)

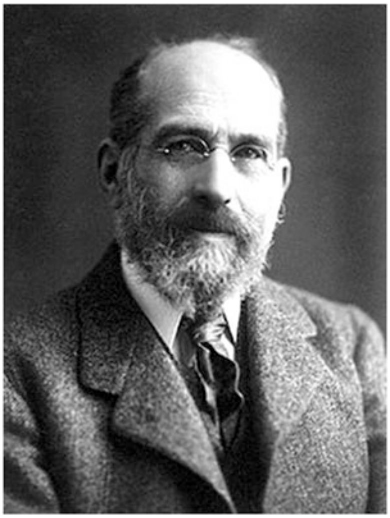

Fig. 15 Arthur Schuster. (en.wikipedia.org)

Kramer 2017: 319; our italics). But on this occasion he invited the British and the French, and both accepted. While the famous French astronomer Pierre Jules César Janssen (1824–1907; Launay 2012) accepted King Rama V's invitation, it was the British expedition that would make most impact (see Lockyer and Schuster 1878), and is discussed here.

The Royal Society decided to send an expedition to Siam, and leading it was the youthful Manchester University astronomer, Arthur Schuster (1852–1934; Fig. 15; Knill 2014) who was only 23 years of age at the time. As Hutawarakorn-Kramer and Kramer 2017: 320) point out, Schuster ". . . considered the task to lead the expedition a great challenge, the outcome of which would determine his future career."

2.8.2 British Observations of the Eclipse

After a 45-day sea voyage from England, the British party reached Siam just 8 days before the eclipse occurred. But when they arrived at their observing camp on sand dunes near the Chao Lai Peninsula (see Fig. 16) they found that the Siamese had already erected houses for them (e.g. see Fig. 17) and an observatory building. Each house contained a dining room, bedrooms, bathroom facilities and storage space for provisions, while

> The observatory consisted of two parts, separated by about 35 m. The smaller part was intended for a siderostat to obtain a spectrum of the prominences and the lower corona . . . The larger part of the observatory was bounded by a dark room on each side, with preparation of the photographic plates on one side and development of them on the other (Lockyer and Schuster 1878). The main part contained an equatorial telescope with a prismatic camera which was of shorter focal length than the camera attached to the siderostat . . . Another equatorial telescope, which was lent to the expedition, had a spectroscopic camera attached in order to also obtain spectra of the prominences and the corona. In

Fig. 16 A map showing the Chao Lai Peninsula eclipse site (the red bull's eye) and the path of totality of the 1875 eclipse across Siam. (Map modification: Wayne Orchiston)

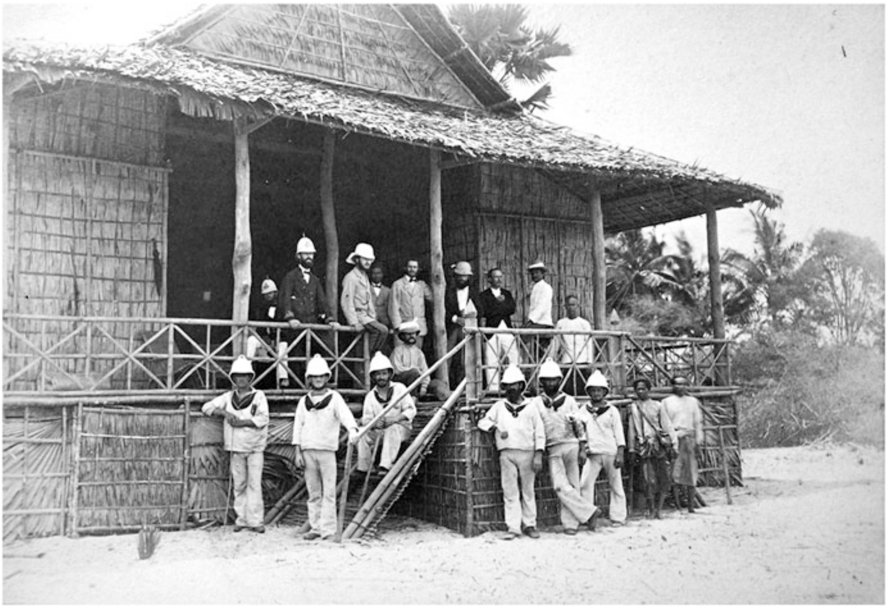

Fig. 17 One of the houses erected for the British expedition. (Courtesy: Royal Astronomical Society)

Fig. 18 The siderostat used during the expedition, with its protective cover removed. The associated telescope and spectroscopic camera were located in the adjacent hut. (Courtesy: Royal Astronomical Society)

> addition, a number of small cameras were available, the pictures from which were to be supplemented by sketches made during the eclipse. (Hutawarakorn-Kramer and Kramer 2017: 321)

As this quotation suggests, the main research focus of the expedition was to be the chemical composition of prominences and the corona, and the aforementioned siderostat is shown in Fig. 18.

Fortunately, clear skies greeted the astronomers on 6 April 1875, and totality commenced at 1130 h, but unfortunately,

> No useful results were obtained with the spectroscopic camera mounted on the equatorial telescope. Lockyer and Schuster (1878) later attributed this failure to the fact that the telescope used was not designed for this purpose. (Hutawarakorn-Kramer and Kramer 2017: 322)

However, spectroscopic studies made with the siderostat were a success, and Lockyer and Schuster (1878) summarized the key results, which included:

1. The upper corona was found to emit a 'homogeneous' photographic spectrum which was attributed to the "... hydrogen line near (Fraunhofer line) G."
2. The lower corona was found to emit a strong continuous spectrum extending into the UV up to a wavelength of 353 nm (i.e. "beyond N"), reaching to a height of about 3′ from the Sun.

3. Photographs showed that the extent of the corona rapidly increased with increasing exposure time, suggesting that the corona had no definite outline.

No mention was made of the ‘coronium’ line. Much later, Schuster (1932) noted that it was their observations of the 1875 eclipse that documented the existence of calcium in prominences and the chromosphere for the first time.

For further details of the British expedition see Hutawarakorn-Kramer and Kramer (2017) and Euarchukiati (2019).

Meanwhile, as with the 1868 eclipse, observations of the 1875 eclipse by members of the Royal expedition made no significant contributions to solar physics, so they are not discussed here.

2.9 The Total Solar Eclipse of 9 May 1929

The path of totality of this eclipse crossed Thailand, Malaysia, Indochina, Vietnam and the Philippines (Fig. 19), and attracted eclipse parties from England, France,

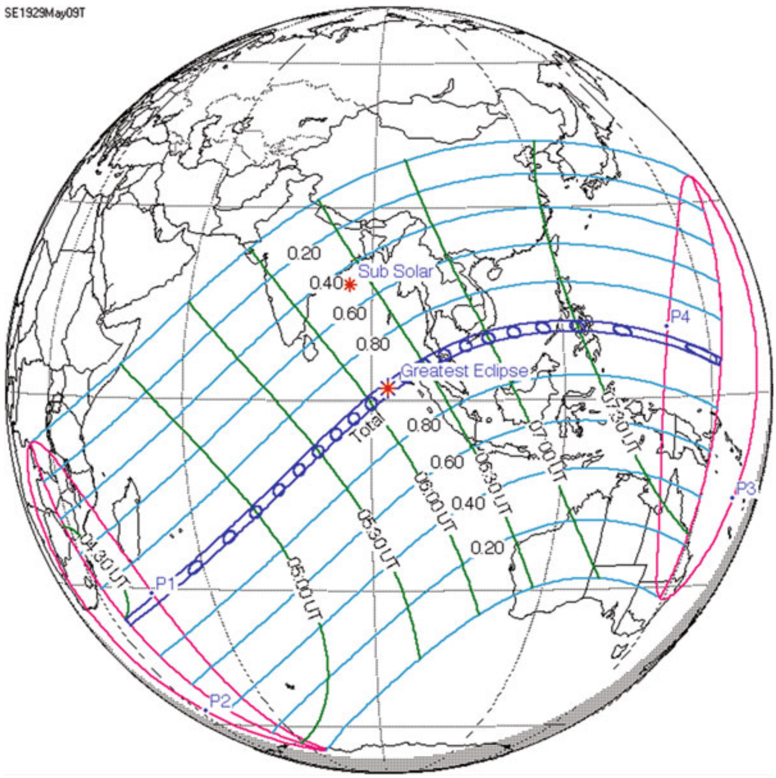

Fig. 19 A map showing the path of totality of the solar eclipse of 9 May 1929. (Courtesy: Eclipse Predictions by Fred Espenak, NASA’s GSFC http://eclipse.gsfc.nasa.gov/)

Table 10 Overseas expeditions and the 9 May 1929 total solar eclipse

Country	Expedition	Observing site
Siam	British	Pattani
	German	Pattani
Federated Malaya States	American	Alor Star
	British	Alor Star
	Japanese	
Dutch East Indies (Sumatra)	Dutch	Idi
	German	Takengong
	Japanese	
Indochina	French	Poulo Condore Island
Philippines	American (4)	
	German	Cebu Island

Germany, Holland, Japan and the USA (see Table 10). With totality lasting about 5 min, this eclipse offered not only an opportunity to investigate the chemical composition of the corona but also to again confirm Einstein's General Theory of Relativity.

In this paper we will discuss only the expeditions that went to Siam. There were two—from Britain and Germany—both there at the invitation of King Rama VII. The King was convinced that the 1929 eclipse observations would benefit science and at the same time "...create good relations between Siam and European countries." (Soonthornthum et al. 2019). So an Eclipse Committee was formed, and suitable facilities were prepared for the two eclipse expeditions.

2.9.1 The British Expedition to Siam: Observers of the Eclipse

Plans for the British expedition were initiated by the Astronomer Royal, Sir Frank Dyson (1868–1939) in 1926, and it was decided that Professor Frederick John Marrian Stratton (1881–1960; Fig. 20; Batten 2014) from Cambridge University and Philibert Jacques Melotte (1880–1961; Teare 2014) from the Royal Observatory, Greenwich, would go to Pattani in the very south of Siam, near the border with Malaya, while John Jackson from Greenwich and Dr. J.A. Carroll from the Solar Physics Observatory at Cambridge would proceed to nearby Alor Star in Malaya (see Fig. 21). Dr. Thomas Royds (1884–1955), Director of the Kodaikanal Observatory in India, also was invited to joined Stratton's party.

2.9.2 British Observations of the Eclipse

The scientific instruments taken to Pattani included two spectrographs, a 13-in f/10.4 astrograph, a coronagraph and a polariscope. The plan was to use these to explore the nature of the corona and photograph stars in the vicinity of the eclipsed Sun (for the

Fig. 20 Professor Stratton in Japan in 1936. (https://commons.wikimedia.org/wiki/File:F.J.M._Stratton_astrophysicist.png)

Fig. 21 A map showing the British Pattani (red bull's eye) and Alor Star (blue bull's eye) eclipse sites and the path of totality of the 1929 eclipse across Siam and Malaya. (Map modification: Wayne Orchiston)

'Einstein experiment'). Unfortunately, heavy clouds prevent any observations on the day of the eclipse—so from a scientific viewpoint, all the preparations and expense had been for naught.

2.9.3 The German Expedition to Siam: Observers of the Eclipse

Leading the German expedition was Professor Hans Oswald Rosenberg (1879–1940; Theis 2014) from the University of Kiel, assisted by Dr. D. Stobbe and W. Pape. Their observing camp was at Khok Pho, Pattani district, 34 km south-west of the British eclipse camp.

2.9.4 German Observations of the Eclipse

Stratton (1928: 200–201) reports that

> The photometry, and spectrophotometry of the corona and its spectrum will be examined over a wide range of spectrum with the aid of a spectrograph of high light-gathering power.

Accordingly, the Germans took four spectrographic cameras to Khok Pho, along with an astrograph.

The sky over Pattani was less than encouraging on 9 May. However, because the German and British observing camps were at different locations, the Germans were able to take a few photographs during totality, although these did not provide details of the solar corona (e.g. see Fig. 22).

2.9.5 King Rama VII and the 1929 Eclipse

It could be argued that Kings Rama IV and V were Siamese 'Sun Kings', in that they both had a personal interest in astronomy, organised their own eclipse expeditions, and observed both eclipses. However, King Rama VII's interest in eclipses was more political than scientific, so even had the skies been co-operative on 9 May 1929 he had no plan to carry out the same range of observations as his illustrious astronomical predecessors. Certainly he hoped to view the eclipse, but instead all he could do was visit the British and German astronomers on the day before the eclipse (e.g. see Fig. 23), and later commiserate with them.

Fig. 22 The Sun at totality taken with the astrograph at the German site at Khok Pho. (Courtesy: King Prajadhipok Museum)

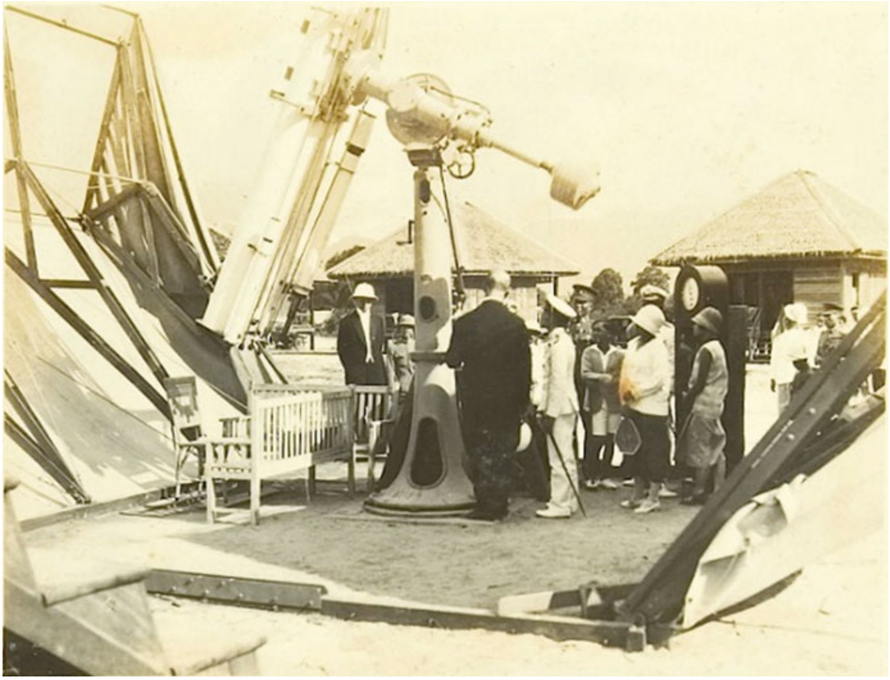

Fig. 23 King Rama VII and the Queen visiting the German eclipse camp on 8 May 1929 and inspecting the astrograph. (Courtesy: King Prajadhipok Museum)

3 The Emergence of Astronomy at Chulalongkorn University

The 1929 eclipse was the catalyst that led to the emergence academic astronomy in Siam, and

> . . . in 1930 astronomical research was established at Chulalongkorn University in Bangkok, the first university in Thailand (and named after King Rama V). (Soonthornthum 2017: 280–281)

Soonthornthum et al. (2019) also report that Colonel Phra Salvidhan Nides (Fig. 24), a prominent member of the Siamese committee that organised the construction of the British and German eclipse camps in 1929 and welcomed the European astronomers, taught astronomy courses at Chulalongkorn University for science and engineering students.

The University's interest in solar astronomy continued when Rawi Bhavilai (1925–2017; Fig. 25) joined the Physics Department in 1944. Bhavilai[11] would remain at Chulalongkorn University until his retirement in 1986, by which time he

[11]Other spellings of his name are Rawee Bhavilai and Rawī Phāwilai.

Fig. 24 Colonel Phra Salvidhan Nides, Siam's first university lecturer in astronomy. (Courtesy: Office of the National Research Council of Thailand)

Fig. 25 Professor Rawi Bhavilai, Siam's first solar physicist. (After Knowledge without bounds, 2008)

was a full Professor (Prominent astronomer . . . 2017). During his tenure he secured a Colombo Plan Scholarship and studied for an M.Sc. degree at the University of Adelaide (Knowledge without bounds 2008), graduating in 1952. Subsequently, he continued this love affair with Australian academia by studying for a Ph.D. in astronomy at the Australian National University in Canberra, while based at nearby Mount Stromlo Observatory. In 1965 he was awarded the doctorate for a thesis titled "The Structure and Dynamics of the Solar Chromosphere" (Rawi Bhavilai 2017).

Professor Bhavilai established a solar research group at Chulalongkorn University and not long before the publication of his book *The Fine Structure of the Solar Corona* (Bhavilai 1971) a 15-cm f/10 Zeiss solar chromospheric telescope was installed at the University. This instrument is described in the book.

This book was one of twenty-one books that Professor Bhavilai wrote or edited, but most were in the fields of literature and Buddhism. So although he is well known as an astronomer,

> His life's work . . . has seen him explore areas as diverse as philosophy, physics, Buddhism and poetry. (Knowledge without bounds 2008)

Professor Rawi Bhavilai was Thailand's first solar physicist, but by 1989 the Physics Department had expanded into astrophysics, and

> In October 1989 a 0.45-m reflecting telescope was donated to Chulalongkorn University by the Government of Japan under a cultural grant aid program for the promotion of astronomical education and research in Thailand. (Soonthornthum 2017: 281).

But Chulalongkorn University was not the first Thai university to embrace astrophysics, for this was pioneered in 1977 at Chiang Mai University in northern Thailand, when astronomy became part of the Faculty of Science curriculum (Soonthornthum 2017). Initially, research projects concentrated on stellar astronomy, and particularly photoelectric photometry. This led, ultimately, to the final phase in the development of professional astronomy and emergence of astrophysics in Thailand, with the establishment in 2009 of the National Astronomical Research Institute of Thailand (NARIT) in Chiang Mai; the founding Director, Boonrucksar Soonthornthum, had been an Associate Professor of Astronomy at the University.

4 The Founding and Development of NARIT

As Soonthornthum (2017: 284) has pointed out,

> The development of astronomical research in Thailand took a crucial leap forward when on 20 July 2004 the Government approved the "Establishment of the National Astronomical Research Institute of Thailand (NARIT)" under the Ministry of Science and Technology. On 1 January 2009 NARIT was approved by the Government and officially established with the status of a public organization responsible for policy-making and strategic planning in the development of astronomy in Thailand.

The growth of NARIT since 2009 has been phenomenal, with vibrant schools and public outreach programs,[12] and a Research and Development Division that carries out wide-ranging astrophysical research.

Some of the observations conducted in the course of this research have been made with the Thai National Telescope (TNT), a new 2.4-m Ritchey-Chrétien telescope (Fig. 26) that is located near the summit of Doi Inthanon, Thailand's highest mountain, not far from Chiang Mai (Fig. 27). Her Royal Highness Princess Maha Chakri Sirindhorn officially opened the TNT in January 2013 (just 4 years after NARIT was founded).

[12]For details of NARIT's education and outreach accomplishments see Soonthornthum (2017).

Fig. 26 Two views of the automated 2.4-m Ritchey-Chrétien Thai National Telescope. Left: undergoing testing prior to its installation at the TNO; right: installed and operational at the TNO. (Courtesy: NARIT)

Fig. 27 The Thai National Observatory (TNO) is located near the summit of Doi Inthanon, a 2-hour drive west-southwest of Chiang Mai. (travel.mthai.com)

Fig. 28 The 0.7-m PlaneWave LDK700 reflector being installed at the Sierra Remote Observatories, USA, in December 2015. Third from the left is Dr. Saran Pochyachinda, the current Director of NARIT. (Courtesy: NARIT)

In order to conduct research collaborations and 24-hour monitoring of target stars, NARIT has also established an international network of 60-cm to 1-m telescopes sited in Australia, Chile, China and the USA (see Fig. 28).

The latest (and current) phase in the development of NARIT's astrophysical instrumentation involves radio astronomy. At the time of writing this paper (2018) a stand-alone 40-m diameter radio telescope is under construction near Chiang Mai (see Fig. 29). The plan is

> . . . that eventually there will be three identical dishes in Thailand, in the north, east and south (to maximize base-lines), and that these will form a Thai VLBI Network, but also work closely with the existing VLBI networks in East Asia (China, Taiwan, South Korea and Japan) and in Australia-New Zealand. (Orchiston and Swarup 2018)

NARIT's astrophysical research is now conducted by a growing pool of tenured astronomers, post-doctoral fellows, research assistants and graduate students. Meanwhile, the Thai Government is promoting this strategy by providing funding so that students can study overseas and obtain Ph.D.s in astronomy. Most of these graduates return to Thailand and to posts at NARIT or at one of the many universities that now teach astronomy.

In order to promote astrophysical research and research collaborations at these universities, in July 2007 NARIT signed memorandums of understanding with 24 different universities in Thailand, while at an international level NARIT has

Fig. 29 NARIT's new 40-m radio telescope will be modeled on this dish at Yebes in Spain. (Courtesy: NARIT)

similar arrangements with various universities, observatories and research institutes in more than 15 countries (Soonthornthum 2017).

Meanwhile, NARIT has been very active promoting research among Southeast Asian nations, and following a meeting in 2007 formed SEAAN, the South East Asian Astronomical Network. The goals of this network are

> . . . to establish strong research collaborations, identify key science appropriate to the region, share instruments and develop and utilize human resources among South-East Asian countries. The network now has annual meetings in different cities throughout the region, and acts as a regional platform to bring the advancement in astronomy to each member country. Research collaborations have been organized or are planned in optical and radio astronomy, in the development of instrumentation, and in history of astronomy, not just within the SEAAN region, but also with institutes in Australia, China, India, Japan, Korea and Taiwan. (Soonthornthum 2017: 289)

One of the primary reasons for the amazing developments that have occurred lately in Thai astronomy is the strong support of King Bhumipol Adulyadej (Rama IX; 1927–2016; Fig. 30) and his second daughter, Princess Maha Chakri Sirindhorn (Fig. 31), both of whom have been passionate about astronomy. This follows a long-standing Royal tradition that began with King Narai, and had circumstances been different it is possible that the late King would have become a professional astronomer. Meanwhile Princess Sirindhorn is an avid 'eclipse-chaser', and also makes observations and carries out astrophotography with various NARIT telescopes (including the 2.4-m Thai National Telescope).

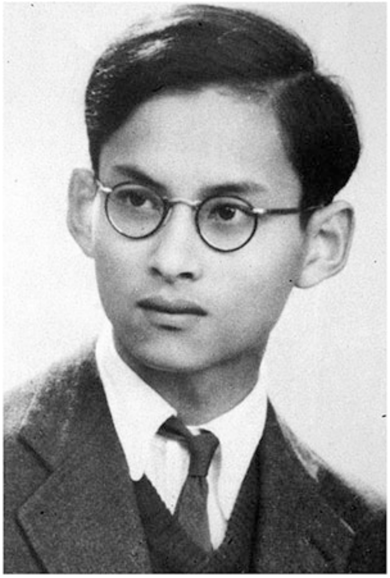

Fig. 30 King Bhumipol Adulyadej (Rama IX) as a young man. (Wikimedia. commons)

Fig. 31 Princess Maha Chakri Sirindhorn (right) examines a scale model of the new NARIT headquarters, now known as the Princess Sirindhorn AstroPark, part of which is still under construction in an outer north-eastern suburb of Chiang Mai. Third from the right is Professor Boonrucksar Soonthornthum who at the time was the Director of NARIT. The current Director, Dr. Saran Pochyachinda, is second from the right. (Courtesy: NARIT)

5 Concluding Remarks

It is well known that throughout history eclipses have filled mankind with dread or wonder. But they have also been party to the development of 'modern astronomy' in many nations and the foundations upon which astrophysics was built. This was no more so than in Siam, where over a period of almost two and a half centuries solar and lunar eclipses were seminal in the emergence of 'modern astronomy' and ultimately in the birth of solar physics and astrophysics.

Moreover, the second half of the nineteenth century was a critical time in the history of astronomy, when spectroscopic, photographic and polariscopic observations of a succession of total solar eclipses led to major breakthroughs in solar physics (Clerke 1893). Siam was able to make an important contribution in this regard, thanks to British and French observations of the 1868 and 1875 eclipses.

An underlying theme throughout this paper has been the significance of royal patronage in fostering European observations of eclipses, and especially total solar eclipses, made from Siam. This patronage was pivotal to the birth of 'modern astronomy' in Siam in the seventeenth century, and continued during the nineteenth and twentieth centuries, finally culminating in the formation of NARIT. France's 'Sun King' aside (see Débarbat 2015), it could be argued that there are few other countries in the world where royal patronage has played so key a role in the long-term development of astronomy, and especially in the emergence of astrophysics.

King Rama IV and King Rama V also used the 1868 and 1875 eclipses as educational vehicles to demonstrate the differences that existed between Western 'scientific astronomy' and Siamese 'traditional astrology', and it is notable that the Thai Royal Family continued this tradition during the twentieth century. Thus, King Bhumipol Adulyadej observed the total solar eclipse of 20 June 1955 and he and Princess Sirindhorn watched the 24 October 1995 eclipse. Both were visible from Thailand, and in 1955 "Radio Thailand station broadcasted a program about the solar eclipse nationwide for the first time in Thai history." (Nitiyanant 2015). By 1995,

> Many Thai people were interested [in astronomy and the eclipse and they] . . . travelled to provinces that the eclipse path passed through and many Thai television channels broadcast live views of the eclipse nationwide . . . (ibid.)

Finally, in this paper we have seen how eclipses, and particularly total solar eclipses, can have important political ramifications. Thus, some of Siam's kings used eclipses, in league with foreign policy, to not only foster international relations but also reinforce Siam's independence, as discussed, for example, by Aubin (2010) and Orchiston and Orchiston (2019) in the case of the 1868 eclipse.

Acknowledgements We wish to thank Visanu Euarchukiati (Bangkok, Thailand) for locating a copy of A.J. Irwin's cadastral map of Lop Buri and making this available to us (so that we could prepare Fig. 4). Apart from the calculations for Tables 2, 3, 5, 7 and 9, which were performed by the third author of this paper, research on the seventeenth century eclipses was largely based on data gathered by the first two authors during a detailed literature survey and on three visits to Lop Buri and Ayutthaya in 2014 and 2015. We are grateful to staff from the Lop Buri City Hall, and the Department of Fine Arts at Kraisorm Siharat Pavilion (the 'Water Reservoir Palace' in Lop Buri) for their assistance. Finally, we wish to thank the King Prajadhipok Museum, Office of the National Research Council of Thailand, Observatoire de Marseille and the Royal Astronomical Society for kindly supplying Figs. 12, 17, 18, 22, 23 and 24.

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Part IV
Mathematical Astronomy, Calendrical Astronomy and Dating

Derivation of the Inclination of Mars' Orbit in the *Almagest*

Mitsuru Sôma

Abstract Ptolemy published the inclination of Mars' orbit as 1.0° in the *Almagest*, which is smaller than the actual value of 1.9°. It is suggested that such a small value was obtained using inappropriate procedures from two values of the observed ecliptic latitudes of Mars that had errors of ~0.3°, and it is shown that a more precise value could have been obtained from the same observational values using another procedure.

1 Introduction

The *Almagest* was written by Ptolemy (Claudius Ptolemaeus in Latin, Κλαύδιος Πτολεμαῖος in Greek), who was an astronomer, mathematician, and geographer of Greek descent who flourished in Alexandria of Egypt during the second century CE. The *Almagest* was translated into Japanese by Yabuuchi (1982) and it was this edition that I read for the current study.

In the *Almagest* the Geocentric model was used to explain the apparent paths of stars and planets. In the Geocentric model each planet moves along an epicycle, the center of which moves along the deferent at a constant angular velocity when viewed at the equant (Fig. 1). The deferent is a circle and the equant is located on the opposite side of the Earth with respect to the center of the deferent, and the distance between the equant and the center of the deferent is equal to the distance between the center of the deferent and the Earth. This model explains direct and retrograde motion and also the variation of the speed of the planet as seen on the sky. In this paper we will concentrate on the orbit of Mars presented in the *Almagest*, and discuss how Ptolemy obtained the inclination of Mars' orbit with respect to the ecliptic.

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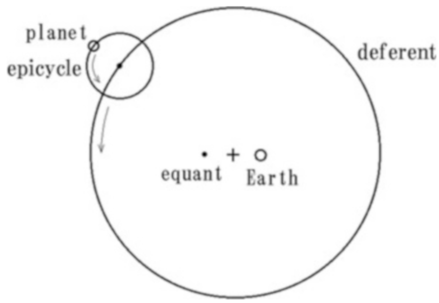


Fig. 1 The motion of a planet according to the theory presented in the Almagest

2 Mars' Orbit as Presented in the *Almagest*

According to the theory of Mars' motion in the *Almagest*, the ratio of the distance between the equant and the center of the deferent, the radius of Mars' epicycle, and the radius of Mars' deferent is 06:39.5:60. We now know that the epicycle is the effect of the orbital motion of the Earth around the Sun and the deferent is the orbit of the planet around the Sun. Fig. 2 shows the comparison of the positions of Mars around the Sun (or the positions of the center of the epicycle around the Earth in the case of the theory as mentioned in the *Almagest*) between those calculated by the theory in the *Almagest* and those calculated by Kepler's laws. The positions are shown for every 1/36 of the Mars' revolution period around the Sun. In the figure, the true orbit of Mars is drawn as an ellipse with the semi-major axis shown as 1.524 au whose eccentricity is 0.092, but it can be seen that the ellipse is very close to an eccentric circle. It can be noted that the maximum error in the heliocentric ecliptic longitude of Mars in the theory of the *Almagest* is only 0.88°. The theory in the *Almagest* assumed the ecliptic longitude Ω of the ascending node of Mars' orbit was 90° larger than the ecliptic longitude $\tilde{\omega}$ of the pericenter. The current precise theory gives the value as 93.8° for the epoch 100 CE, so it can be seen that the *Almagest's* assumption was a good approximation.

From the Geocentric model and parameter values for Mars motion in the *Almagest*, one can calculate the position of Mars at any given time. Figure 3 shows Mars' actual path based on the current theory, and its path based on the model in the Almagest from 1 September 147 to 31 March 148. The two bright stars shown on the right are Pollux (β Gem) and Castor (α Gem). It is well known that the Geocentric model in the *Almagest* can produce direct and retrograde motions of planets, but it should be noted from Fig. 3 that it can also give the planets' positions accurately.

3 Derivation of the Inclination of Mars' Orbit

In the *Almagest*, the inclination of Mars' orbit was obtained from the latitudes of Mars observed on two occasions: one was $4\frac{1}{3}^{\circ}$ at apogee opposition (the angle KEA in Fig. 4) and the other was 7° at perigee opposition (the angle XEB in Fig. 4). Note

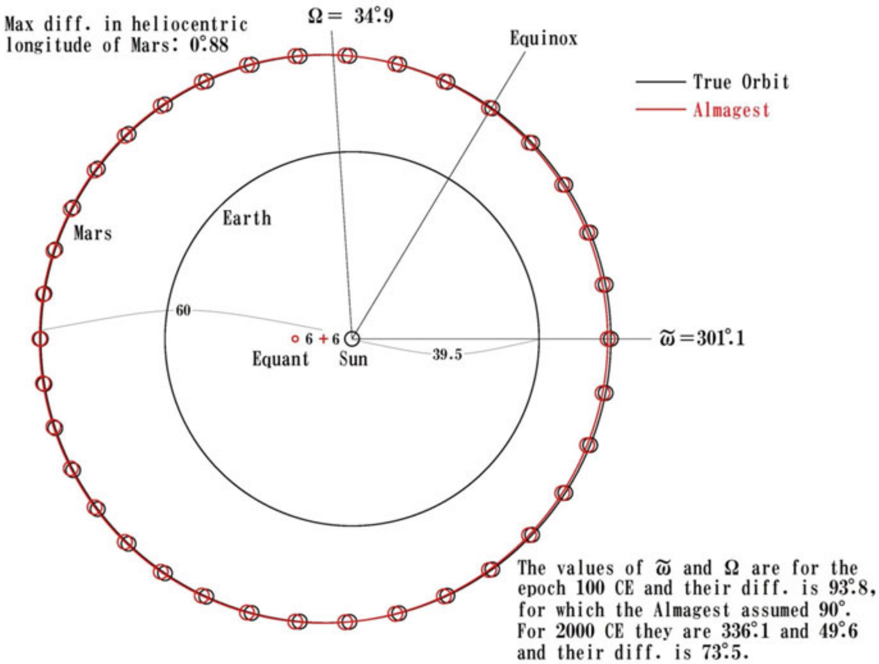


Fig. 2 Comparison of the positions of Mars between the theory in the Almagest and Kepler's laws

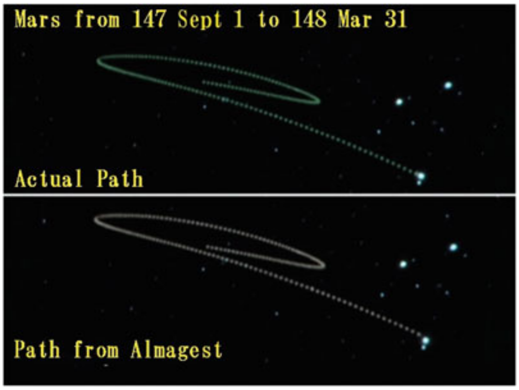
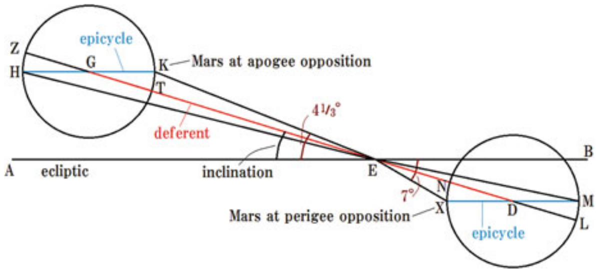


Fig. 3 The motion of Mars from CE 1 September 147 to 31 March 148 based on current theory and on the model in the Almagest (courtesy: Tamarokuto Science Center in Tokyo, Japan)

that the 'latitude' is used as the 'ecliptic latitude' in this paper. The actual values for the latitudes given above are 4.7° and 6.7°, so the error was ~0.3° for each of them. As shown in Fig. 5 the radius of the deferent for Mars' orbit in the *Almagest* is 60, the radius of the epicycle is 39.5, and the distance between the center of the deferent and the Earth is 6. Hence the ratio of the distances to Mars at perigee opposition and apogee opposition is

Fig. 4 The latitudes of Mars at apogee opposition and perigee opposition



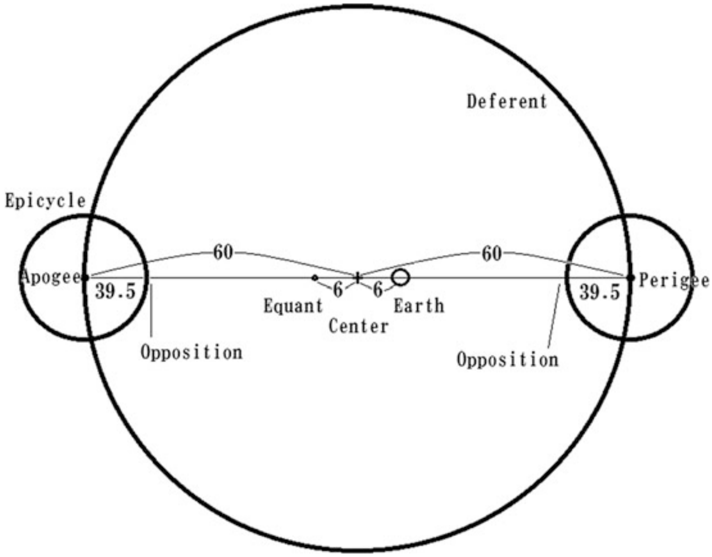
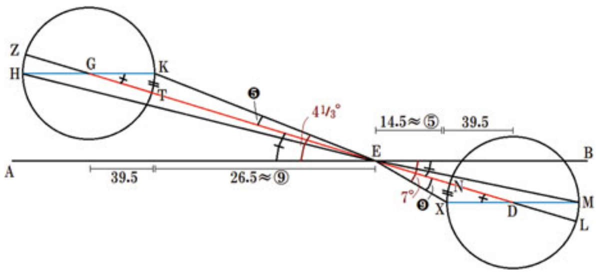


Fig. 5 Various sizes relating to Mars' orbit

Fig. 6 Derivation of the inclination of Mars' orbit



$$(60 - 6 - 39.5) : (60 + 6 - 39.5) = 14.5 : 26.5 \approx 5 : 9. \quad (1)$$

In Fig. 6 these two distances are denoted by ⑤ and ⑨. Since $\angle KGT = \angle XDN$ ($\because GK \| DX$), we obtain

$$\angle\text{KET} : \angle\text{XEN} \approx 5 : 9. \tag{2}$$

In Fig. 6 the two angles ∠KET and ∠XEN are denoted by ❺ and ❾. As shown in Fig. 6,

$$\angle\text{GEA} = \angle\text{DEB}. \tag{3}$$

Hence

$$4⅓° - \text{❺} = 7° - \text{❾}, \text{ therefore } \text{❾} - \text{❺} = 7° - 4⅓°. \tag{4}$$

$$\therefore \text{❹} = 2.67°. \tag{5}$$

$$\therefore \text{❶} = 0.67°. \tag{6}$$

Therefore

$$\text{inclination} = 4⅓° - \text{❺} = 1.0°. \tag{7}$$

The actual value of the inclination is 1.9°, so the derived value is about half of the actual inclination. The reason why such a small value for the inclination was obtained can be seen as follows:

- the latitude 4⅓° (true value 4.68°) at apogee opposition was too small by ~0.3°;
- the latitude 7° (true value 6.71°) at perigee opposition was too big by ~0.3° and therefore ❹ = 7° − 4⅓° = 2.67°

The inclination was derived from 4⅓° −❺ where 4⅓° was too small by ~0.3° and ❺ = 3.34° was too big by ~0.7°, so the derived inclination was too small by nearly 1.0°, i.e. the derived inclination was almost half of the actual inclination.

If we adopt the value 1.0° for the inclination, the latitudes of Mars at apogee opposition and perigee opposition are obtained from Figs. 5 and 6 as follows:

$$\angle\text{KEA} = \arctan\left((60 + 6)\ \tan\ 1^{\circ}/26.5\right) = 2.5^{\circ} \tag{8}$$

whose observed value was 4⅓° and

$$\angle\text{XEB} = \arctan\left((60 - 6)\ \tan\ 1^{\circ}/14.5\right) = 3.7^{\circ} \tag{9}$$

whose observed value was 7°. It is very interesting that Ptolemy did not make these calculations to confirm whether the derived value for the inclination was consistent with the observed latitudes of Mars or not.

There is another way of deriving the inclination from the same observational data. From the left-hand side of Fig. 7 the quantity g can be obtained as

$$g = 26.5 \tan 4⅓° = 2.01. \tag{10}$$

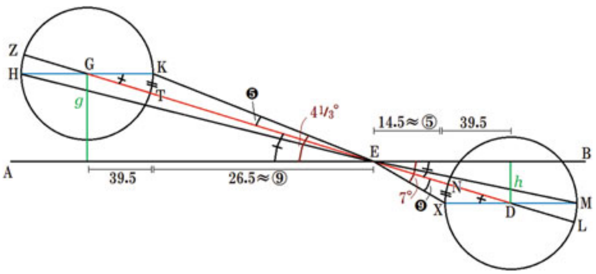


Fig. 7 Another way of deriving the inclination

Therefore, the inclination is obtained as

$$\text{inclination} = \arctan\,(2.01/66) = 1.74^{\circ}. \tag{11}$$

Likewise from the right-hand side of Fig. 7,

$$h = 14.5\ \tan\ 7^{\circ} = 1.78. \tag{12}$$

$$\therefore \text{inclination} = \arctan\,(1.78/54) = 1.89^{\circ}. \tag{13}$$

By taking the average of the above two results we obtain 1.8° as the inclination, which has only a 0.1° error.

4 Conclusion

Ptolemy obtained the inclination of Mars' orbit as 1.0° in the *Almagest*, which is too small compared to the actual value of 1.9°. He obtained it from two ecliptic latitudes of Mars at the apogee and perigee oppositions. Although the values of the ecliptic latitudes he used had only ~0.3° errors, his result about the inclination of Mars' orbit had an error of ~0.9° because his derivation procedure was inappropriate. It is shown that a more precise value could have been obtained from the same observational values had he used another procedure.

Acknowledgements Tamarokuto Science Center in Tokyo kindly showed the paths of Mars on the sky using their planetarium based on the calculations of the present author. This is shown in Fig. 3 in this paper.

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The Yogyādi-Vākyas: A Numerical Table for Computing the Longitude of the Sun

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Abstract In the vākya system of astronomy prevalent in South India, the true longitudes of the Sun, the Moon, the planets, and the associated quantities can be directly found using vākyas or mnemonics. The set of vākyas for a specific physical variable presented at regular intervals is essentially a numerical table. One such set of vākyas, namely, the yogyādi-vākyas, acts as a numerical table and is used to determine the longitude of Sun. In this paper, we shall explain how these sets of 48 vākyas works in obtaining the longitude of Sun. We shall also discuss the rationale for these vākyas based on the text *Vākyakaraṇa* by Parameśvara.

1 Introduction

The term vākya literally means a sentence consisting of one or more words. In the context of astronomy, it refers to a phrase or a string of letters in which numerical values associated with various astronomical parameters are encoded. The vākyas are composed using the kaṭapayādi system (see Sect. 2) of numeration. The strings used in composing vākyas are chosen so that they not only represent numerical values, but are also in the form of beautiful meaningful phrases and sentences that convey worldly wisdom and moral values (Pai 2013, Pai et al. 2015).

The vākya method of finding the true longitude of the Sun, Moon and the planets (sphuṭagraha) is a brilliantly designed simplified version of the methods outlined in the various *Siddhāntas*. As per the Siddhāntas, we first find the mean longitudes of the planets and then apply a few saṃskāras known as mandasaṃskāras and śīghrasaṃskāras to get their true positions. The mandasaṃskāra has to be applied in the case of the Sun and the Moon, whereas both the manda-saṃskāra and śīghrasaṃskāra are to be applied in the case of the other five planets (Pai et al. 2009). On the other hand, the vākya method, by making use of a few series of vākyas

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presents a shortcut directly leading to the true longitudes of the planets at certain regular intervals, starting from a certain instant in the past. We will discuss about this instant, which is also closely linked with other notions such as khaṇḍa and dhruva, during the course of our discussion. At this stage it would be sufficient to mention that this vākya method provides a simple elegant method for computing the true longitudes without having to resort to the normal procedure of calculating sequence of corrections involving sine functions and so on, which would be quite tedious and time consuming. Therefore, the vākya method became very popular in South India and even today some *pañcāngas* are published using the *vākya* method in the southern states of India (Pai et al. 2016, 2018).

2 The Katapayādi System of Numeration

The Kaṭapayādi is one of the systems of numeration that was developed in India for the representation of numbers using Sanskrit phrases or words. As per the system, each consonant in the Sanskrit alphabet has been assigned a number. The number ranges from 'one (1)' to 'zero (0)'. The vowel does not have any numerical significance. However, the vowel which is 'standing alone' represents the number '0'. The mapping of the letters to the numerals is given in Table 1. This table contains 33 consonants and the corresponding numbers assigned to them. In the next subsection, we will explain how to decode the number from a phrase by choosing an example from the yogyādi-vākyas itself.

2.1 De-codification of the Number

We explain how to decode the number from a phrase using a simple algorithm. For this, we choose the fifth phrase, dhanya, from Table 2:

1. First, divide the phrase into syllables. By splitting dhanya into syllables, we have dha and nya.
2. Assign the number (in Table 1) corresponding to each syllable. Since the vowel does not have any numerical significance, the number associated with the syllable is nothing but the number associated with the consonant. Hence, the number corresponding to the syllable dha is the number corresponding to dh which is '9'.

Table 1 33 Sanskrit consonants and the numbers associated with them

Number	1	2	3	4	5	6	7	8	9	0
Consonants	*K*	*kh*	g	gh	*ṅ*	c	ch	j	jh	ñ
used to	ṭ	ṭh	ḍ	ḍh	ṇ	t	th	d	dh	n
represent	P	ph	b	bh	m	–	–	–	–	–
numbers	Y	r	l	v	ś	ṣ	s	h	–	–

Table 2 The 48 yogyādivākyas mentioned in the commentary

Month name	Yogyādivākyas (in minutes)								
Meṣa (Aries)	–	yogyo	11 (11.2)	vaidyaḥ	14 (13.5)	tapaḥ	16 (15.7)	satyam	17 (17.7)
Vṛṣabha (Taurus)	–	dhanyaḥ	19 (19.3)	putraḥ	21 (20.9)	kharo	22 (22.3)	varaḥ	24 (23.3)
Mithuna (Gemini)	–	vīraḥ	24 (24.1)	śūraḥ	25 (24.5)	śaro	25 (24.6)	vajrī	24 (24.4)
Karkaṭaka (Cancer)	–	bhadram	24 (23.9)	gotro	23 (23.1)	ruruḥ	22 (21.9)	karī	21 (20.5)
Siṃha (Leo)	–	dhanya	19 (18.9)	sevyo	17 (17.0)	mayā	15 (14.9)	loke	13 (12.7)
Kanyā (Virgo)	–	kāyo	11 (10.6)	dīnaḥ	8 (8.2)	stanām	6 (5.8)	ganā	3 (3.3)
Tulā (Libra)		yājño	−1 (−1.5)	yajñam	+1 (+0.8)	ganā	+3 (+3.0)	śūnā	+5 (+4.9)
Vṛścika (Scorpio)	+	steno	6 (6.2)	dīno	8 (7.7)	dhunī	9 (8.9)	naṭaḥ	10 (9.9)
Dhanus (Sagittarius)	+	āpaḥ	10 (10.3)	pāpaḥ	11 (10.7)	payaḥ	11 (10.8)	pathyam	11 (10.5)
Makara (Capricorn)	+	pūjyā	11 (10.2)	dhenuḥ	9 (9.4)	dine	8 (8.2)	rthinaḥ	7 (6.8)
Kumbha (Aquarius)	+	tanuḥ	6 (5.7)	bhinnā	4 (3.9)	khanī	2 (1.9)	jñaanī	0 (−0.3)
Mīna (Pisces)	–	ratnaṃ	2 (2.0)	bhānuḥ	4 (4.4)	suniḥ	7 (6.8)	nayaḥ	10 (9.3)

After Nayar (1956)

3. However, in the case of the second syllable nya, since there are two syllables (n and y), we need to consider only the one which is closer to the vowel. In this case, y is more proximate to the vowel. Hence, the number corresponding to the syllable nya is ‘1’.
4. Now, by reversing the order we get the number ‘19’ which is the number corresponding to the phrase dhanya.

Like this, we can decode the numbers corresponding to different phrases in Sanskrit. The numbers correspond to all yogyādi phrases are listed in Table 2.

3 The Yogyādi-Vākyas

The name yogyādi-vākyas stems from the fact that the set of 48 vākya*s* begin with the word yogya. These vākyas enable us to find the longitude of the Sun at any given instant. There are 4 vākyas corresponding to each solar month. Each month is divided into four parts, with a maximum of 8 days per part. An English translation of all 48 vākyas is given below.

> A qualified doctor; [Speaking] truth [by itself] is austerity; A blessed son; A donkey is better; A skilful warrior; Indra’s arrow; This clan is safe; The antelope and elephant; In the world only; Pitiable is the state of the body; A lady with big breasts; The wife of the Yajamāna and performer if the sacrifice is swollen; The thief is miserable; The river is the dancer; The water is the culprit; Milk is good; Cow is to be worshipped during the day by those desirous of becoming wealthy; The body has been split; The wise is like a mine; The Sun is a pearl; The one who is completely unscrupulous. [Initially translated by the author and later refined by Professor K. Ramasubramanian]

The yogyādi-vākyas as given in the edited version of the commentary of KP are listed in Table 2. Apart from the vākyas (here in the form of one word, which forms part of meaningful sentences), the signs are also given in the commentary. Except in the case of Tulā, all the 4 vākyas corresponding to a particular raśi have the same sign (+ or −), indicated as such in the table. For Tulā, the sign for the first vākya is − and the signs for the other three are all +, as indicated in the table.

The first column in the table represents the names of the 12 months in Sanskrit, along with their English equivalents (in parenthesis). The second column gives the negative (−) or positive (+) sign corresponding to each month. The third, fifth, seventh and ninth columns give the yogyādi mnemonics, and the corresponding even columns (the second, fourth, sixth and tenth) give their numerical equivalents. The definition of the yogyādi-vākyas and the method of applying them to obtain the true longitude of the Sun at an interval of 8 days in a solar month, are given in verse 24, chapter 7 of the *Karaṇapaddhati*. First, the difference in the true longitudes of the Sun in degrees at 8-day intervals from the beginning of the month is found. The difference between this value and the eight constitutes the yogyādi-vākyas. These are applied positively or negatively, depending upon whether 8 is lesser or greater than the difference in longitudes at each 8-day interval respectively, to obtain the true Sun at any given instant (Pai et al. 2015, 2018).

4 Finding the True Longitude of the Sun from the Yogyādi-Vākyas

One can obtain the true longitude of the Sun on any day using the yogyādi-vākyas, and linear interpolation. For example, suppose we would like to find the true longitude of the Sun after the lapse of 18 days in the Vṛṣabha (Taurus) month. This (18 days) comes in the third part (khaṇḍa). Therefore, the approximate value of the true longitude of the Sun after 18 days elapsed would be

$$\theta' = 30^{\circ} + 18^{\circ} = 48^{\circ}.$$

A correction which can be called yogyādi-saṃskāra $\Delta\theta'$ has to be applied to θ' in order to obtain the true longitude θ. Now, the correction for 8 days of the third khaṇḍa is given as 22′ (khara) in Table 2. Hence the correction for 2 days is (22 × 2)/8 minutes. The first two vākyas are dhanya and putra and the numbers encoded in them are 19′ and 21′ respectively. Adding their sum to (22 × 2)/8, we get

$$\Delta\theta' = 19 + 21 + (22 \times 2)/8 = 45.5'.$$

These corrections are indicated as negative in the listing of the vākyas in the Table 2. Hence, applying this result negatively to θ', the true longitude of the Sun, at the end of the 18th day of the solar month, Vṛṣabha or Taurus, is obtained. That is,

$$\theta = 48^{\circ} - 45.5' = 47^{\circ}14.5',$$

where θ is the true longitude of Sun.

5 Rationale for Yogyādi-Vākyas

Verses 26–30 in the *Vākyakaraṇa* of Parameśvara give the rationale for yogyādi-vākyas, and my English translation is given below:

> Having obtained the mean longitude of the Sun at its transits, find the mean longitudes for 8, 16, 24 and 32 days using the mean rate of motion of Sun. Add these results to [the mean longitudes at the transit] and find the true longitudes of them separately. The true longitude at the transit is to be subtracted from the first true longitude of the Sun. The first one from second, second from third and third from the fourth. All these to be kept separately. Eight is to be subtracted from these obtained results. The remainder obtained would be the yogyādi-

vākyas respectively. If the remainder is greater [than 8], then the vākya is positive and it is negative if it is smaller [than 8].

We shall now explain the rationale behind these yogyādi-vākyas. The best way to understand the rationale is by considering some examples. Hence, we explain this by taking a couple of concrete examples.

Consider the solar month of Mithuna (Gemini). The true longitude of the Sun is $\theta = 60°$ at the beginning of the month. The mean longitude θ_0 can be determined (using the method explained above), and we find

$$\theta_0 = 59^\circ\ 18.7'.$$

Using the fact that the rate of motion of the mean longitude of the Sun is 59.136′ per day, the mean longitude is $\theta_0 = 67°\ 11.8'$ after 8 days in the month of Mithuna. The eccentricity correction $(\theta - \theta_0)$ corresponding to this value of θ_0 is found to be 24.1′. Adding this to θ_0, we find the true longitude after 8 days to be 67° 11.8′ + 24.1′ = 67° 35.9′. Hence the increase in the true longitude after the first 8 days of the month is 7° 35.9′. As the longitudinal difference is less than 8°, the yogyādi-vākya is negative and is given by $-(8° - 7°\ 35.9') = -24.1'$, compared with the value of $-24'$ as given by the vākya 'vīraḥ' in the commentary (Nayar, 1956).

After 16 days in the month of Mithuna, the mean longitude

$$\theta_0 = 59^\circ\ 18.7' + 59.136' \times 16 = 75^\circ\ 4.8'.$$

The true longitude corresponding to this is found to be $\theta = 75°\ 11.4'$. Hence the difference between the true longitudes at the beginning and at the end of the second part is 75° 11.4′ – 67° 35.9′ = 7° 35.5′. Here again, as the longitude difference is less than 8°, the yogyādi-vākya is negative and is given by $-(8° - 7°\ 35.5') = -24.5'$, compared with the value of $-25'$ as implied by the vākya śūraḥ in the commentary.

6 Relations Between the Mean and the True Longitudes of the Sun

As per the standard procedure laid down in Indian astronomical works, once the mean longitude of the Sun, θ_0, is known, a correction known as mandaphala has to be applied to it to obtain the true longitude, θ. This essentially takes care of the eccentricity of the apparent orbit of the Sun around the Earth. The equivalent of this in modern astronomy is the 'equation of centre'. Conversely, the mean longitude can be obtained from the true longitude by applying mandaphala inversely to it.

The method given in the Karaṇapaddhati for finding the mandaphala of any planet, including the Sun, can be explained with the help of the epicycle model represented in Fig. 1. The mean planet P_0 is assumed to be moving on a deferent circle centered on O (the centre of the Earth), whose radius, $OP_0 = R$ (trijyā). OΓ

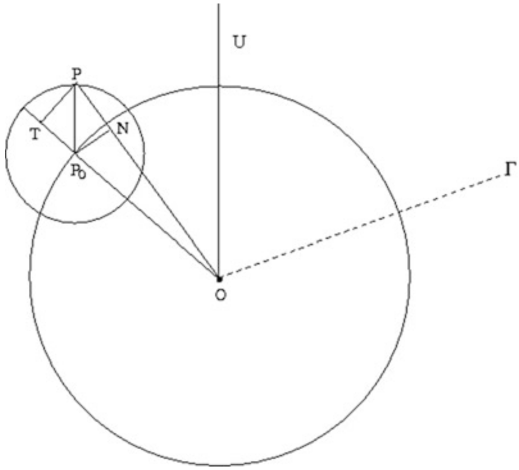

Fig. 1 Obtaining the mandasphuṭa in the epicycle model

represents the direction of Meṣādi or the first point of Aries. OU is in the direction of the apogee, or mandocca, whose longitude is given by $\Gamma O\hat{U} = \theta_m$. The longitude of the mean planet P_0, or the mean longitude, is given by $\Gamma O\ {}^\wedge P_0$. Draw a circle of radius r around the mean planet, P_0. This is the epicycle. The true planet, P, is located on the epicycle such that $PP_0 = r$ is parallel to OU (the mandocca direction). The true longitude of the planet is given by $\Gamma O\ {}^\wedge P = \theta$. Join OP and draw PT perpendicular to the line OP_0, extended further.

The difference between the mean longitude, θ_0 and the longitude of the mandocca, θ_m, is given by

$$U\hat{O}P_0 = P\hat{P}_0T = \theta_0 - \theta_m, \tag{1}$$

and is known as mandakendra. Now, the mandakarṇa, K, is the distance between the planet and the center of the deferent circle. Clearly,

$$K = OP = \sqrt{\left[OT^2 + PT^2\right]} = \sqrt{\left[(R + r\ \cos(\theta_0 - \theta_m))^2 + (r \sin(\theta_0 - \theta_m))^2\right]}.$$

Now, $P\hat{O}P_0 = \Gamma\hat{O}P_0 - \Gamma\hat{O}P = \theta_0 - \theta$. In the right triangle POT,

$$PT = OP \sin\left(P\hat{O}P_0\right) = K \sin(\theta_0 - \theta). \tag{2}$$

Considering the right triangle PP_0T,

$$PT = PP_0 \sin\left(\widehat{PP_0T}\right) = r \sin(\theta_0 - \theta_m). \tag{3}$$

Equating the above two expressions we have

$$\mathrm{K}\sin(\theta_0 - \theta) = \mathrm{r}\sin(\theta_0 - \theta_m), \tag{4}$$

$$\text{or } \sin(\theta_0 - \theta) = \frac{\mathrm{r}}{\mathrm{K}}\sin(\theta_0 - \theta_m), \tag{5}$$

6.1 Obtaining the True Longitude from the Mean Longitude

In Indian astronomy, particularly in the Kerala School, the radius of the epicycle, r, was assumed to vary in such a way that it was actually proportional to the karṇa, K. In other words, the motion satisfied the equation

$$\mathrm{r}/\mathrm{K} = \mathrm{r}_0/\mathrm{R},$$

where r_0 is the stated value of the radius of the epicycle in the text (Ramasubramanian et al. 2008; Ramasubramanian and Sriram 2011). Using this, Eq. (5) can be written as

$$\mathrm{R}\sin(\theta_0 - \theta) = \frac{\mathrm{r}_0}{\mathrm{R}}\mathrm{R}\sin(\theta_0 - \theta_m). \tag{6}$$

Hence, the mandaphala, which is the arc corresponding to the difference between the mean and true longitudes, that is, $\mathrm{R}(\theta_0 - \theta)$, is given by

$$\mathrm{R}(\theta_0 - \theta) = (\mathrm{R}\sin)^{-1}\left[\frac{\mathrm{r}_0}{\mathrm{R}}\mathrm{R}\sin(\theta_0 - \theta_m)\right]. \tag{7}$$

This is essentially the content of the verse 5 in Chapter 7 of the *Karaṇapaddhati* (Koru 1953; Nayar 1956; Sāśtrī 1937; Pai et al. 2018), an English translation of which states that

> The Rsin(e) [of the mandakendra, obtained by subtracting the apogee of the planet from its mean longitude] multiplied by the true/actual circumference (sphuṭavṛtta) and is to be divided by 80. The arc (Rsine-inverse) of the result [obtained] would be the mandaphalas of the planets beginning with the Sun.

Here, sphuṭavṛtta stands for the stated value of the circumference of the epicycle, when the circumference of the deferent circle is taken to be 80, that is,

$$\frac{\mathrm{r}_0}{\mathrm{R}} = \frac{\text{stated } \textit{sphuṭavṛtta}}{80}.$$

For the Sun, sphuṭavṛtta is stated to be 3. Hence,

$$\frac{r_0}{R} = \frac{3}{80}.$$

The longitude of the apogee of the Sun, θ_m is given as 78° in the text. With the knowledge of the mean longitude θ_0, and the mandaphala $R(\theta_0 - \theta)$, we obtain the true longitude, θ from Eq. (6).

6.2 Obtaining the Mean Longitude From the True Longitude

The method that was used to find the true longitude from the mean longitude cannot be used to obtain the mean longitude, θ_0, with the knowledge of the true longitude, θ, as the expression for the mandaphala involves θ_0. However, it is possible to obtain θ_0 from θ by this method using an iterative procedure. This is not mentioned in the *Karaṇapaddhati* but it is discussed in the Gaṇita-Yukti-bhāṣā (Ramasubramanian et al. 2008). In the first step to obtain θ_0 from θ, θ_0 is replaced by θ in the RHS of (6), and $(\theta_0 - \theta)$ and thereby θ_0 is calculated. In the second step, this computed value of θ_0 is used in the RHS, and θ_0 is calculated again. In this manner, the iteration process is carried out until the successsive values of θ_0 obtained are the same, to a desired accuracy.

Alternatively, the method can be modified to obtain an expression for the mandaphala in terms of the sphuṭa-doḥphala, $r_0 \sin(\theta - \theta_m)$ involving the mandakendra obtained by subtracting the apogee from the true longitude θ, and the concept of viparyāsakarṇa or viparītakarṇa or vyasta-karṇa (inverse hypotenuse). The viparyāsakarṇa (inverse hypotenuse) is the radius of the deferent OP0, in the measure of the karṇa *K*, that is, when K is set equal to the trijyā, R. It is denoted by R_v. Obviously,

$$\frac{K}{R} = \frac{R}{R_v}$$

$$\text{or } K = \frac{R}{R_v}.R$$

$$\text{Also } r = \frac{r_0}{R}.K$$

$$= \frac{R}{R_v}.r_0.$$

Verses 17 and 18 in Chapter 7 of the *Karaṇapaddhati* (Koru 1953; Nayar 1956; Sāśtrī 1937; Pai et al. 2018) describe the procedure for finding the viparyāsakarṇa:

> The [longitude of the] mandocca has to be subtracted from the true longitude of the Sun at the end of the rāśi. Having obtained the Rsine and Rcosine of that [result], and multiplying it by 3 and dividing by 80, the doḥphala and the koṭiphala are obtained [respectively]. The koṭiphala has to be added to or subtracted from the radius depending upon whether [the

kendra is] karkyādi or makarādi respectively. The square root of the sum of the squares of the result thus obtained and of the doḥphala would be the viparyāsakarṇa here. (My English translation).

Now θ is the true longitude and θ_{m} is the longitude of the mandocca. The [sphuṭa]-doḥphala and [sphuṭa]-koṭiphala are given by

$$\begin{aligned}\text{[sphuṭa]-doḥphala} &= \frac{\mathrm{r_0}}{\mathrm{R}}\mathrm{R}\mid \sin(\theta-\theta_m)\mid \\ &= \frac{3}{80}\times \mathrm{R}\mid \sin(\theta-\theta_m)\mid \\ [\textit{sphuṭa}]\textit{-koṭiphala} &= \frac{r_0}{R}\mathrm{R}\mid \cos(\theta-\theta_m)\mid \\ &= \frac{3}{80}\times \mathrm{R}|\cos(\theta-\theta_m)|.\end{aligned}$$

Draw P0N perpendicular to OP (see Fig. 1). Now

$$\mathrm{P_0\hat{P}N = P\hat{O}U = \Gamma\hat{O}P - \Gamma\hat{O}U} = \theta - \theta_m.$$

Then, considering the right triangle $\mathrm{P_0NP}$,

$$\mathrm{NP_0 = PP_0}\sin\left(\mathrm{P_0\hat{P}N}\right) = \mathrm{r}\mid \sin(\theta-\theta_m)\mid$$

and

$$\begin{aligned}\mathrm{NP} &= \mathrm{PP_0}\cos\left(\mathrm{P_0\hat{P}N}\right) \\ &= \mathrm{r}\mid \cos(\theta-\theta_m)\mid.\end{aligned}$$

Now,

$$\begin{aligned}\mathrm{OP_0} \quad &= \mathrm{R} = \sqrt{\mathrm{ON}^2 + \mathrm{NP_0}^2} = \sqrt{(\mathrm{OP}-\mathrm{NP})^2 + \mathrm{NP_0}^2} \\ &= \sqrt{(\mathrm{K} - \mathrm{r}|\cos(\theta-\theta_m)|)^2 + (\mathrm{r}\sin(\theta-\theta_m))^2} \\ &= \frac{\mathrm{R}}{\mathrm{R_v}}\sqrt{(\mathrm{R} - \mathrm{r_0}|\cos(\theta-\theta_m)|)^2 + (\mathrm{r_0}\sin(\theta-\theta_m))^2},\end{aligned}$$

using the expression for K and r in terms of R and $\mathrm{R_v}$. Hence,

$$\mathrm{R_v} = \sqrt{\left(\mathrm{R} - \frac{3}{80}\times|\mathrm{R}\cos(\theta-\theta_m)|\right)^2 + \left(\frac{3}{80}\times \mathrm{R}\sin(\theta-\theta_m)\right)^2}.$$

The above expression for the vyastakarṇa is applicable when the kendra is makarādi (that is, lies in the first or fourth quadrant). Here, makarādi means half the ecliptic, from 270° to 360° (fourth quadrant) and 0° to 90° (first quadrant).

Karkyādi means half the ecliptic from 90° to 270° (second and third quadrants). If the kendra is karkyādi, then the expression for R_v is given by

$$\sqrt{\left(R+\frac{3}{80}\times|R\cos(\theta-\theta_m)|\right)^2+\left(\frac{3}{80}\times R\sin(\theta-\theta_m)\right)^2}.$$

Both the relations can be combined in the single formula, and R_v is given by

$$\sqrt{\left(R-\frac{3}{80}\times R\cos(\theta-\theta_m)\right)^2+\left(\frac{3}{80}\times R\sin(\theta-\theta_m)\right)^2}$$

Verse 19 (Koru 1953; Nayar 1956; Sāśtrī 1937; Pai et al. 2018) gives the procedure for finding the mean longitude, θ_0 from the true longitude, θ:

> The arc of the [quantity obtained by] multiplying the doḥphala by radius and dividing by this [vyastakarṇa] has to be added to or subtracted from the true longitude of the Sun when [the kendra is] meṣādi or tulādi respectively. The result would be the mean longitude of the Sun at the transit. (My English translation).

Thus,

$$\begin{aligned} NP_0 &= OP_0\sin\left(P_0\hat{O}N\right) \\ &= OP_0\sin\left(\widehat{POP_0}\right) \\ &= R\sin(\theta_0-\theta). \end{aligned}$$

Also

$$NP_0 = r\sin(\theta-\theta_m).$$

Equating the above two expressions, we have

$$R\sin(\theta_0-\theta) = r\sin(\theta-\theta_m).$$

Now

$$r = r_0.\frac{K}{R} = r_0.\frac{R}{R_v}.$$

Therefore,

$$R\sin(\theta_0-\theta) = r_0\sin(\theta-\theta_m)\frac{R}{R_v}. \tag{8}$$

Hence,

$$\begin{aligned} R(\theta_0 - \theta) &= (\mathrm{Rsin})^{-1}\left[r_0 \sin(\theta - \theta_m)\frac{R}{R_v}\right] \\ &= (\mathrm{Rsin})^{-1}\left[\frac{3}{80} \times R\sin(\theta - \theta_m)\frac{R}{R_v}\right]. \end{aligned} \tag{9}$$

In the above expression, since θ is known, the mean planet, θ_0, can be obtained by adding the above difference to the true planet θ. ($\theta_0 - \theta$) is positive when the *kendra* (anomaly) $\theta - \theta_m$ is within the six signs beginning with Meṣa (Aries), viz., $0° \leq \theta - \theta_m \leq 180°$, and negative when the kendra is within the six signs beginning with Tulā (Libra), viz., $180° \leq \theta - \theta_m \leq 360°$, as implied in the verse.

7 Concluding Remarks

It is clear from the examples given above, that this method can be used to determine the true longitude at any instant during the day using interpolation. In Table 2, our computed values for the difference between 8° and the actual angular distance covered by the Sun in 8 days (i.e., the difference between the true longitudes computed after a separation of 8 days) is given in the parenthesis below the vākya value. It is clear from these figures that the yogyādi-vākyas are very accurate. More importantly, what is noteworthy here is the phenomenal simplification that has been achieved in computing the true longitudes of the Sun at any moment using the yogyādi-vākyas.

By simply memorizing the vākyas, one can find out the longitude of Sun on any given day at any given instant with reasonable accuracy. In fact, for all practical purposes, but for some crucial computations involved in eclipses wherein very high accuracies are required, the inaccuracies noted in Table 2 are negligible. This is a very small price paid for the enormous simplification and fun involved in computing the longitudes by simple arithmetic calculations.

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Indian Astronomical Tables of the Saura Paddhati – In Historical Perspective

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Abstract The period including the latter half of the fifteenth century and the earlier half of the sixteenth century witnessed a big resurgence in the development of astronomy, not only in Europe but also in India. In Europe we had great pioneers like Galileo, Copernicus and Tycho Brahe, the illustrious galaxy being crowned by Johannes Kepler (1571–1630) a little later.

On the Indian scene, during that period we had two remarkable stalwarts, Parameśvara Nīlakaṇṭha and Gaṇeśa Daivajña. In the tradition of computation of planetary positions, astronomical phenomena and calendrical data, the role of astronomical tables for Indian calendrical purposes (pañcāṅga) cannot be exaggerated. We have different genres of such tables known differently as sāriṇīs, padakas, koṣṭakas and vākyas.

In this paper we present some salient features of a few prominent handbooks (karaṇas) and tables belonging to the Saurapakṣa School of Astronomy, based on a popular Indian astronomical treatise, the *Sūryasiddhānta* (*SS*).

1 Introduction

In the European astronomical tradition, starting with Ptolemy's second century CE *Handy Tables*, De la Hire's tables etc. were used in calculating ephemerides. In an Indian context, for both calendrical purposes and the computation of planetary positions, different schools (pakṣas) viz., Āryapakṣa, Saurapakṣa, Brāhma (Paitāmaha) pakṣa and Gaṇeśapakṣa, were in vogue. In these distinct schools both handbooks with ready-to-use algorithms and astronomical tables emerged in quick

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succession. The Saurapakṣa tables, based on the *Sūryasiddhānta* (Burgess and Gangooly 1989) became very popular in the northern part of India. On the other hand, the Āryabhaṭan School—fostered by Bhāskara I (CE 629)—was followed exclusively in Kerala (Southern India).

Around CE 1520 the *Grahalāghavam* (*GL*), a text written by the Maharashtrian astronomer Gaṇeśa Daivajña who was based in Banaras, became extremely popular throughout Maharashtra, in the major part of north India, and also in north Karnataka, particularly in the Belgaum and Gulbarga regions. The popularity of Gaṇeśa's School often exceeded the other schools mainly because Gaṇeśa Daivajña completely dispensed with the use of trigonometric ratios, replacing them with very good algebraic approximations. In fact, this thoughtful innovation relieved the pañcāṅga-makers of the bugbear of handling the cumbersome values of trigonometric ratios. Based on the *GL* there are many astronomical tables belonging to the Gaṇeśapakṣa.

In the Saurapakṣa, the most popular astronomical tables were the *Makaranda sāriṇī* of Makaranda (CE 1478), the *Pratibhāgī Gaṇakānanda* (*GNK*) and the *Tyāgarthi* manuscripts. In the following sections we provide a few glimpses of a couple of these Saura tables.

The famous Andhra astronomer Sūrya, son of Bālāditya, composed his famous karaṇa (handbook) called the *Gaṇakānanda*. His more illustrious protégé, Yalaya, composed his exhaustive commentary, *Kalpavallī*, on the well-known *SS* treatise.

Yalaya belonged to kāśyapa Gotra, and his genealogy is as follows: Kalpa Yajvā (great grandfather) – Yalaya (grandfather) – Śridhara (father) – Yalaya.

His father, Śridhara, was an expert in Sanskrit stotras (and was different from his namesake, the author of the *Pāṭīgaṇita* and the *Triśatikā*). Yalaya received his training in astronomy from his instructor, Sūryācaryā, the author of the *Gaṇakānanda*. Yalaya spoke highly of his guru and even compared him with the Vedic sage Brihaspati.

Yalaya quotes from his instructors three works: the *Gaṇakānanda* (composed in CE 1447), the *Daivajñābharaṇa* and the *Daivajñabhūṣanạ*. Yalaya resided in a small town to the north of *Addankī* (latitude 15°.49 N, longitude 80°.01 E) called Skandasomeśvara, in Andhra Pradesh. This small town was south-east of Śriśaila, the famous pilgrimage centre.

In his commentary on the *Laghumānasa* of Mañjula (CE 932), Yalaya provides the astronomical data for Tuesday noon, of the beginning of Chaitra māsa corresponding to 18 March 1482 CE. Yalaya wrote his commentary *Kalpavallī* on *SS* in CE 1472 and that on the *Āryabhaṭiyam* in CE 1480.

Interestingly, Yalaya records some contemporary astronomical events. A few of them are as follows:

1. A lunar eclipse on Saturday, *Phālguna paurṇimā*, *śaka* 1407, corresponding to 18 February 1486 CE.
2. A solar eclipse on Friday, *Phālgunā Amāvāsyā*, *śaka* 1389, i.e. on 25 March 1468 CE.

3. A solar eclipse on Friday, *Bhādrapada Amāvāsyā*, *śaka* 1407, i.e. 9 September 1485 CE, visible from his native place.
4. A Jupiter-Moon conjunction on Saturday, *Āṣādha paurṇimā śaka* 1408, i.e. 17 June 1486 CE.
5. Commencement of *Adhik*a (intercalary) *Śrāvaṇa-śukla pratipat śaka* 1408, i.e. Sunday, 2 July 1486 CE.

Balachandra Rao and Venugopal (2008) have verified the genuineness of the above eclipse recordings by using the software prepared by them based on modern computations.

In the following section we consider a few examples to give a feel of these classical tables and handbooks.

2 The *Gaṇakānanda* (*GNK*)

The karaṇa text *Gaṇakānanda* is the most popular text in regions of Andhra and Karnataka. Apart from the regular topics the text contains tables of astronomical phenomena. The text belongs to the Saurapakṣa and was authored by Sūryācārya, the son of Bālāditya who came from the Andhra region. The text based on the *Sūryā-siddhānta* is in Telugu, and the script was edited and published by Vella Lakshmi Narasimha Sastri from Machalipatnam in the Andhra region and reprinted in 2006. The epochal date of the text is 16 March 1447 CE.

3 Makaranda Sariṇī (MKS)

A large number of Indian astronomical almanacs (pañcāṅga) which are composed annually according to the Saurapakṣa are based on the *MKS.* The author of the *MK*S declares:David Pingree had provided very useful and often exhaustive information on the contents of the *MKS* and also on the availability of the manuscripts in his two famous catalogues, *Sanskrit Astronomical Tables in the United States* (SATIUS) and *Sanskrit Astronomical Tables in England* (SATE).

In the following section, to check the correctness of the *MKS* and the *GNK* parameters and procedures, we have computed and compared, as an example, values of the true sidereal (*nirayaṇa*) longitude of the Sun for the date 3 April 2012 at mean sunrise at Ujjayinī (6^h 27^m IST). These are shown in Table 1.

This particular date was chosen since around that date every year the Sun's equation of centre (mandaphala) is maximum. In Table 1 we note that the *MKS* values of mean longitude and the equation of centre are close to the modern ones. But the Sun's true longitude differs from the modern value by about 9′ 7″ and the equation of centre (mandaphala) by 16′ 16″. These differences are mainly because in modern computations gravitational periodic terms are considered. In the classical

Table 1 Sun's sidereal true longitude for 3 April 2012

Text	Mean Sun	Equation of centre	True sidereal Sun
MKS	347° 19′ 07″	2° 10′ 32″	349° 29′ 39″
GNK	348° 02′ 49″	2° 10′ 32″	350° 13′ 20″
Modern	347° 44′ 30″	1° 54′ 16″	349° 38′ 46″

Now Ānanda's son, named Makaranda, brings forth at Kāśī, by the blessings of the instructor (*guru*), folios of *tithi* etc., based on the *Sūryā-siddhānta* school of thought, properly for the benefit of the world. (*Makaranda* . . ., 1998: *śl.* 1; our English translation)

Table 2 The Sun's sidereal true longitude on 3 April 2012

Text	14 January 2012	28 November 2012
MKS	21° 02′ 29.13″ S	21° 08′ 51.91″ S
GNK	21° 10′ 10.64″ S	21° 16′ 36.97″ S
Modern	21° 11 00.00″ S	21° 17′ 00.00″ S

Indian texts, even as in the European tradition before Kepler, epicyclic theory was adopted. The results obviously vary a little compared to those of Kepler's heliocentric elliptical theory. The equation of centre in siddhāntas is governed by the radii of the epicycles.[1]

4 The Sun's Declination (Krānti)

In the computation of solar eclipses and transits we need to use the declination (krānti) of the Sun. In Table 2 we compare the values of the Sun's declination (δ) for 2 days when the Sun's rays fall directly on the Shiva lingam at the famous Gaviganġadhareśvara Temple in Bangalore (see Vyasanakere et al., 2008).

From Table 2 we notice that on 2 days of the year 2012, namely 14 January and 28 November, the declination of the Sun has the values 21° 02′ 29.13″ south and 21° 08′ 51.91″ south respectively according to the *MKS*, and the corresponding values according to the *GNK* are 21° 10′ 10.64″ south and 21° 16′ 36.97″ south. It should be noted that the declination is calculated according to these texts for the same time. The difference in arcminutes for the two dates according to a particular text indicates that the corresponding azimuths and the altitudes of the Sun differ a little. The difference in the values of δ according to the two classical texts as compared to the modern values is due to the fact that the Indian classical texts considered the obliquity of the ecliptic as 24° while the modern known value is around 23° 26′. It is significant to note that the *GNK* values are closer to the modern ones.

[1]See *Siddhānta Ganakānanda Bodhini* (2006).

Table 3 The conjunction of the Moon and Jupiter on 19 May 1472

	Yalaya	Modern
Conjunction time	18.05 h IST	20 h IST
True Moon	207° 26′ 08″	205° 24′ 28″
True Jupiter	207° 28′ 28″	205° 24′ 28″

5 The Conjunction of the Moon and Jupiter on 19 May 1472

In his commentary *Kalpavallī* on the *SS*, Yalaya gives an example of the lunar conjunction with Jupiter for (Nandana saṃvatsara, Jyestha Śukla12, Śaka 1394) i.e. Tuesday 19 May 1472. According to his text the conjunction took place around 44 ghaṭis from the midnight between 18 and 19 May 1472, i.e. 17.6 h p.m. (LMT) or around 6 p.m. (IST) on 19 May 1472. Let us compare Yalaya's result with a modern computation, which comes out to about 20 h (IST). The difference of about 2 h is mainly due to the fact that in Yalaya's computation the gravitational terms are not taken into consideration. For 2 h the relative motion of the Moon with respect to Jupiter is about 1°, which was not easily perceptible without a telescope. Furthermore, the difference between the ephemeris time and the universal time, Δt, also plays a role, though a marginal one. In Table 3, the true tropical longitudes of the Moon and Jupiter according to Yalaya and modern computations are compared.

According to the *SS*, the accumulated precession of the equinox (i.e. the ayanāṃśa) works out to be 14° 25′. The example given by Yalaya is a valid one.

6 The Lunar Eclipse of Friday 22 May 1472 (i.e. Nandana samvatsara, Jyeṣṭha śūkla paurṇimā, Friday)

Yalaya explains the procedure for the computation of a lunar eclipse with his contemporary example dated 22 May 1472. According to him, the middle of the eclipse is 3–33 ghaṭis after sunset. The instants of the beginning and the end of the eclipse are 1–13 ghaṭis before and 8–13 ghaṭis after the sunset, respectively. Similarly, the beginning and the end of totality are 1–25 ghatis and 5–37 ghatis after sunset, respectively. The duration of the entire eclipse is 9–26 ghatis. In Table 4 Yalaya's results are compared with those derived from modern computations.

From Table 4, we observe that the timings recorded by Yalaya are close to those we get from the modern computations for that date.

Table 4 Circumstances of the lunar eclipse dated 22 May 1472[a]

	Yalaya		Modern
	Ghatis	IST	
Beginning of eclipse	– (1–13)*gh*	$18^h\ 07^m\ 11^s$	$18^h\ 02^m$
Beginning of totality	+(1–25)*gh*	$19^h\ 10^m\ 23^s$	$19^h\ 20^m$
Middle of eclipse	+(3–33)*gh*	$20^h\ 01^m\ 35^s$	$19^h\ 49^m$
End of totality	+(5–37)*gh*	$20^h\ 51^m\ 11^s$	$20^h\ 39^m$
End of eclipse	+(8–13)*gh*	$21^h\ 53^m\ 35^s$	$21^h\ 36^m$

a(1) The modern computations are according to the software *Occult 4*
(2) In column 2, the '–' sign indicates timings before sunset and '+' indicates after the sunset, as given by Yalaya

Table 5 Vyatipata on 20 April 1148

Time (IST)	Declination of the Moon	Declination of the Sun
13^h	13° 05′ N	13° 41′ N
$8^h\ 30^m$	13° 32′ N	13° 42′ N
9^h	13° 40′ N	13° 43′ N

7 The Inscriptional Evidence, 1148

7.1 The Solar Eclipse of 20 April 1148

The reference for this eclipse is: EKU Vol. 1 No. 23, Source: 20 April 1148, 11th regnal yr., Vibhava, Chaitra 30, Chalukya of Kalyana, Jagade-kamalla.

The inscriptional data are very interesting since on the very same day three important phenomena occurred: a solar eclipse, a lunar occultation of Mercury and vyatipata (see Table 5). We computed that a transit of Mercury occurred 3 days later, but this was not recorded. Following are the parameters required for the computation of the eclipse:

Tropical long. of the Sun: 36° 13′ 8″.
Tropical long. of the Moon: 33° 52′ 36″.
Latitude of the Moon: 0° 16′ S.
Instant of New Moon: $10^h\ 34^m$.

The eclipse turned out to be total. Here are the details:

Beginning of Eclipse: $7^h\ 50^m$.
Beginning of Totality: $8^h\ 46^m$.
Middle: $10^h\ 34^m$.
End of Totality: $12^h\ 21^m$.
End of Eclipse: $13^h\ 18^m$.

Re Table 5, it should be noted that if the declinations of the Sun and the Moon are equal in both magnitude and direction then that phenomena is called Vyatipata.

During the solar eclipse it can be observed that the declinations of the Sun and the Moon are equal.

7.2 Transits and Occultations

The procedure for recording transits and occultations is similar to that of solar eclipse. The participating bodies in the case of transits will be Sun and the planets Mercury or Venus, and for occultation, the Moon and the planet or a star. Transits of Mercury and Venus occur when either of them is in conjunction with Sun as observed from the Earth, and subject to prescribed limits (see Balachandra Rao and Venugopal, 2009).

Transits of Venus occur less frequently than transits of Mercury. For example, after the transit of Venus in June 2004 the next occurrence was on 6 June 2012. After that, the subsequent Venus transit will be about 105.5 years later (i.e. in December 2117).

While detailed working of planetary conjuncttions is discussed in all traditional Indian astronomical texts in the chapter titled *Grahayuti*, it has to be noted that the transits of Mercury and Venus are not explicitly mentioned. This is mainly because when either of these inferior planets is close to Sun it is said to be 'combust' (*asta*) and hence not visible to the naked eye. Transits of Mercury or Venus are called sankramaṇa (of the relevant planet), or 'gādhāsta'. In a transit of Mercury or Venus the planet passes across the bright disc of Sun as a small black dot.

7.3 The Lunar Occultation of Mercury on 19/20 April 1148

The computational procedure is similar to that for a solar eclipse. The details are as follows:

Instant of conjunction: 17^h IST
Sidereal longitude of the (retrograde) Mercury: $29° \ 6'$
Sidereal longitude of the Moon: $29° \ 1'$
Mercury's latitude: $0° \ 49'$ N

7.4 The Transit of Mercury of 23 April 1148

The computed details are as follows:

Instant of conjunction: 13^h IST
Beginning of the transit: $14^h \ 0^m \ 31^s$
Internal ingress: $14^h \ 0^m \ 48^s$

Middle of the transit: $15^h\ 45^m\ 0^s$
External Ingress: $17^h\ 29^m\ 11^s$
End of the transit: $17^h\ 29^m\ 28^s$

8 Conclusion

In the preceding sections we have introduced some features of the astronomical tables belonging to the Saurapaksa. Using the tables of the *MKS* and the *GNK*, both from the Saurapaksa, we have computed and compared some events, like a lunar eclipse, a lunar conjunction of Jupiter, a lunar occultation of Mercury, and the equality of the Sun's declination when the Sun's rays fall directly on the deity at a famous shrine in Bangalore. In all of these cases the related parameters according to the traditional tables were compared and found to be close to those obtained by modern procedures.

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On the Lenth of the Year After Varāhamihira's *PanchaSiddhantika*

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Abstract By the Siddhantika Period (Aryabhata and Varāhamihira, possibly around AD 550), the position of the aphelion, the nodes (intersection of the orbit of the planet with ecliptic) and the orbital periods of the planets were fairly well determined. Varāhamihira also documented the correct ayanamsha (precession of the equinoxes, the points of intersection of the ecliptic with the celestial equator) of about 0.0141 days per year. Considering this, it is strange that the length of the year was believed to be 365.2584 days as against our presently accepted mean value of 365.2562 days for the sidereal year. This could have been due to one of two reasons: (1) The Earth's spinning around its axis has slowed down, thereby decreasing the orbital period by 0.0022 days over about 1500 years. Then, any astronomical calculations based on data for more than 4000 years, which might have used the Earth's rotational period as a unit, have to be re-examined. There appears to be substantial geological evidence consistent with this hypothesis; or, (2) The year might have been determined based on time taken by the Earth to move from aphelion to aphelion (aphelion, mandochcham, is important in astrology). If this was the convention for orbital periods, it is surprising that this information is not recorded nor discussed in relation to the origin of the co-ordinate system, even though we certainly shifted the start of the year from a position near Antares to the current position in Aries.

1 Introduction

The Patna mathematician-astronomer Aryabhata (AD 476–550) probably was the originator of Siddhantic Astronomy. The sayana (including precession of the equinoxes) and nirayana (time measurement based on fixed star reference) systems were

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formalised and, by about the fifth century AD, standardisation of the zodiac (rashis) of the West and nakshatras of the Indian system had occurred. Possibly *Gola* (*Treatise on Spherics*) of the Ujjian astronomer Varāhamihira (AD 505–587) dealt with some of the rationale in fixing this system, but we have only reference to *Gola* from later astronomers. By this time, the precession of the equinox, position of aphelion of the planets and the nodes (intersection of the planes of their orbits with the ecliptic) were fairly accurately determined, although the physics and astronomy might not have been understood.

Aryabhata gives the length of the nirayana year as 365.2586 days as measured from the rotational period of the Earth, while the present value is approximately 365.2562 days. We understand that at the time there were at least 18 works relating to planetary positions, both Indian and Western, and the astronomers were familiar with each others' works. Varāhamihira reviewed the five Siddhantas, two from the West, one from *Vedanga Jyotish* (Indian astronomy) and two that might have been influenced by the West. He concluded that the Surya Siddhanta was the most accurate of these treatises. Indian tradition says that the Surya Siddhanta is due to Maya (Ravana's father-in-law). It appears to have been revised a few times, and the version due to Latadeva, Aryabhata's student, might have been referred to by Varāhamihira.

But Varāhamihira and Aryabhata used slightly different norms for their ephemerides. Bentley (1825) and many others refer to a particular version of the Surya Siddhanta that dates to the tenth century AD.

The theoretical computation of the orbits of planets appears to be complex in the Surya Siddhanta. In Kerala, south-west Karnataka and possibly in Tamil Nadu, a simplified system called *Parahita*, probably devised by astronomers led by Haridatta (b. about AD 650) in the seventh century AD., was widely used up to the mid-nineteenth century. Parameshvara (ca. 1380–1460) tried to correct it in the fifteenth century, based on observations of eclipses, and he devised a system known as Drigganita, but it turned out to have the same defects as the Parahita system. Thus, in the coastal region between Thiruvananthapuram and Kundapura, the Parahita system continued to form the basis for almanacs until last century. Consequently, my arguments in this work are based on the Parahita system. The *Deshamitra* (Thiruvananthapuram), *Yogakshema* (Kunnamkulam), *North Malabar* (Payyanur) and *Srikrishna* (Vitthal) *Almanacs* were used by me for the computations, where I have used kalidina for 15 November 2016 at local sunrise to be 1869217.0. The length of the nirayana year (not considering the precession of the equinox) based on these almanacs using the Parahita system is 365.2484 days, which is slightly shorter than Aryabhatiya's value of 365.2586 days.

Because of the tradition of using eclipse observations to correct the Siddhantic computations and recordings of any conjunctions of a planet with a star or another planet, I assume that the numbers given were reasonably accurate when they were determined, at least after the third century BC,[1] and any true conjunction, with the accompanying change in the observed colour, should have been easily noticeable. Consequently, my view is that within the accuracy of the measurement of the time of the night (or day), recorded conjunctions should be a valuable probe for ephemerides computations.

In the next section, certain Vedic hymns and Abhyankar's discussion of Agasthya will be presented to argue that systematic observations and computations should have been available by the fourth millennium BC, and therefore a consistent combination of these recordings should have enabled far more accurate ephemerides than we might otherwise have thought possible. In the following section, the various measures of the mean day and year will be mentioned and subsequently arguments for a faster spinning Earth in earlier epochs will be presented. Furthermore, the case for an alternative definition of the year by the early Indian astronomers will be presented.

2 Certain Observations from the *Vedas*

I find it difficult to get definitive astronomical results or specific unambiguous presentation of the work of the sages from the *Vedas*. In general, the verse had an originator sage, a rhythm and a god on whose honour it is constructed. However, in the *Rigveda* there are two hymns where some verses have the same sage and god (obviously, this was done at a later stage when the *Vedas* were collected, edited and the *Rigveda* was organised into ten mandalas). In the seventh Mandala, Hymn 33, Vasishtha and Vasishthaputras are sages as well as gods. From the presentation, it is fairly clear that there was a war between ten kings (possibly helped by Brigu or Vishwamitra) and Puru (Trtsu) was helped by Vasishtha. Indra praised Vasishtha, whose efforts lead to the subjugation of the ten kings. In an almost similar tone, in Mandala 5, Hymn 40 refers to an eclipse. Atri, the sage and god referred there, knew about the eclipse. Atri removed the Sun's darkness (Atrih suryasya ... maya aghukshath). Normally Mitra and Varuna are referred to as gods in many hymns, but here Mitra and King Varuna are friends of Atri (the god of the verse). Was the eclipse recorded because both Mitra and Varuna were together at the time of the eclipse (which means that the Sun was close to the winter solstice) or were Mitra and Varuna friends because Atri had mastered the technique of eclipse prediction?

If the former is the explanation, the eclipse is likely to have been around the fourth millennium BC according to a blog on the site 'bharatkalyanan97.blogspot.in' by S. Balakrishnan. It is possible that the actual recordings of the *Vedas* as we now

[1]The start of some of the Yugas is believed to have been when certain important conjunctions took place. Both Aryabhatiya and Surya Siddhanta give 3102 BCE as the starting day of 'Kali Yuga'. According to Abhyankar (2007), the starting point of Kali Yuga coincided with a rare planetary alignment (depicted in the Mohenjo-Daro seals – WIKIPEDIA on Kali Yuga). But there is no evidence to identify the start of various Yugas with planetary alignments.

know them only occurred in the second or third millennium BC when the star Radha became Vishakha (i.e. when the star lay on the ecliptic).

The main texts of the *Rigveda* probably were formed over about ten generations of the chief seven sages, when many of them were inter-related. Among them, Agasthya is believed to have moved south, crossing the Vindhya Mountain Range. This was probably a rare action because evidence points to little mingling between the populations north and south of these mountains for many millennia. According to Abhyankar (2007), Agasthya noticed the bright star Canopus when he crossed the mountain range and this could have happened around the fifth or the fourth millennia BC. Independent support for this hypothesis is offered by Tamil literature of the Sangam Period: about 197 Pandya kings ruled during the three Sangam literary periods that extended approximately from Agasthya's arrival up to the third century AD.

Based on these records, it is tempting to argue that between fourth and second millennia BC there were records made of astronomical events and there were experts who could compute eclipses. But in order to interpret observations extending over several thousand years, they also needed expertise in computations with large numbers. In the *Krishna Yajurveda*, the last verses of a hymn called Chamaka Prashna specifically mention ten-based numbers, indicating that people could present numbers in systematic order.

There also were observations and theoretical developments in Egypt, because of the importance of tracing the floods and water in the Nile for agriculture and animal husbandry. A different system was probably in place in the Middle East.

Given these indications, it is not surprising that there were about 18 Indian treatises on astronomy, but most were considered to be very inaccurate by Varāhamihira's time. In order to gain a coherent picture from there, a few precautions are needed, for reasons described in the next section.

3 Measures of Time

We can consider the following three measures of the solar day:

1. The true solar day is the interval from true noon to noon with respect to the Sun. This varies during the year. When the Earth is close to perihelion, the time taken is slightly longer and when the Earth is near aphelion, solar time is shorter. There is also variation depending on the distance to the solstice (it is also longer near a solstice). Consequently, the true solar day, as measured by the apparent maximum altitude of the Sun, is maximum on 22 December by almost 30 s and is shorter on 16 September and 26 March.

   The mean solar day is the true solar day averaged over the year.
2. We can also define the stellar day based on the fixed stars. The mean solar day defined this way is 86164.098903691 s of mean solar time, as we use now.

3. We can define a sidereal day with respect to the vernal equinox, where the time interval will be based a fixed observer on the Earth seeing the rise of the equinox. This means the solar day will be 86164.09053083288 s.

There is similar definition for the mean year too. Precession and nutation due to changes in the Earth's rotational axis produce irregularities in the orbital period of the Earth around the Sun in a complex way. But for the first order, the tropical year, the interval for the Earth to cross the same intersection point between the ecliptic (the orbit around the Sun) and the celestial equator (representing the Earth's rotational axis) is well defined over several thousand years. The sidereal year, the time interval as measured by a fixed star, is probably a more stable quantity. However, almost all nearby useful stars move with respect to the Sun and hence, over 5000 years, their position in the sky is shifted by a good fraction of a degree. I might venture to suggest that when this problem was recognised the start of the year was moved from Moola (near Sagittarius) to Aries, and to other positions at various epochs.

4 Change in the Spin Period: Physical

So far the complexities have been purely due to the perturbations in the orbits of the planets. However, transport of angular momentum is an important problem both in stars and planets, and most planets—including the Earth—will have an evolution of their spin (and orbits for exoplanets) due to tidal effects. It is argued that the Earth's rotation was slowed significantly by tidal acceleration through gravitational interaction with the Moon, and angular momentum was transferred to the Moon at a rate proportional to r^{-6}, where r is the orbital radius of the Moon. This resulted in a tidally locked lunar orbit. However, 600 Myr ago Marinoan or Sturtian glaciation broke the stable configuration. So, the Earth's spin period of 21 h about 600 Myrs years ago has increased to almost 24 h now (cf. Bartlett and Stevenson, 2016; Wu and Peltier, 1984).

This is also understandable, in a sense, by comparing the spin periods of the planets in the Solar System:

1. The major planets, Jupiter, Saturn, Uranus and Neptune, have spin periods of 10–16 h. But planets with solid crusts (Mars, Earth, Venus, Mercury and perhaps Pluto) have higher spin periods, and there is no pattern in it.
2. If we assume the outer layers of Jupiter and Earth had the same specific angular momentum at the time of formation, the rate of the Earth's loss of angular momentum could have been over a time scale of 700 million years, or less if Jupiter also has slowed since it was formed.[2]

[2]But there is no strong justification for this as-sumption, because of the formation of planets from planetismals.

3. The Siddhantic evidence: if we assume that the planetary ephemerides of Aryabhatiya or the *Surya Siddhanta* version of the sixth century AD were accurate and the definitions of the year and the day were the same as we use now, we can compare the Siddhantic values with the corresponding present-day values to determine the slowing down of the Earth's spin rate. We find that the Earth's spin has slowed by about 0.0021 days over 1600 years, which corresponds to a slowing time scale of 270 million years (if the slowing down had been steady) and so it is not an exotic value.

While this gives a factor of ten faster spin-down rate compared to the value provided by the geological data, we have an independent measure of the slow down based on eclipses (see Tanikawa et al., this volume), which suggests a factor of 20 higher spin down rate. This needs to be reconciled.

5 Faster Rotation: The Implication

A definitive implication of faster rotation in earlier times (the Earth's spin with a period ~5 h a Giga year ago) would be faster mixing in the oceans and more turbulent atmospheric circulation. Above all, this has crucial implications for the evolution of life on Earth.

Is there geological indication of a faster spin rate in the Proterozoic era? Brosche (1982) has given a lucid picture of how the tidal friction between the Earth and the Moon, mediated through oceanic tides, slowed down the Earth's spin and extended the orbit of the Moon. He quotes the observations, tracing different time scales like growth rhythms in fossil animals, ancient solar eclipses and transits of Mercury to argue that the length of the Earth's day has increased by 2.1 millisecond per century over the 500-Myr period of the animal fossils studied. This is one order of magnitude less than the value we found for the last 1600 years. The values quoted by Wu and Peltier (1984) and Bartlett and Stevenson (2016) are consistent with Brosche's values, but all of them are averages over hundreds of millions of years.

In concluding this section, it is desirable to assume that both geological and astronomical evidence support the slowing down of the Earth's spin. Given the varied effects and irregularities, the astronomical numbers discussed here could be taken as short-term variations while the geological values listed by the authors quoted here certainly represent the long-term evolution of the Earth's spin.

6 Aphelion Instead of a Fixed Star?

Did Varāhamihira consider his year to be the time taken for the Earth to move from aphelion to aphelion? This is not as strange as appears, in view of some of the religious discussions presented below.

In Indian tradition, at some stage they used Mula (one of the bright stars in Scorpio, towards the Galactic Centre) as the reference point for the start of year. In about the third millennium BC, possibly Gargya shifted it to Krittika (the Pleiades), and later, to have conformity with the West, the origin became Ashwini. In his book on *Pre-Siddhantic Indian Astronomy*, Abhyankar (2007) mentions that Ashvinikumara hymns in the *Rigveda* correspond to the sacrifice time of Ashvini during the winter solstice around 7200 BC. It was shifted to Chitra during the Taittariya Samhita period, and further modifications were introduced from time to time.

But all the reference stars have proper motions of a few tens to hundreds of milliarcseconds a year. If various civilizations recorded planetary positions based on different stars, over 5000 years the discrepancy would be half a degree (e.g. The apparent shift of Abhijit (Vega) and Mula (ε Scorpii) are similar in magnitude, but the changes in their Right Ascensions and Declinations are in opposite directions).

If the recorded star-based position was converted to one with aphelion as the reference point at each epoch, this discrepancy could be rectified. About 11 arcminutes precession of the Earth's aphelion over a 60-year interval was reasonably well determined by the Siddhantic Period. After this shift is taken into account the orbital period would be close to 365.259 days. Many people question the rationale of using such an observationally complex procedure. But it should be noted that Varāhamihira or any other experts could have taken the recordings from various sources, converted them to one uniform co-ordinate system and then compared or combined them. So, the complications of using aphelion would only have arisen in the final computations.

7 Concluding Remarks

The Earth's orbital period recorded in the sixth century AD differed from the modern-day value by nearly 0.0022 days.

That the Earth is slowing down is a possibility because the solid planets have much less specific angular momentum on the surface than the gaseous planets in the Solar System, which themselves have a value lower than that of the solar surface. Geological evidence from a multitude of observations supports this hypothesis, although the time scale is about an order of magnitude larger. But there could be contamination in both kinds of estimates.

Using aphelion as a reference point at each epoch is a possibility because the reference stars have proper motions of a few tens to hundreds of milliarcseconds a year, and using the vernal equinox is not a solution in the very long term due to multiple factors affecting the Earth's spin and orbit.

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Analysis of Asu (阿修) and Gaoyue (高月) Recorded in the Indian Calendar, Jiuzhi-Li (九執曆)

Eun Hee Lee

Abstract The Indian Navagraha Calendar was translated into Chinese by Gutama Siddha (瞿曇悉達) who was an official astronomer and astrologer during the Tang 唐 Dynasty (AD 618–906). In China it was called the Jiuzhi-li (九執曆) which means the calendar of 'Nine Luminaries', namely the Sun, Moon, five planets and two imaginary stars, Rahu (羅睺) and Ketu (計都). In the Jiuzhi-li, however, the term Rahu is mentioned as Asu (阿修), and Ketu is not seen in the text. Instead, the term Gaoyue (高月), which means the lunar apogee, is explained. This paper examines and discusses the astronomical meaning and constants of Asu and Gaoyue described in the Jiuzhi-li.

1 Introduction

During the Tang Dynasty the Indian Jiuzhi-li Calendar was compiled in 718 by the order of Emperor Xianzong (玄宗). It is preserved as one of 120 sections of the astrological treatise of the Kaiyuan Reign-period (called the Kaiyuan Zhanjing, 開元占經) compilation of astronomical and astrological lore, mostly from Chinese traditions, assembled by Gutama Siddha (van Bladel, 2015). However, the Kaiyuan Zhanjing was hidden as a secret treatise after the Tang Dynasty, and no one knew about its existence until it was discovered in the belly of a Buddhist statue in 1666 (during the later Ming Dynasty). For this reason, it is known that only two scholars of the Qing (靑) period (1636–1912) studied it (Chen, 1996). The question of the source (or sources) of the Jiuzhi-li is open, and it is not even known whether it is a translation or a compilation of Indian texts. Clearly, however, the Chinese text preserves Indian methods of astronomical calculation, although the motions of the five planets are omitted (Martzloff, 2000).

According to the Van Bladel (2015), the Jiuzhi-li is mainly based on known Sanskrit astronomical works, particularly the *Panca-Siddhantika* composed by Varāhamihira (507–587) in Ujjain during the sixth century AD. The title, Jiuzhi

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(九執) is a literal rendering of the Sanskrit astrological term ‘Navagraha’ (Sadeghi et al., 2014). It can be translated as ‘nine seers’ or ‘nine luminaries’, seven of which were visible (the Sun, Moon and five planets), while two (Rahu and Ketu) were invisible. Also, the name Rahu came from the Vedic legends of India. Rahu had the head of a demon and a dragon’s tail.

In China, the term Rahu first appeared in the Modengji-Jing (摩登伽經; Matanga-sutra) which was translated from Sanskrit in AD 230 (Lee and Chen, 1998). Hence, it is considered that Rahu was first introduced into China with the translation of the esoteric sūtra, Modengji-Jing (Niu, 2006). Interestingly however, in this sūtra, Rahu and a comet, instead of Rahu and Ketu, are the two invisible ‘luminaries’ (Chen et al., 2006). Since then, terms for two invisible luminaries have been found in the Chinese translated sūtras and in Chinese calendars.

On the other hand, it is generally known that the astronomical meaning of Rahu and Ketu are the ascending and descending nodes of the lunar orbit respectively, and Yueb*o* (月孛) is the lunar apogee. However, we notice that the names and meanings of these terms described in the Chinese calendars and sūtras are not consistent. As well, it is known that in China, the calendar in which the terms Rahu and Ketu were first mentioned is the Jiuzhi-li, but these terms are not seen in the text. Instead, Asu and Gaoyue, which mean lunar ascending node and apogee, are explained in detail in their respective chapters.

2 Invisible Luminaries Described in Chinese Calendars and Sutras

In the sky, seven luminaries (the Sun, Moon and five planets) are to be seen revolving, but imaginary objects such as the lunar nodes and apogee do not have a visual appearance (Sub-barayappa and Sarmar, 1985). Nonetheless, these invisible luminaries were considered important elements in the calculation of solar and lunar eclipses since ancient times. Historically, however, we notice that the real meanings of the invisible luminaries were not clear and were confused.

Generally, it is known that the tradition of Rahu and Ketu as two nodal points was incorporated into the Hindu scheme of astronomy. In the Jiuzhi-li, however, Asu which means Rahu is the ascending node, but it is not accompanied by Ketu. Instead Gaoyue, which means lunar apogee, is explained.

In the Chinese translated sūtras, furthermore, Rahu is the ascending node, but Ketu means the lunar apogee or a comet. According to Niu (2006), in the esoteric sūtras such as the Qiyao Rangzai Jue (七曜禳災決) and the Fantian Huoluo (梵天火羅九曜), Ketu is the lunar apogee. Meanwhile, in the esoteric sūtras such as the Modeng Jijing and the Beidou Qixing Humo Fa (北斗七星护摩法), it is described as a comet. As well, in the Chinese-Islamic Huihui-li (回回暦) Calendar, Ketu is the ascending node, and Rahu the descending node. This means that the astronomical meanings of Rahu and Ketu recorded in the Chinese and Islamic calendars are completely opposite. Due to this confusion, we examine and compare the names

Table 1 Names and meanings of the invisible luminaries recorded in the ancient calendars and esoteric sutras

Sources (Calendars and Sūtras)[a]	Year (AD)	Invisible Luminaries (Described Names)	Ascending Node	Descending Node	Lunar Apogee
(Calendars)					
Jiuzhi-li (九執曆)	718	Asu, Gaoyue	Asu		Gaoyue
Shoushi-li (授時曆)	1281	Rahu, Ketu, Yuebo, Zi-qi	Rahu	Ketu	Yuebo
Datong-li (大統曆)	1384	Rahu, Ketu, Yuebo, Zi-qi	Rahu	Ketu	Yuebo
Huihui-li (回回曆)	1385	Rahu, Ketu	Ketu	Rahu	
Chiljeongsan Naepyeon (七政算内篇)	1444	Rahu, Ketu, Yuebo, Zi-qi	Rahu	Ketu	
Chiljeongsan Oepyeon (七政算外篇)	1444	Rahu, Ketu	Ketu	Rahu	
(Esoteric Sūtras)					
Moden Jiejing (摩登伽經)	230	Rahu, Comet	Rahu		
Fantian Huoluo (梵天火羅九曜)	?	Rahu, Ketu	Rahu		Ketu
Beidu qixing huma fa (北斗七星護摩法)	?	Rahu, Comet	Rahu		
Qi Yao rang Zai Jue (七曜禳災决)	806	Rahu, Ketu	Rahu		Ketu

[a]The calendars and sūtras listed in Table 1 can be classified as follows: Indian origin: Jiuzhi-li and esoteric sūtras; Chinese traditional calendars: Shoushi-li, Datong-li and Chiljeongsan Naepyeon; Islamic origin: Huihui-li and Chil-jeong-san Oepyeon.

and meanings of the invisible luminaries described in the Chinese calendars and sūtras in Table 1.

In this table, we notice that the names and meanings of the invisible luminaries described in the Chinese translated sutras and calendars are not consistent, but represent some rule or pattern. Descriptions of and information about the invisible luminaries listed in Table 1 can be summarized as follows.

(1) In the Jiuzhi-li and esoteric sūtras of Indian origin, the meaning of Rahu is the ascending node, but the term for the descending node is not listed.
(2) The terms for the ascending and descending nodes are Rahu and Ketu in the Chinese calendars, but Ketu and Rahu in Chinese-Islamic calendars. As well, in the Chinese esoteric sūtra, Rahu is the ascending node, but Ketu means lunar apogee or a comet.
(3) In the Indian calendar Jiuzhi-li, Asu and Gaoyue are mentioned as two invisible luminaries, while in the Chinese calendars, Rahu, Ketu, Yuebo and Zi-qi (紫氣) are described as four invisible luminaries.
(4) Both Chinese terms, Gaoyue (高月, the farthest Moon) and Yuebo (月孛, the slowest moving point of the Moon) mean the lunar apogee. Probably, those

terms were used since the Moon moves most slowly at the lunar apogee, which is most distant from the Earth.

According to Kochhar (1990), the earliest reference to Rahu is in the *Atharvaveda*, where he is a demon that eclipses the Sun. Ketu appears in the Vedic texts, not in connection with Rahu, but as a flag or a banner. Elsewhere, Ketu means a meteor or a comet. A scientific explanation of eclipses was first given in India by the noted astronomer-mathematician Aryabhata, born AD 476, who borrowed the Vedic terms Rahu and Ketu to denote the ascending and descending nodes of the lunar orbit. From his explanation, we notice that the meaning of Rahu and Ketu were clearly defined as the ascending and descending nodes after the fifth century in India, and we have come to understand why their names and meanings were not inconsistent and unclear in the Chinese translated sūtras. However, we are also concerned about the opposite meanings of Rahu and Ketu mentioned in Chinese-Islamic and Chinese traditional calendars. Probably, it seems that their meanings and names were changed and confused in the process of being transmitted or translated at different times.

On the other hand, we find that four invisible luminaries are described in Chinese calendars. In China, the 'four invisible luminaries' were called Si-yu (四餘, four remainders), Si-anxing (四暗星, four hidden stars) and Si-yinyao (四隱曜, four hidden luminaries). According to Lee and Jing (1998), in China the Shoushi-li was the first official calendar that clearly explained the astronomical meanings and constants of the four invisible luminaries. In their study, they report that the Shoushi-li Licheng (授時曆立成, astronomical tables of the Shoushi-li), which are not extant in China, has been preserved in the Gyu-janggak (奎章閣) Archives in Korea, and the astronomical information on four invisible luminaries is given in part of the Si-anxing of the Shoushi-li Li-cheng. As well, terms for the four invisible luminaries also are seen in the Korean Chiljeong-san Naepyeon (七政算內篇) astronomical calendar. Its name as described in the Korean calendar is Si-yuxing (四餘星). This means that the knowledge of the four invisible luminaries also was transmitted to Korea.

The complex story of the invisible luminaries travelled to different countries and cultures in different periods (Lee et al., 2014). Consequently, the terms and their different meanings and origins were transmitted to China and Korea by different routes, and in the process their names and meanings changed considerably, and were mixed with Western and Chinese elements.

3 The Asu and Gaoyue Described in the Jiuzhi-Li

Astronomically, Asu means the ascending node of lunar orbit, which is one of the important elements in the calculation of solar and lunar eclipses. While, Gaoyue means the lunar apogee, which is one of the decisive factors to determine the eclipsing time. According to the records of the Jiuzhi-li (Gutama, 718), the epoch was the vernal equinox of AD 657, which corresponded to the beginning (conjunction day) of second month (of Xianqing 顯慶 2 years) in the Chinese lunar calendar. At that time (AD 657), the ecliptic longitude of the solar apogee was 80° (in the text, it was described as 10° before the summer solstice). Meanwhile, the ecliptic longitudes of Asu and Gaoyue were 174°.6667 and 343°.75 respectively. Also, the retrograde cycle of Asu was 18.5996 years (=6794 days) and the prograde cycle of Gaoyue was about 8.85 years. According to records in the Jiuzhi-li (Gutama, 718) and the study of Chen (1996), astronomical constants and information in the Jiuzhi-li can be summarized as Table 2.

Hence, the position of Asu and Gaoyue described in the Jiuzhi-li can be represented as shown in Fig. 1.

Using the Meeus' formula (1998) and its revised algorithm (2017) based on the DE431 (JPL Ephemerides), in AD 657 the Sun passed through the solar apogee on 10 June, while the Moon passed by the lunar apogee and ascending node on

Table 2 Astronomical constants and information included in the Jiuzhi-li

Astronomical Elements	Jiuzhi-li (九執曆) (compiled AD 718)
Epoch	Vernal equinox of AD 657 (= AD 657.03.20).
1 sidereal year	365.2762 days
1 solar year	365.24669 days
1 synodic month	29.530583 days
Solar apogee	10° before the summer solstice (λ ≈ 80°)
Lunar apogee (Gaoyue)	1 sidereal period = 8.85 years
Ascending node (Asu)	1 sidereal period = 6794 days = 18.5996 years

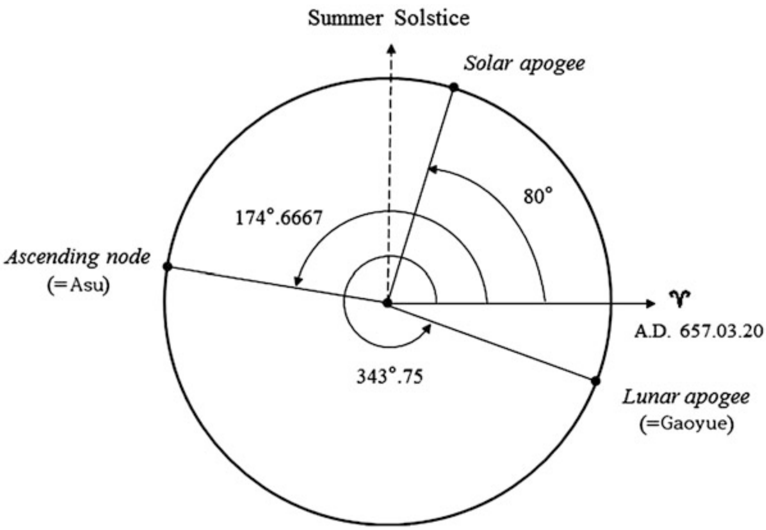

Fig. 1 The position of Asu and Gaoyue in AD 657

Table 3 The positions of the solar and lunar apogee and the ascending node in AD 657

Orbital elements (Corresponding date)	Jiuzhi-li (Recorded values)		Meeus (1998)	DE431 (2017)[a]
Solar apogee (A.D. 657. 06.10)	2相20度	80°.0000	81°.1670	81°.1038
Lunar apogee (A.D. 657. 02.20)	11相 13度 45 分[b]	343°.7500	343°.6656	343°.7566
Ascending node (A.D. 657. 04.02)	5相 24度 40分	174°.6667	176°.1681	176°.1207

[a]DE431 (2017) means the revised algorithm of Jean Meeus' methods based on DE431 (JPL Ephemerides), developed by D.B. Kim for this paper.
[b]In fact, the value of Gaoyue recorded in the text of Jiuzhi-li was "1相13度45分 [= 43°.75]." However, Yabuuchi (1984) suggested that "1相13度45分 was a misprint for 11相13度45分 (=343°.75). Therefore, we adopted 343°.75 in the calculation of Gaoyue for AD 657. A comparison of the recorded and calculated values listed in Table 3 confirms Yabuuchi's claim.

20 February and 2 April, respectively. In order to verify the astronomical meanings and constants of invisible luminaries recorded in the Jiuzhi-li, in Table 2 we compare them with their passaging times and positions calculated by modern methods.

The comparison of recorded and computed values given in Table 3 shows that the values of Asu and Gaoyue recorded in the Jiuzhi-li nearly correspond to the lunar ascending node and apogee of AD 657. Therefore, we confirm that the recorded values in the Jiuzhi-li are undoubtedly based on the observations or calculations of the epoch year (AD 657), when we consider the calculation error for the time difference over a period of 1300 years.

4 Discussion and Concluding Remarks

In this paper, we examine the names and meanings of the invisible luminaries described in the Chinese ancient calendars and sūtras, and trace their confusing story. As well, in particular, astronomical meanings and calculations of Asu and Gaoyue recorded in the Jiuzhi-li are analyzed and compared with the results obtained by modern methods. Through this study, we find and confirm the following:

1. In China, the Jiuzhi-li was one of the precious literary sources for the study of ancient Indian astronomy. Generally, it is considered that Indian astronomy was officially introduced into China through the Jiuzhi-li, which was translated by Gutama Siddha. During the Tang Dynasty, Gutama's (瞿曇) family served as official astronomers in important positions in the Astronomical Bureau for more than 110 years. They contributed much to the development of Chinese calendar systems, and introduced Greek astronomical and mathematical knowledge to China through the Indian astronomy and calendar system (Shi, 1996: 74–76).
2. In the study of names and meanings of the invisible luminaries, we find that the terms of the two invisible luminaries are mainly seen in Indian and Islamic calendars and esoteric Buddhist sūtras. However, terms for four invisible

luminaries are found in Chinese calendars, Chinese sūtras of Sogdian origin and Daoism sūtras. In fact, these invisible luminaries—such as lunar nodes and apogee—were related to the calculation of solar and lunar eclipses, but they were mainly used for astrological purposes in Chinese sūtras.

3. The astronomical meanings of Rahu and Ketu recorded in Chinese and Islamic calendars are completely opposite each other. Interestingly, this is also confirmed in the Korean Chiljeongsan Naepyeon (七政算內篇) and Chiljeongsan Oepyeon (七政算外篇) Calendars, which were based on the Chinese and the Islamic calendar systems, respectively.
4. From the explanations of Asu and Gaoyue in the Jiuzhi-li, we confirm that their meanings are obviously lunar ascending node and apogee respectively, and their recorded values were based on observations or calculations corresponding to the epoch year of the Jiuzhi-li (AD 657). We consider that in China the Jiuzhi-li was the first official calendar to explain the calculations of the lunar ascending node and apogee using the Indian method.
5. Consequently, we consider that the terms Rahu and Ketu originated from the Indian Vedic legend, and that their astronomical meanings were clearly defined as the ascending and descending nodes in India after the fifth century. Also, the Jiuzhi-li is mainly based on known Sanskrit astronomical works, particularly the *Panca-Siddhantika*, which was composed in the sixth century. In the text of the Jiuzhi-li, however, Ketu is not mentioned. Instead, calculation of Gaoyue, which means lunar apogee, is explained. Probably, this means that in the Jiuzhi-li, there still remains a tradition in which Rahu is not accompanied by Ketu.
6. Finally, we conclude that the complex story of Rahu and Ketu and confused meanings among the invisible luminaries mainly came from the different origins and the processes of transmission through different routes and during different periods.

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Ragoonatha Charry and His 'Scientific' *Pañcāṅga*

T. V. Venkateswaran

Abstract The early part of the nineteenth century witnessed the widespread circulation of printed pañcāṅga (traditional Hindu calendars or almanacs) in the Madras presidency. Computed using the vākya algorithms, these pañcāṅga were full of errors, such as local circumstances of eclipses. Chinthamani Ragoonatha Charry, hailed as the first Indian to make modern astronomical discoveries and an employee of the Madras Astronomical Observatory, advocated the reform of the traditional South Indian pañcāṅga. Unhappy about the errors in the traditional pañcāṅga, during the 1870s he took it upon himself to publish 'scientific' pañcāṅga in Tamil and Telugu, two principle languages of the presidency, drawing upon the computations of modern astronomy. These almanacs confirmed to the ritual demands of the traditional pañcāṅga even while drawing upon elements of the almanacs published by the British settlers in the Madras Presidency. Charry's pañcāṅga not only provided the computation of traditional elements, such as tithi, nākṣatra, yoga and karaṇa, but also elaborated on stellar phenomena, particularly those which are visible to the naked eye, and gave accurate predictions for solar and lunar eclipses, occultations, and so on. Convinced by the arguments advocated by Charry and the accuracy of his predictions, two major religious sects—the Smārta sect of Kanchi Kamokoti Mutt and the Aiyangar subsect owing allegiance to Jeears of Ahobila Mutt—supported his 'scientific' pañcāṅga.

Hitherto, Indian colonial science studies have focussed on the engagement between Europeans and Indians either as a process of philosophical rationalisation reconciling old and new forms of knowledge, or as a cross-cultural negotiation within Indian responses to Western science. Positing that the engagement during the colonial period was both philosophical and practical, this paper presents the context and an overview of the pañcāṅga reform attempted by Ragoonatha Charry. As such, it is a contribution to the debate on Indian modernity.

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1 Introduction

Around 1820s, a lunar eclipse was predicted by a pañcāṅga-maker in Madras in his Madras pañcāṅga. Purohits (family priests) told their clientèle about the impending eclipse and directed them to perform appropriate ritual ablutions. At the appointed time, a huge crowd of people gathered on the beach at Madras awaiting the foretold lunar eclipse, so that they could perform the rites laid down in the śāstras. However, their waiting was in vain, as the Full Moon shined unblemished many hours past the predicted time of the eclipse. No eclipse occurred, and the bemused crowd scorned the pañcāṅga-maker, laughed at him, jeered him, and went back to their homes to sleep (see Warren, 1825: 347).

This was not an isolated miscalculation. Earlier, in 1807, pañcāṅga-makers in Travancore had predicted that a solar eclipse *and* a lunar eclipse would be visible in that region on 19 May. However, no such eclipses took place.[1] William Tobias Ringeltaube, a missionary serving in Travancore, noted that

> The Brahmins had predicted a double eclipse of Sun and Moon on this day and a great mortality to ensure from hence. Clouds prevented their astronomical prophecy from being put to blush . . . (Ringeltaube, 1807: 139).

The abject failure of the traditional predictions to match modern computations and observations was readily apparent during the second half of the nineteenth century when the pañcāṅga were printed and circulated in large numbers.

Why were the traditionally computed pañcāṅga faulty, and why did they lack observational accuracy?[2] Essentially, until the nineteenth century, all aspects of pañcāṅga in the Tamil region, including eclipse circumstances, were computed using algorithms stated in the traditional texts called vākya (or vākyams, which are in the form of sentences, formulae and mnemonics). The vākya texts were composed during the fourteenth century AD, and with the passage of time became outmoded.

It is in this context that Chinthamani Ragoonatha Charry endeavoured to compute and publish pañcāṅga based on modern positional astronomy computations. In this paper, we examine the vākya method; the emergence of printed pañcāṅga and their relationship with con-temporaneous European almanacs; and finally, the socio-cultural context, reception, and reaction to Ragoonatha Charry's 'scientific' pañcāṅga.

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[1]However, there was a solar eclipse on 6 June 1807 and a lunar eclipse on 21 May 1807, but neither was visible from southern India.

[2]Inaccuracies arising from the non-uniform nature of the motion of celestial bodies are inherent. The question is why there was a substantial divergence from prediction and observation with regard to say the timing of onset, the extent of geographical visibility and the magnitude of eclipses. Tamil proverb states that the 'correct prediction of eclipses is the test of sastras' indicating the popular perception (Percival 1877; 299) and Kochhar (2010) notes that in modern times, the almanacs borrow data from modern sources for computation of phenomena like eclipse, while retaining the computations following ancient texts with regard other aspects.

2 The Vākya System

European travellers, traders, missionaries and scientists who travelled to the rural parts of southern India during the eighteenth and early nineteenth centuries noted the extensive presence of pañcāṅga computers, known as panchangins or panjangan (e.g. see Buchanan, 1807: 632 and 645; Ellis, 1818; Maitland, 1843: 105; and Warren, 1825). Jean Baptiste Joseph Le Gentil, a French astronomer who came to Pondicherry to observe the 1769 transit of Venus, gathered information about indigenous astronomy from a Tamil astronomer, Mariadas Pillai (a recent convert to Christianity, who hailed from a family of astrologers and pañcāṅga computers). With the help of an interpreter, Le Gentlil asked Pillai to compute the circumstances of the lunar eclipse of 30 August 1765, which would be visible from Pondicherry. While the times computed by the Tamil astronomer were 41 s earlier than the actual observations made by Le Gentile, the best European astronomical ephemeris available in his time—provided by Tobias Mayer—also was inaccurate. Mayer’s table was later by 1 min and 8 s. Pillai’s calculated time of totality was 7 min 48 s early and Mayer’s was 25 s late.

What amazed Le Gentil was that Pillai used memorised tables and shells to compute the eclipse circumstances rather than any printed mathematical tables (Neugebauer, 1975: 820). Another pañcāṅga computer, Sami Naden Sashia, used shells arranged on the ground and mathematical tables memorized using artificial words and syllables to calculate the circumstances of the lunar eclipse of 31 May-1 June 1825, with an error of +4 min for the beginning, −23 min for the middle and −52 min for the end (Warren, 1825: 334–337). If we set aside for a moment the issue of the degree of accuracy, it will not fail to amaze anyone that with what appeared to be a crude arrangement, phenomena like eclipses could be foretold, even with some degree of exactitude.

During the late eighteenth century and early nineteenth century, European scholars were amazed and mystified by the seemingly primitive cosmology of the Indians, with its flat Earth, epicycles and geocentricism, yet reasonably accurate algorithms that yielded predictions of celestial phenomena like eclipses and occultations.[3] Amazed at the ingenuity of the vākya system, Le Gentil obtained another table from a Brahmin at ‘Tirvalore’ (Thiruvarur) on the Coromandel coast, west of ‘Negapatnam’, and published it in 1772 (cited in Playfair, 1790: 137). A contemporary school history textbook states:

> It is above a century since the French philosophers evinced, by the evidence of a Siamese manuscript, containing tables for calculating the places of the heavenly bodies, the astonishing advancement made by this ancient people in the science of astronomy. A set of tables, obtained lately from the Bramins by M. Gentil, goes back to an era, termed Calyougham,

[3]See Young and Jebanesan (1995) for an account of the ambivalent responses of European missionaries towards the traditional vākya system. See, also, Joseph (1995) for ‘wonder and respect’ in the case of Burrow, ‘scrutiny and creeping condescension’ in case of Playfair and ‘silence and indifference’ in the case of Whish, in encountering traditional Indian astronomy.

> commencing 3102 years before the birth of Christ. These tables are used by the modern Bramins, who are quite ignorant of the principles on which they have be constructed, and which M. Bailly has shown to be the same employed by the moderns, but with which the Greeks and Chaleans were utterly unacquainted. (Tytler, 1844: 187).

Warren and Le Gentil were not aware of the source of the artificial symbols and words deployed by their informants in computing the eclipses. But scholars, since then have found the texts and traditions that gave rise to these unique astronomical methods and Tamil pañcāṅga computations. Now we know that both Warren's and Le Gentil's informants were using fourteenth century texts and vākya tables for their computations, and these are used even today by vākya pañcāṅga-makers in computing the elements and aspects of the pañcāṅga.

In the vākya system, the true longitudes of the Sun, the Moon and the planets can be found at regular intervals, using vākyas or mnemonics. For each celestial body, periodicity is computed and the vākyas provide the longitudes at mean sunrise for each day during that period. For example, the nine anomalistic months of the Moon are very nearly 248 days, and correspondingly, there are 248 candravākyas (literally 'Moon sentences') for the Moon, which give the longitudes of the Moon at mean sunrise on 248 successive days, beginning with the day at mean sunrise on which the Moon's anomaly is zero (for a discussion on the history of the 248-day scheme see Jones, 1983). Thus, if one memorizes the 248 positions, given in the form of words, then after computing the number of days that have passed from the date of the zero anomaly, the longitude of the Moon can be obtained. The system was an evolution of similar karna (manual), text tradition (see Montelle & Plofker, 2014 for an interesting older text).

Similar tables or vākyas for the longitudes of the planets, which involve their zodiacal anomaly as well as the solar anomaly, were composed into texts (Mahesh, 2014; Sriram, 2014). The versified vākyas were obtained by assigning each of the consonants of the Sanskrit nāgari or Tamil alphabet to one of the ten decimal digits, and then making up a short Sanskrit/Tamil sentence for each given data value that contained consonants chosen and ordered to correctly represent its numerals (for example, the sentence 'viṇṇōrnāthan' in the Tamil alphabet, implies that the Moon's ascension is $0° 7' 23''$). Versified vākyas assisted the ease of orally transmitted learning, "… whose astronomical authors generally attempted to keep their verse tables brief and memorable." (Plofker, 2014: 89).

One of the earliest karaṇa (astronomical manuals) is the *Khaṇḍakhādyaka* of Brahmagupta, dating to around AD 665, which literally means 'eating candy' and was intended as an easy ride for the reader to negotiate a complex maze of computations that formed part of the Siddhānta texts. Brahmagupta states

> I now write *khaṇḍakhādyaka* which give the same results as those obtained from Āryabhata's formulas. His rules are lengthy and hence impracticable for daily purposes, such as marriage, birth and alike. Mine, on the other hand are brief, yet yield similar results. (Chatterjee, 1970: 7).

Karaṇa texts were like concise astronomical manuals that sought to imitate the general structure of siddhānta but simplify its methods.

> In particular, a karaṇa specifies initial planetary positions for a recent epoch, usually some date within the lifetime of its author, rather than using the start of the kalpa or kaliyuga as its zero point. The formulae for calculating current celestial positions are generally simpler approximate versions of the siddhānta procedures. (Plofker, 2009: 105).

They were simple in operation and more limited in application, and it is

> . . . a series of versified algorithms relying on a given starting point or epoch date, usually occurring within the author's own lifetime, and reduced versions of astronomical parameters to make computations easier. The position of celestial bodies at the moment of the given epoch are listed in tables . . . (Plofker, 2012: 179).

which the pañcāṅga-maker was expected to memorise.

In southern India, traditions of computational astronomy based on the Ārya and Saura Siddhānta emerged, ". . . but largely independent of the traditions in the rest of India." (Pingree, 1981: 47). Particularly during the fourteenth and fifteenth centuries, centred on Kerala, without having any effect whatsoever on the north, three interrelated systems developed: the Parahita and Vākya, following the Āryapakṣa, and the Dṛgganita, following the Saurapakṣa. Further, a genre of literature called tantra or karaṇa evolved which dealt with selected practical problems in astronomy rather than giving a complete system as a siddhānta or northern karaṇa would (Pingree, 1981: 47; see also Sarma, 1972). Further,

> . . . unlike the northern version consisting of tables with numerals, the southern karaṇa texts depicted the daily motions of the planets, sines of their equations, and other matters in the form of verses with meaningful words and sentences employing the facile notation of kaṭapayādi numerals. (Sarma, 2008a, b: 320).

The Parahita system was first embodied in the *Grahacāranibandhana* of Haridatta, and was further improved with Bīja corrections of Mahāmārganibandhana. Haridatta prepared tables, (which he called as vākyas), which gave the mean daily motions of the planets according to the Āryapakṣa in intervals of 3.45°. Chandra vākyas, attributed to Vararuci, perhaps was composed in AD 1184. Such karaṇa astronomical manuals usually consists of five chapters, one each for computation of the five elements of pañcāṅga, and they also were called vākyapañcādhyāyī.

The number of works in Tamil as well as Sanskrit that were produced between fifteenth century and the early nineteenth century suggests that a significant amount of energy was spent by Indian astronomers devising easy methods for computing tables from which pañcāṅga for civil and ritual uses and planetary positions for astrological prognostications could be computed (Sastry, 1989a). Many of these methods were not original, but commentaries on the karaṇas with improvements to the constants.

The vākyas employed in the Tamil region were drawn from the *Vākyakaraṇa*,[4] which has been attributed to Vararuci, the legendary progenitor of the vākya-based

[4]This critical edition prepared by Kuppuswamy Sastry and K.V. Sarma (1962) contains the commentary Laghuprakasika by Sundararaja, along with a valuable introduction and a resume of the text in English.

planetary computation (the text has three references to him—see Sastry and Sarma, 1962), which is thought to have been composed between AD 1282 and 1306 (ibid.). This treatise is also known as the *Vākyapañcādhyāyī*, and is based on the earlier works of Bhāskara and Haridatta of the Kerala tradition (Hari, 2001).

A number of manuscripts of the work are available in the libraries of south India. The *Vākyakaraṇa* was composed in this tradition and was elaborately expounded by another Tamil astronomer, Sundararaja, in about AD 1500.[5] Sundararaja's commentary *Laghudipikd* or *Laghuprakāśika* on the *Vākyakaraṇa* employs 248 Moon sentences of the ancient astronomer Vararuci for the computation of the position of the Moon. However,

> . . . for the five planets, the author himself computed 82 tables devoted to different planet- ary cycles, containing in all 2,075 mnemonic sentences or *kujādi-pañcagraha-mahāvākyas*. (Sarma, 2008b: 2180).

These karaṇa consist of computational tables expressed in mnemonic sentences, phrases, and words, making them easy to memorise.

The Tamil pañcāṅga-makers used exclusively the vākyakaraṇa for computation of the pañcāṅga. After all, if the pañcāṅga-makers could memorise the vākyas, they could almost mechanically compute the various aspects without any reference to underlying theories of cosmology.[6] Over the years the pañcāṅga-computers were unaware of the astronomy or mathematics behind the 'rules' they followed, but they found these rules to be reasonably useful and effective, so they began to treat these texts and mnemonic sentences as authoritative and sacrosanct.

However, when these vākyas were composed, they were supposed to assist computation for a century or so, for it was well known that with the passage of time accumulated errors would show. For example, nine anomalistic months is about 247.99095 rather than 248,[7] the number of Moon sentences. Hence,

> Not accuracy, but ease of computation was the aim of these works and they were intended to be used only for a few hundred years, not more, because errors would accumulate. (Sastry, 1989b: 458).

Further, both the *Āryapakṣa* and *Saurapakṣa* assumed inaccurate values for constants: for example, the modern value of the sidereal year is 365.25636 days, but in

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[5]The historian K.V. Sharma (1972: 196) says that Sundararaja was "... the son of Anantanarayna and protégé of Somadeva." He had contacts with the Kerala astronomer Neelakanta Somayaji, who wrote a book titled *Sundararajaprasnottara* (*Answers to Questions from Soundaraja*) clarifying certain astronomical problems related to the computation of eclipses and so on.

[6]Perhaps this separation helped the local pañcāṅga-maker overcome the dilemma of 'Virodha', i.e., the inconsistency between the practised astronomical theories of the Siddhāntas which were at odds with the puranic fantasy. See Minkowski (2001; 2004)

[7]The Candravākyani attributed to Vararuci uses the relation of 9 anomalistic months = 248 days. The larger cycles are 110 anomalistic months = 3031 and 449 anomolitic months = 12,372 days. Now the modern value of the anomalistic month is 27.55455 days on an average. Therefore, for say a longer cycle of 449 anomalistic month 12,371.99295 is much closer to 12,372. But then the pañcāṅga-maker would have to memorise 12,372 sentences, a herculean task.

the *Āryabhaṭīya* it is taken as 365.258681 days and in the *Surya* Siddhānta 365.258756 days. Such inaccuracies accumulate and impact the precision of the computations. Hence it is not surprising that with the passage of time the vākya engine of the pañcāṅga missed the beats. By then, for most pañcāṅga-computers using karaṇa, the astronomy behind it became opaque. Thirdly, the effects of gravitational perturbations of the Sun on the Moon or the gravity of Jupiter on Mars, and so on, were not considered at all in the traditional computations. Such factors also impacted on the precision with passage of time. With the ubiquitous circulation of mechanical clocks, errors became readily apparent in such phenomena like eclipses, occultations, and conjunctions, as the pañcāṅga computations became out of step with reality during the early nineteenth century.

3 *Pañcāṅkam* in Print

Numbers of pañcāṅga are printed, published and circulated widely in Tamilnadu today. The *Srirangam pañcāṅkam*, *Suddha Tirukanitha pañcāṅkam*, *Arcot Sri Seetharamaiyar Sarva Muhurtha pañcāṅkam*, *28th Number pañcāṅkam*, *Pambu pañcāṅkam*, *Sri Kanchi Sri Acharyar Madathu pañcāṅkam*, *Tirunelveli Vākya pañcāṅkam* and *Tirukoil Anushtana Vākya pañcāṅkam* are a few of them. Following the Tamil tradition, Tamil pañcāṅkam are also published in South East Asian countries such as Sri Lanka and Malaysia. The variations in the pañcāṅga are at a trivial level due to the location of the people for whom they are computed. More significant factors are the sectarian differences between various castes and caste sub-groups. At a more serious level, different pañcāṅga-makers use differing algorithms to compute the positions of celestial objects.

Even before the availability of printed pañcāṅga, there were extensive hand-written manuscripts on palm leaves and parchment paper in circulation (Bayly, 2000). These hand-written pañcāṅga were used to announce festivals and feasts, and also to alert the public to imminent celestial events such as eclipses for ritual observances. Often they were supplemented with astrological divinations and prognoses.

Chola inscriptions of the tenth to twelfth centuries inform us that Perungani (chief astronomer/astrologer) and gani (astronomer/astrologer) were appointed in each village to provide calendrical advice to farmers for their expanding agricultural operations (Aiyangar, 1994). Inscriptions by Uttamachola mention astrologers as *tirukkal*, and Rajendra's inscription calls them Perungani and Ganithadhirajan. These 'time keepers' appointed by the Chola kings carried with them Nāḷōḷai ('Nāḷ' = day; 'ōḷai' = palm leaf; literally 'calenders'), and were able to recite the changes in the movements of the stars and planets every day. These rural pañcāṅkam-computers were expected to compute the passage of time and assist farmers in selecting the right times to sow, water and reap their crops (Stein, 1980: 152). Marco Polo, the legendary traveller from Venice, mentions pañcāṅga written in Tamil (Marsden, 1818: 646).

Perhaps since the Chola period, village servants with hereditary rights, were provided for by land grants issued by the kings from time to time, and in return the village pañcāṅkam was expected to cast horoscopes for new-born child and expound the almanac, which more or less continued even when parts of southern India came under Islamic rulers.[8]

However the arrival of the printing press brought about significant changes in the preparation and distribution of pañcāṅga. Printing technology arrived in southern India during the late eighteenth century, and two printing presses were functioning in Madras and Tranquebar, both under missionary control. Then Tanjore, a princely state, acquired a printing press and in 1807 King Serfoji II established the Navavidya Kalasala-Varnayantra, a printing establishment that published works in Marathi, Tamil and Sanskrit during the 1800s (Nair, 2005, 2014). From this press came the first edition of the book *Raghuvamśa* in Sanskrit, and the main aim was to print copies of major purānic and literary works, in particular for the use of students studying in the schools and the miniature university called the Navavidya Kalanidhi Sala established by the King. Works in Persian, Arabic, Telugu, Sanskrit, Marathi and English on subjects such as the arts, philosophy, astronomy, fine arts and linguistics were published by this press. Meanwhile, the two printing presses in Madras and Tranquebar were largely used by the missionaries and the East India Company to print administrative and religious publications.

In the Madras Presidency, until 1835 printing was the exclusive privilege of the East India Company. Only the missionaries and the Government were permitted to licence printing presses, and Indians were prohibited from publishing or owning printed books. The floodgates for native publications were opened when Sir Charles Metcalf rescinded the restriction on Indians establishing printing press, and soon mass-produced pañcāṅga replaced the hand-written manuscripts that previously had been produced by panjangins for local use. A contemporary periodical captured the rapid change that took place:

> . . . old written almanacs produced by temple Brahmins were disappearing and the publication of these works has fallen into the hands of book-selling fraternity, a large and growing body. (*Friend of India,* 12 February 1842).

It is to be noted that one of the early publiations from the Tanjore printing press was a pañcāṅga, which over time was to become famous as the 'Tanjore' pañcāṅga. In fact, even before the arrival of printing, Tanjore palace had been supporting the computation of pañcāṅga, which were in circulation in the southern parts of India, especially in the Tamil region. Buchanan (1807: 202), who travelled through southern regions, observed that

> The . . . vulgar men of the world, throughout the countries in which Tamil language is spoken, use a solar year called Suryamanam in Sanskrit.

[8] See for example the *Hukkuma* issued by Tipu Sultan. During Tipu's reign the practice was to provide for the village astrologer from the public funds as a share from the tax collected (see Deshpande and Malini, 2008).

> The almanac here came from Tanjore, the great seat of learning in the southern part of India. The current year is as follows. It is reckoned the year 1722 as salivahanam and 4901 as kaliyugam. This, it must be observed differs one year in the former era and seven in the latter from the reckoning in Karnata.

A missionary who worked in the hinterland of Tamil region during 1770s wrote

> The Tamils reckon thirty-two kinds of pious actions . . . [including] the building of hospitals . . . giving food to those in employment is devotion . . . [and] supplying calendars or almanacs . . . (Beschi, 1871: 19).

That is, making copies of pañcāṅga and supplying them to others was considered a pious act, and rich and wealthy individuals were expected to provide support.

The missionaries and colonial officials had introduced the tradition of preparing and printing almanacs into India during the early part of the nineteenth century. From 1799, an almanac called the *Madras Register* was published in Madras, but soon the name was changed to *Madras Almanac*. Later it came out as the *Asylum Press Almanac*, until around the first decade of the twentieth century. This yearly volume continued to be published until its demise in 1935.

In addition to providing useful community information, such as births, deaths and marriages, and it also had short reports on domestic occurrences in the Madras province amongst the European settlers. The *Madras Almanac,* shaped on the lines of English almanacs, offered “. . . exciting glimpses into the secret and forbidden world of high politics while also supplying a fund of utilitarian information.” (Capp, 2004: 3). While such ‘official’ local almanacs were circulated, various other almanacs produced in England and America also were popular.

The European almanacs were divided into two sections, the almanac proper and the astrological prognostications. The almanac section contained astronomical and astrological data for the year ahead—a calendar, the times of sunrise and sunset, lunar cycles, the zodiac, eclipses, and saints’ days. Some editions gave two facing pages for each month. The right-hand page might be used to supply additional information, such as notable anniversaries, festivals and feasts (Capp, 1979, 2004; Chapman, 2007; Nicolson, 1939).

Naturally the *Madras Almanac* was styled on the then-prevailing customs of the homeland. Each month was given two facing folios. One side of the folio was a table that extended for almost two thirds of the page. This date-wise table gave the day the week, important events associated with the day, and so on. The remaining one third of the page was devoted to tables of information on astronomical phenomena, such as the rising time of the planets, conjunctions and lunar occultations. The meridian passage of the planets was also given. The facing page of this folio contained remarks on the weather, such as temperature, wind, and so on. It also had a table of phases of the Moon, perigee and apogee times, and the Sun’s right ascension and declination.

In the second folio of the month, one page had a table of data on the daily sunrise times for Madras, Calcutta and Bombay; and the Moon’s age, rising, meridian and setting times, and its semi-diameter. The facing page of this folio was left blank for the insertion of 'memoranda'. In this blank space the user could jot down the events taking place, or appointments, and use the almanac as a diary.

After all, the almanac served as a handbook for colonial administrators, hence it was imperative that they were aware of the impending native feasts and festivals, as much as their own ones. Therefore, the *Madras Almanac* devoted twelve pages to the 'Indian calender'. Against each of the Western months of the year, the dates of major festivals and feasts shown in the Tamil, Malayalam, Telugu and Mohamaden calenders prevailing in southern India were listed, along with any relevant specific remarks. The dates of the native festivals computed by the traditional pañcāṅga-makers were given in the *Almanac*. During the early nineteenth century the astronomical calculations for the *Madras Almanac* were prepared by Venkata Soobah Siddantha Shastry, the son of Authe Shashya Siddantha Shastry Pundit, the late native astronomer of the College of Madras.[9] One can conclude that the format and style of presentation of the printed Tamil pañcāṅga that emerged in the mid-nineteenth century drew upon the format and presentation of the European almanacs in circulation at that time.

One of the earliest printed pañcāṅga published in Calcutta during the 1830s was printed by a native blacksmith who was employed by the Serampore missionaries for many years in cutting punches for their mission press. He fabricated an iron press on his own, and using this contraption he set up a printing office and commenced printing. He soon found printing pañcāṅga to be more profitable, and in a few years embellished his publications with pictures of the gods and goddesses of the Hindu pantheon. By employing hawkers, bundles of these cheap publications were sold widely, and made the former blacksmith a substantial profit. After just a few years, in Bengal province "... the Hindu almanac enjoyed extensive circulation with 22 editions, amounting to not less than 1,70,000 [sic] copies ..." in 1867–1868, and the print run of the almanacs was "... second only to school text-books." (Ghosh, 2002: 4333 also see Ghosh 1998 and 2003). The Reverend J. Long (1859: xx–xxi) noted that pañcāṅga were amongst the most widely-publicised books, and remarked that

> ... the Bengali almanac is as necessary for the Bengali as his hooka or his pan; without it he cannot determine the auspicious days for marrying (22 in the year), for first feeding an infant with rice (27 days in the year), feeding the mother with rice in the fifth month of gestation (12 days), for commencing the building of a house, for boring the ears, putting chalk into the hands of a boy to teach him to write, when a journey is to be begun, or calculating the duration and malignity of a fever.

This phenomenon was not limited to Bengal. In the Madras presidency Murdoch (1865: 145) noted that pañcāṅga were "... published in large numbers, in various forms, and are widely circulated." While some of these publications were slim and cheap,

[9]This institution also was known as the College of Fort St George, was established in 1813 to train junior British civil servants before deployment in administration of native territories (see Basu, 1867).

> . . . others [were] large and profusely illustrated with pictures representing the signs of the zodiac, figures denoting the Sun in different months, etc. (ibid.).

Pañcāṅga like the *Pakya pañcāṅkam, Punjankum Visoovavasoo* (*Trustworthy Pañcāṅga*) were printed during the 1840s (East India Company, 1845, 1851). Seeing the commercial returns pañcāṅga publication offered, publishers came forward to reap benefits from the profitable business. In 1884, Konnur Manicka Mudhaliar established the Manonmani Vilasam Press exclusively for printing pañcāṅga. This yearly publication alone was adequate for him to make a living. Even today this pañcāṅga, the *Pambu Pañcāṅkam or Asal No.28 Pañcāṅkam*,[10] survives and has a worldwide circulation of more than 3 lakhs copies (i.e. more than 300,000). The *Maruthuvakkudi pañcāṅkam* traces its origin to pañcāṅga-computers such as Kanjanoor Appanaiyangar and his son Annavaiyengar during the 1850s. Pañcāṅkam publishers employed or teamed up with reputed pañcāṅkam computers. Jyothi Sastris in the employment of Princely States such as Tanjore and Pudukkotta were in repute, and thus Annavaiyengar, who adorned the court of Tanjore and Pudukkotta, and his *Kanjanoor vākkiyam,* became famous. This was so much so that the idiom ‘as if Kanjanoor pañcāṅkam fizzled’ came into colloquial use. (See Kane, 1968: 641–43 for multitude of almanacs in South India during early 20th century)

Printing offered options for organising and presenting complex information in tabular format with ease. Thus, the printed Tamil pañcāṅkams were fashioned on the English almanacs and were essentially monthly tables with entry for each day of the month. Necessary astronomical data and feasts and festivals for each month were tabulated in a two page folio, and the second part contained astrological prognostications. The prognostications offered predictions and observations based on astronomical and astrological data in the first section. Short notes on mythologies and purānas were printed, and when the lithographic technology improved they were adorned with spectacular and emotive illustrations. Almanacs that reported calendrical computations and astral events alongside tales and pictures from Hindu mythology were by far the most common form of printed literature throughout India by mid-[nineteenth] century.” (Bayly, 2000: 262–263), and

> With the slow improvement of communication, soothsayers and astrologers moved out into back lands and camps of the migrant tribals and low castes bringing the almanac and horoscope to new audiences. (Bayly, 2000: 253).

[10] This pañcāṅga always had 28 pages, and it was published from a premises having door no 28. Asal in Tamil implies ‘original’.

4 Tamil *Pañcāṅkam*: An Introduction

Although there are different pañcāṅkam traditions, there are certain commonalities in Tamil pañcāṅkam (for a detailed expose of the Tamil calendrical system see Fuller, 1980). Firstly, along with rest of the pañcāṅkam in India, the core elements (Pañca = five, and ñga = limbs/parts) remain the same in Tamil pañcāṅkam. These core elements (see Balachandra Rao, 2000 for a details and Sharma, 1998 for history) consists of

(a) Vāra, that is, the week day;
(b) Tithi, that is, the lunar day (which is indicative of the phase of the Moon);
(c) nakṣatra, that is, the position of the Moon in the nakṣatra division (or lunar lodge);
(d) *Yoga* (literally meaning ‘addition’), that is the time period when the longitudinal motions of the Sun and the Moon when added amounts to $13^{\circ}\ 12'$ or its integral multiple; and.
(e) Karaṇa, that is, half the period of a tithi.

All these details are computed for every civil day of the year.

Essentially, the Tamil calendar is a solar calendar, with aspects of the lunar cycle incorporated for fixing certain religious and temple festivals. The Tamil month begins when the Sun enters a particular iraci (rāśi-zodiac). Therefore, the number of days in a particular month does not remain constant or equal, although on the average the length of the year is 365 days. The number of days in a month can be as high as 32 or as low as 29. For example, the Tamil year ‘Jaya’ (2014–2015) had Chitirai 31, Vaikasi 31, Aaani 32, Aadi 31, Aavani 31, Purattasi 31, Aipaasi 30, Karthikai 29, Margazhi 30, Thai 29, Maasi 30 and Panguni 30, totalling 365 days.[11] The names of the Tamil months are almost the same as the lunar months (except Aani, which perhaps is a corruption of Agni, Jeasta) of northern Indian calendar, deluding many to think that both calendars are lunar.

Although the word pañcāṅga simply implies five elements, there is lot more to a printed pañcāṅkam than the mere listing of these core elements. A significant portion of the printed pañcāṅkam is occupied by the non-mathematical aspects of jyotisha, such as the derivation of propitious times for various religious and other karmas (acts), which are themselves based on astronomical positions of celestial bodies. Thus, astronomical data on the times of sunrise and moonrise, eclipses, conjunction, and occultations of planets by the Moon are included in addition to the core five elements.

Another aspect associated with pañcāṅkam is astral prognostication based on planetary positions. Among these astral beliefs, tyājyam is a unique concept in Tamil

[11]On the other hand, in typical northern Indian calendars the months are lunar (each month having either 29 or 30 days) and hence a typical year has only 354 days. By the periodic addition of an intercalary month (Adik masa) once in a while, the length of the years of northern Indian calendars are adjusted to coincide with the solar cycle.

pañcāṅkam. It literally means ‘to be avoided’ or ‘a nefarious duration of time’, and such durations are considered as inauspicious in general, or inappropriate for specific actions, like commencing long-distance travel.

There are three types of tyājyam: daily, monthly and nakshatriram. The daily tyājyam are Gulika, Yama ganḍam (the God of death in Indian mythology), and Rāhu kālam (the demon snake in the Hindu mythology that is supposed to eat the Sun during eclipses). The starting times and durations of all of these ‘kālams’ depend on the weekday as well as duration of the daytime of that specific civil day. No important ritual will begin during the highly inauspicious Rhāgukālam, and very important rituals will also avoid the Yamaganḍam. Visiting the house of a dead and such undesirable tasks are not supposed to be commenced or concluded in the Gulikan time period. The times of these specific periods are provided in the pañcāṅkam. The monthly tyājyam are also called as Kari Nāḷ, which are certain fixed days in each month. Then there are nakṣatra tyājyam, also called yogams.[12] There are three yogams in the second sense: amirtham (nectar), ccittam (auspicious) and maranam (death). Each of these lasts for 1/15th the duration of the nakṣattiram of the day. While the first two are considered auspicious, the third one is considered adverse.

A typical Tamil printed pañcāṅkam is a folio containing one sheet for each month, and these twelve pages contain most of the information ordinarily needed by the users. In a typical pañcāṅ kam monthly sheets, there is one entry for each day which records the day of the week, followed by the tithi, nakṣattiram, yogam and karaṇam, time of sunrise, together with the times at which these phenomena end on that day. For each day, concordance in English and Islamic Hijira calendars is also provided. Furthermore, whether the month is in the Uttarāyaṇa or the Dakshinayaṇa is also given.[13]

Then a ‘Remarks’ column provides information on days of fasts, temple festivals of major temples patronised by the readership, and eclipses, planetary conjugations and lunar occultations. Only small numbers of festivals are fixed by the day of the week or a date in the month. The majority of domestic festivals and ritual dates practised by individuals and most temples, and communal festivals which follow their own traditions, are largely based on particular tithis or nakṣattiram that fall on a fixed day. Thus, precise astronomical data with certain details are crucial for the fixing of festivals and ritual timings.

[12]This should not be confused with ‘yoga’ of the five core elements of Panchanga. In Tamil pañcāṅga, the Yogam is used in two senses. Firstly, it is the sum of the angle of the Moon and the Sun as explained above, while in the second sense it is the combination of the day of the week (vāram) and nakṣattiram.

[13]The Uttarāyaṇa is supposed to commence on the winter solstices and the Dakshinayṇa on the summer solstices, but due to the precessional motion of the Earth currently they actually occur about 21 days before the dates marked in the Tamil pañcāṅga.

An irachi cakkiram (zodiac table) is printed for each month giving the positions of the grahas (planets)[14] in the zodiac at the beginning of the month. The irachi cakkiram typically used in southern India is a central square surrounded by twelve smaller squares. Each of the smaller squares represents one irachi (30° of zodiac). As Tamil months are solar, for the whole duration of the month, needless to say the Sun remains in the same irachi. The position of the Moon is omitted as it moves around the zodiac once in 27 days. The position of the remaining seven grahas at the commencement of the month is inscribed on the irachi cakkiram. Usually in any 1 month most of the grahas will remain within the same irachi. However, if they move from one *irachi* to another (this is called graha peyarchi) during a particular month then the date and time of this shift is inscribed in the central square of the cakkiram.

Dates and times which are auspicious due to 'correct' planetary alignments, called cubha-Muhurtham (meaning, 'propitious timing') are also provided in the pañcāṅkam. Typically, the momentous ritual in traditional marriage ceremony would take place at the cubha-Mugurtham time. Elsewhere, in the almanacs are given details on how to compare the horoscopes of possible marriage partners; omens; and a host of other astrological and predictive information that are in vogue among the readership. Further, some pañcāṅkam catering for farmers provide prognostications of rainfall estimates, forecast pest attacks, and general predictions for the year. Some pañcāṅkams also provide divination on gecko sounds, and so on. In a nutshell, three aspects—calendrics, astrology, and divination—form the content of a typical Tamil pañcāṅkam.

5 Ragoonatha Charry: A Short Biography

Chinthamani Ragoonatha Charry[15] (Fig. 1) occupies an exceptional place in the history of modern astronomy in India, as the first Indian-born astronomer to publish a research paper, "The determination of personal equation by observation of the projected image of the Sun" in the *Monthly Notices of the Royal Astronomical Society* (Charry, 1859). Further, Ragoonatha Charry was the third Indian to be elected to the Royal Astronomical Society, and the first Indian to make a 'modern' astronomical discovery of a variable star, R Reticuli, in 1867. He also has been

[14] In Indian astronomy/astrology the Sun and the Moon are also taken as Grahas, as are two imaginary/shadow planets, Rahu and Ketu (the ascending and descending nodes of the Moon), which along with the five visible planets make the Grahas total nine.

[15] His name is spelt in various ways in the contemporary literature and later literature. While the obituary (Obituary, 1881: 180) records 'Chintamanny', his own submissions to the *Monthly Notices of the Royal Astronomical Society* were by Charey (Ragoonatha Charey, 1859) and Chary (Ragoonatha Chary, 1868b). A contemporary chronicler refers him as Cintamani Raghunatha Acarya (Dikshit, 1981: 181). Following Rao et al. (2009) we adopt the spelling of his name as it appears in his signature: Chinthamani Ragoonatha Charry.

Fig. 1 Ragoonatha Charry (en.wikipedia.org)

credited with the discovery of a second variable star, V Cephei, in 1878 (see Rao et al., 2009; Shylaja, 2012).

Ragoonatha Charry was born on 17 March 1828 (Dikshit, 1981: 181) and following in the footsteps of his father who was an Assistant at Madras Observatory, he joined the Observatory in 1847. In his 40-year service at the Observatory, he served under five Directors, commencing with T.G. Taylor in 1847, followed by W.S. Jacob, W.K. Worster, J.F. Tennant and N.R. Pogson. All of these Directors were impressed with his observational skills, especially N.R. Pogson, who 'took him under his wing'.

Ragoonatha Charry was not formally trained in modern astronomy, but learnt everything on his own. He excelled so much so that all the Directors under whom he worked expressed satisfaction. During early 1800s, when N.R. Pogson's request for European assistants were turned down by the India Office in London, he had to resort to three Indians who were then working in the Observatory (Sashoo Iyer, Ragoonatha Charry and Moottoosamy), to assist him in operating the instruments, and engaging in observations for the preparation of the southern star catalogue. The three were intensely trained in the use of the old meridian instruments for about a year, and once they became proficient, they were engaged by Pogson to independently "... determine instrumental corrections in the ordinary course of the night observations." (Sen, 1989: 258). With the death of the senior observer, Sashoo Iyer in March 1863, Ragoonatha Charry, through his studious efforts and "... better mathematical abilities and general aptitude for science ..." succeeded him (Sen, 1989: 257) and became the First Assistant in 1864, the highest rank an Indian could reach in this colonial establishment.

Crediting Ragoonatha Charry's role in the discovery of the minor planet Asia, Pogson (1861: 101) commented:

> . . . the positions marked R were observed and calculated by one of my native assistants, C. Ragoonatha Charry, whose aptitude in thus picking up a new and rather confusing method of observation and reduction, and that too in leisure time as a voluntary contribution to science, reflecting the highest credit upon him.

Owing to ". . . his personal exertions . . ." (Pogson, 1871) and methodical hard work, Ragoonatha Charry was able to make about 38,000 observations for the Madras catalogue of stars. During the 'Great Indian' total solar eclipse of 18 August 1868 Ragoonatha Charry assisted Pogson in the study of the prominences, polarisation of the light of the corona, and micrometric measurements of the bright lines in the corona. One outstanding outcome of these observations was that Pogson noticed that the supposed D line of sodium was misplaced, suggesting the presence of a new element—later named helium (see Nath, 2013). Pogson (1871) also observed that Ragoonatha Charry possessed ". . . ready skill as an observer, combined with accuracy and speed in computation, and a fair and useful amount of self-acquired mathematical knowledge . . ." and that until ill health impaired him, he was ". . . in-valuable in the Observatory." Ragoonatha Charry also led a observational team during the Great Indian Total Solar Eclipse of 1868 (See Pogson 1868). Keeping his contributions in mind, Pogson and the noted amateur astronomer E.B. Powell, FRAS, who happened to be the Director General of Public Instruction in the Madras Presidency, recommended Ragoonatha Charry for membership of the Royal Astronomical Society, and he was elected a Fellow in 1872.

Ragoonatha Charry was not only a professsional astronomer, but he also endeavoured to popularise science. Whenever the occasion warranted, he wrote in vernacular languages, and his booklets were published in Tamil, Telugu and Kannada, and reach out to the larger masses (see entries in the References section of this paper). He also gave popular talks for the benefit of the public and had a modest observatory at his house, which he used to provide views of the heavens for curious native pañcāṅkam-makers and astronomy enthusiasts in order to convince them of the need to use 'modern' methods when computing pañcāṅkam. Thus, Charry (1874: 7–8) wrote:

> I keep at home [astronomical instruments] expressly for the purpose of explaining to our countrymen their nature and use. One of them is a five foot equatorial telescope through which I will show you the Moon, some of the planets and stars tonight . . .

When the new series of *Madras Almanac* was commenced as the *Asylum Press Almanac* in 1862, the publishers sought the services of Ragoonatha Charry to prepare the astronomical tables and pañcāṅkam for inclusion in the *Almanac*. Perhaps, this experience gave Ragoonatha Chary the confidence to commence his own pañcāṅkam written in Tamil and Telugu, and based upon modern astronomy.

The first issue of Ragoonatha Charry's pañcāṅkam, called the *Thirukanitha Pañcāṅkam*, was brought out during 1869–1870, just a few years after he commenced editing the Hindu almanac section of the *English Almanac*. The *Thirukanitha Pañcāṅkam* (see Fig. 2) was published annually by him up until his death in 1880. Perhaps his son Chinthamani Raghava Charry assisted him in publishing the last issue. Subsequently his two sons continued the publication, and

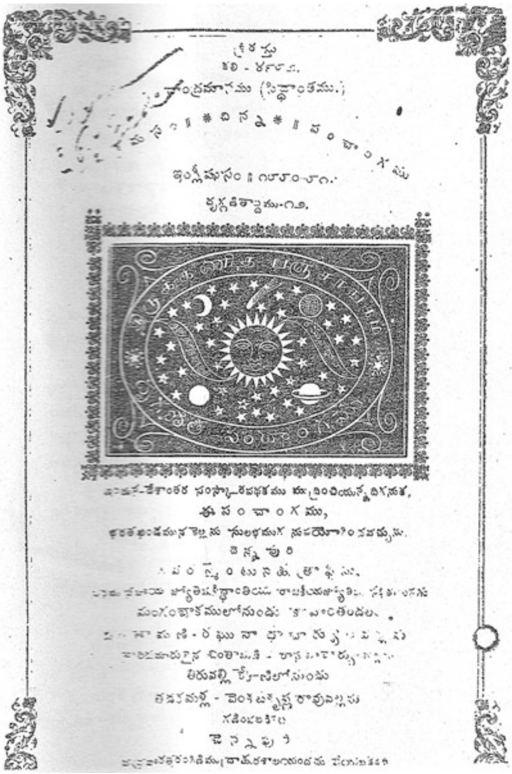


Fig. 2 The title page of the *Thirukanitha* ***Pañcāṅkam.*** (Courtesy: Theosophical Society Library, Chennai)

with the death of his elder son, C. Raghava Charry, in 1890 the publication was carried on by his younger son, Chintamani Venkatachari, and brother-in-law, P. Raghava Charry (who by then was a First Assistant at Madras Observatory).

While he was alive Ragoonatha Charry complied a periya (large) edition of the *Thirukanitha Pañcāṅkam*, however later only a siriya (short) *Thirukanitha Pañcāṅkam* was published by his sons. This *Pañcāṅkam* was also called the *Nungambaukam Almanac* or the *Nākṣatra Office Pañcāṅkam* (referring to the place of publication). However, the zeal with which Ragoonatha Charry published the *Thirukanitha Pañcāṅkam* did not last long after his death. Thus, in 1910 Ramanan (1910: 376) noted that the *Nungambaukam Almanac*

> . . . has fallen considerably from the pedestal of purity and accuracy which it once occupied, when its founder was alive and ready to bring to bear on its calculations his first-hand scrutiny and practical skills as astronomer.

6 Ragoonatha Charry's *Pañcāṅkam*

As we saw in Sect. 2 above, originally the traditional pañcāṅga were of little observational accuracy because of approximations made in the karaṇa rules, composed centuries earlier. Inaccurate values for constants also were used, and the effects of gravitational perturbations of the Sun on Moon or the gravity of Jupiter on Mars were unknown. Thus, by the mid-nineteenth century, the vākya-based pañcāṅkam were perceptibly out of step with the actual astronomical events.

The abject failure of the traditional predictions to match the modern computations, or even naked eye observations, was readily apparent and often embarrassing during the second half of the nineteenth century. Pañcāṅkam-makers from the town of Aska in the zilla Ganjam and Thanjavur had predicted a solar eclipse on 18 June 1871, and had computed the magnitude of the eclipse as visible from India. Indeed, on that day there *was* a total solar eclipse, but it was far away, near Australia and Pacific Ocean and was not to be visible from anywhere in India (Charry, 1871: 12). Perhaps the monumental failure of the traditional pañcāṅkam-makers to realize the inadequacies of vākyas to provide the required accuracy when compared to what the modern astronomy was able to offer in 1850s galvanized Ragoontha Charry into action.[16]

In this section, we briefly describe the features that forms part of the Ragoonatha Charry's *Thirukanitha Pañcāṅkam* (see Fig. 3). This *Pañcāṅkam* was titled the *Thirukanitham* (sometimes corrupted to *Tirukkanda*) *Pañcāṅkam* or the *Dṛggaṇita Pañcāṅkam* in Tamil (where *Tiru* = *Sri*, an honorific, and *Kanitham* = mathemati-

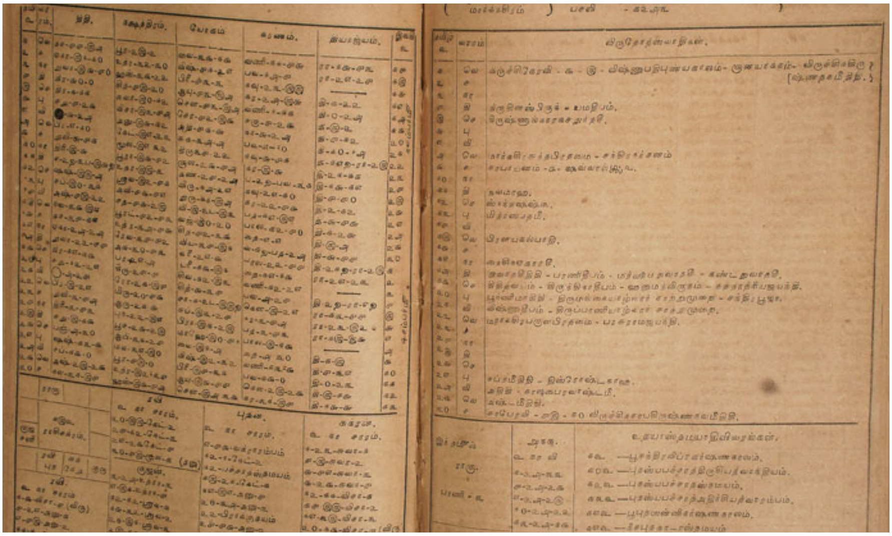


Fig. 3 Two folio pages of the Ragoonatha Charry's *Pañcāṅga*. (Courtesy: Theosophical Society Library, Chennai)

[16]We should note that Ragoonatha Charry was not alone in this, as the movement for Dṛggaṇita Pañcāṅga also was supported by Bapudev Sastri, Nilamber Sharma, Kero Lakshman Chhatre, Vishnu Ragunath and Khetkar Madhab Chandra Chatterjee in other parts of the country.

cal), and the *Dṛgganita-Panchangamu* in Telugu. While Ragoonatha Charry wrote the Tamil version, Tadakamalla Venkata Krishna Rao from Triplicane helped him prepare the Telugu version. This *Pañcāṅkam* was printed at the Vyavahara Tarangini Mudrakshara Sala in Chennapuri (i.e. Madras), and was published annually in Tamil and Telugu following the norms and formats of other contemporary printed Pañcāṅkams for about three decades from its inception in 1869–1870.

The Tamil term *Thirukanitha* can be read also as a colloquial corruption of the Sanskrit term *Dṛggaṇita*, which usually refers to astronomical calculations (*gaṇita* = that which is reckoned) that are based on, or corrected by, observation (*Dṛg* = *Dṛk* = *Dṛś* = observe). This tradition of Pañcāṅkams stood in direct contrast to the traditional vākya paramparā (traditional) Pañcāṅkams in vogue at this time. It computed the elements of the Pañcāṅkam, such as tithis, nakṣatras, times of sunrise and moonrise, eclipses, other planetary conjunctions, and occultations, using modern astronomical tools and computational methods.

Ragoonatha Charry’s *Pañcāṅkam* adopted the format of tabular presentation of pañcāṅkam elements in its style of presentation.[17] For the Tamil year, the *Pañcāṅkam* provides the corresponding Gregorian, Fasili and Hijra dates, as well as those of the Kali and Kolam eras. Monthly folio sheets tabulated the five core elements of the *Pañcāṅkam* along with tyājyam elements peculiar to southern Indian pañcāṅkam tradition. One of the tables in Charry’s *Pañcāṅkam* provides the sunrise time, time at noon and sunset times on the 1st, 11th, and 21st of each month for Madras in hours and minutes. Furthermore, one folio provided a table of moonrise times for each day and also the date and time of uccha (the Moon at apogee) during the month; the rise time of the planets, and select nakṣattirams, which are beyond the five core elements, but were necessary for astrological and divination interpretations.

Further circumstances at the time the Sun moved from one iraci (zodiac) sign into another during that year were computed and based on this the divinations for the month were provided. In like manner, taking into account the movements of the planets from one iraci to another during the year, divinations were computed. As the year began at a particular combination of planetary positions, divinations for the whole year also were worked out. Also listed are Vivaha Muhurta, the dates and times appropriate to conduct marriage ceremonies. A list of dates and times identified as Duṣṭa kālam (unlucky) and amiritha yogam (lucky) is provided. In these listings there was not much that differed from other pañcāṅkam, except for the computation of the astronomical position of celestial objects based upon modern astronomy.

What was particularly distinctive about Ragoonatha Charry’s *Pañcāṅkam* was the presence of a popular description of the important astronomical events (e.g. see Fig. 4) with extensive scientific illustrations (Fig. 5) of the phenomena,

[17]We were able to access compilations of pañcāṅga prepared by Ragoonatha Charry from 1869–1870 to 1879–1880. All of these were in Telugu, except for one (for 1873–1874), which was in Tamil. The overall formats of the Telugu and Tamil versions were similar. The descriptions presented in this paper are based on the Tamil version for the year 1873–1874.

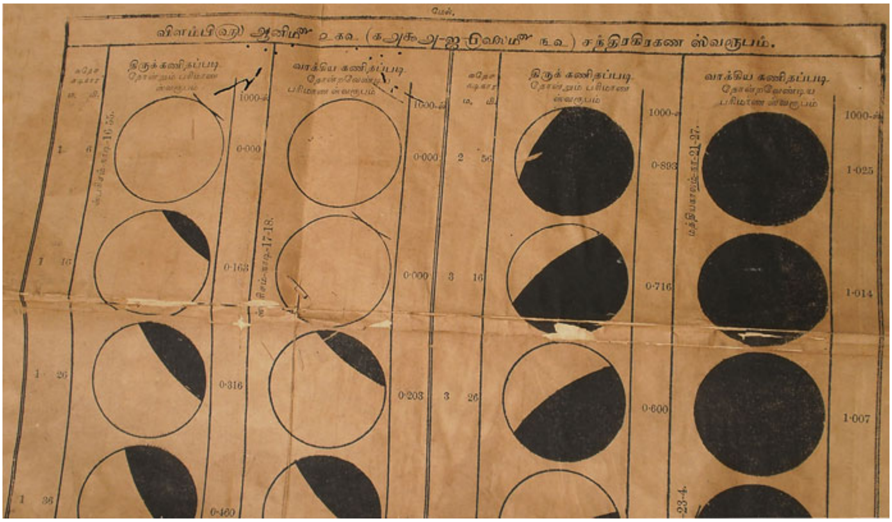
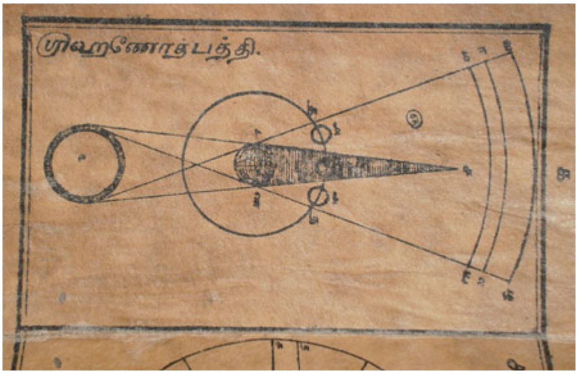


Fig. 4 Ragoonatha Charry provided circumstances of the lunar eclipse visually as computed by vakya and his drg method so that the readers could satisfy themselves. (Courtesy: Theosophical Society Library, Chennai)

Fig. 5 Ragoonatha Charry used illustrations to explain the celestial phenomena in simple manner. (Courtesy: Theosophical Society Library, Chennai)



circumstances, and tables of data for different towns and cities. In addition, it contained detailed quotes from sacred texts and religious authorities for the need to align the computations with the observations, and it emphasised the dṛg philosophy. A specific table provided a list of observable astronomical events, such as occultations, and conjunctions of planets visible to the naked eye (Fig. 6).

Note that this Pañcāṅkam is in Tamil and uses now non-extant Tamil numerals notations. The page numbering, timing, and all the numerical data (including fractions) are noted in the Tamil numeral system. Although, conforming to the

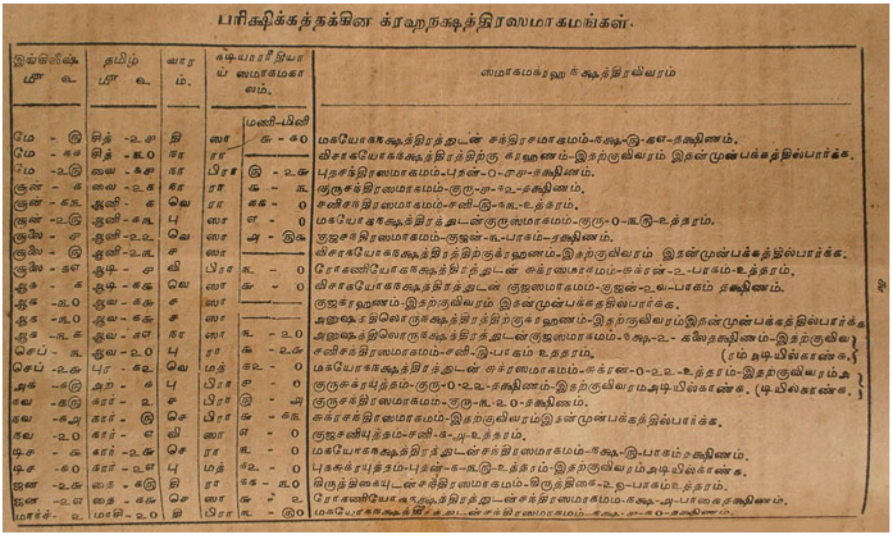


Fig. 6 Important celestial events accessible to the naked eye were tabulated and presented, again enabling readers to check if the drg computations were indeed accurate. (Courtesy: Theosophical Society Library, Chennai)

Government regulation[18] to provide corresponding dates in the Gregorian calendar, English months and dates are given, but in Tamil numerals. The primacy accorded to the Tamil numerals in the tables indicates that most readers were still using them in their daily lives and were quite familiar with them.

Ragoonatha Charry's *Pañcāṅkam* used three different units for time measurements. For elements like tithis, etc., the traditional and familiar time measurement of nāḷikāi/vināḍi was used.[19] The use of nāḷikāi and vināḍi was essential for the purpose of rites and rituals. These are the elements that are used for arriving at the propitious and appointed time for the performance of rites, etc. In places, in particular related to the Sun, the aṅgulam (the shadow length of the gnomon) is provided. On the other hand, curiously, for events that were observable by readers, such as occultations and so on, clock times in hour and minutes are provided. Ragoonatha Charry explicitly states that these times are provided to enable readers to use their own watches and clocks to verify the veracity of the computations presented by him.

[18]On 26 March 1878 the Madras Government issued a proclamation that time-keeping henceforth would be based upon the standard Christian calendar in all official records and deemed it necessary that all the pañcāṅga published in its jurisdiction provide corresponding dates, months and years in the Gregorian calendar system, along with any preferred traditional system. (*Proceeding No 521*, 1878).

[19]In this system, a day consists of 60 nāḷikāi (or nāḍikā) and one nāḷikāi is 60 vināḍi. Therefore, one nāḷikāi is approximately 24 min.

Ragoonatha Charry's *Pañcāṅkam* also contains many pages devoted to adducing and advancing arguments aimed at convincing the readers of the appropriateness of the *Thirukanitha Pañcāṅkam* for both social and sacred purposes. Select Sanskrit quotes from religious sources written in the Tamil-Granth script are provided with translations. While on the one hand Purānic stories such as Rāhu/Ketu are shown to be mere allegories and should not be taken literally, interpretations are adduced to show that only the dṛg system is appropriate and sanctioned by Dharmaśāstras. Furthermore, extracts from readers' letters certifying the accuracy of earlier predictions are reproduced, along with statements from public persons on the propriety of the tirukanitha computations for religious purposes. Scathing replies to objections by other pañcāṅkam-computers are also given.

After only a few years, Ragoonatha Charry Thriukanitha method of pañcāṅga computation received a wide reception and many pañcāṅkam-makers came forward to support his endeavours. Karthikeya Iyer, a Jyotis, came all the way from Jaffna in Ceylon and was tutored by Ragoonatha Charry's son, Venkata Charry, and he then computed *Thirukanitha pañcāṅkam* for the Ceylon region. Likewise, Sundareswara Srautigal, a well-respected Professor of Mathematics at Tiruvadi Sanskrit College and was impressed, and convinced of tirukanitham after checking the events predicted by it. He commenced publication of his *Thirukanitha Pañcāṅkam* in the Thanjavoor region, and his son Viswanatha Srautigal continued the tradition. Prior to this, Professor Sundareswara Srautigal and his family had been preparing the *Kumbakonam Mattaththu Pañcāṅkam* for many years.

As the correct computation of tithis, nakṣatras and other features of pañcāṅga were crucial for religious and cultural practices, naturally the dispute reached the doors of religious institutions in southern India, the Sankara mutt in Kumbakonam (which was later shifted to Kanchipuram) and the Ahobilam mutt (a southern Indian Vaishnavaite sect that considered Tamil hymns, as equal in authority to those of the Vedas. Ragoonath Charry belonged to this sect). The Kumbakonam mutt organised a sadas, an assembly of experts and people of standing, convened by a reputed religious head to decide on contentious issues related to the interpretation of śāstras.

This sadas was scheduled for 22 February 1873 to examine the appropriateness of adopting the *Thirukanitha Pañcāṅkam* for religious purposes. As the invitation arrived late Ragoonatha Charry did not attend, but Sundareswara Srautigal was present to submit the case for thirukanitham (Charry, 1873: 10). In the debate, Karunkulam Krishna Josiyar, another reputed Jyotis, argued against the thirukanitha methodology for computation of the pañcāṅga and favoured the use of the age-old vākyas. Asserting that the *Thirukanitha Pañcāṅga* was computed assuming that the centre of the Earth and the centre of the celestial sphere were one and the same, Krishna Josiyar (1868) argued that as per the Siddhānta, and in particular the Nīlakaṇṭha Siddhānta, the centre of the Earth was offset from the centre of the celestial sphere.[20] Furthermore, he asserted that for computing tithis and other pañcāṅga elements accordance with observation was not necessary and that the vākya results were sacrosanct for religious observations.[21]

Sundareswara Srautigal showed that the vākyas pañcāṅga prepared by various pañcāṅga-computers differed from one another in their computations, even with basic elements such as the times of onset of tithis and so on (see, for example, Charry (1871: 32), a table comparing the predictions made by other vākya pañcāṅga, which were not only incorrect but also differed with one another). Sundareswara Srautigal made a convincing case for using the *Thirukanitha pañcāṅga*, and argued that only dṛg could give the desired precision.

However, this matter was not resolved at the time, and so another sadas was held during December 1877. After examining the arguments, intriguingly the mutt did not stand in support of the orthodoxy of the Krishna Josiyar, but supported the reform proposed by the Dṛg School, and concluded that for religious observance one should adopt the thirukanitha method for the computation of tithis, nakṣatras and so on. On 13 December 1877 the mutt issued a srimugam (message of blessing) and authorised the publication of the *Tirukaitha Matathu Pañcāṅkam* (the mutt's *Dṛg pañcāṅ*g).[22] In like manner, soon the Ahobila mutt also endorsed the *Thirukanitha Pañcāṅkam.* Following these developments, the Government of Madras issued an order that only Thirukanitha Pañcāṅkam should be practiced with registration of documents (Proceedings No 521, 1878). [See Venkateswaran (2009) for details, and a discussion of the secularisation of time, reform of pañcāṅga and the emergence of an industrial society in India.]

Today most pañcāṅkam-makers candidly admit that they use the data computed from the positional astronomy centre in Kolkata for computing elements such as eclipse circumstances, and so on. Even most vākya pañcāṅga are computed using data from the positional astronomy centre with respect to eclipses, but follow the vākya rules for other, not so easily-observable, pañcāṅga elements.

7 Indian Modernity and Ragoontha Charry's *Pañcāṅkam*

While the study of history of pre-colonial and pre-modern astronomy in India is laced with both Indological perspectives and Sanskrit scholar-ship, recent trends emphasis the trans-cultural nature of pre-modern astronomy with clear evidence of

[20]Indian astronomy used both the epicycle model (with the Earth at the center) and the deferent model where the center of the Earth was not at the center of the celestial sphere for the computation of the position of the planets.

[21]Nīlakaṇṭha, interestingly, was one of the progenitors of a new school, the Dṛggaṇita system. His cosmological model is said to be semi-heliocentric, that the inner planets revolved around the Sun and the exterior planets revolved around a point in space away from the centre of Earth (see Ramasubramanian et al., 1994; Sarma, 1972).

[22]However, some rival mutt, like the Sringeri Mutt, were livid, but the controversy that Ragoonatha Charry engendered will be the topic of another paper.

interactions between Indian, Babylonian, Greek and Islamic (Arabic) regions. The encounter of modern astronomy (and science) in a colonial settings is a different quest. While the Eurocentric diffusionist perspective presented it as a progressive foisting of 'Western' science in what was seen essentially as a 'stagnant' native society, in recent scholarship there is a critical shift away from simply seeing modern science as being diffused from Europe to India. While some scholars have explored the colonial imperatives in the introduction of modern science into India (see Baber, 1996; Kumar, 1997; 1991), others have attempted to understand the interaction of traditional Indian and modern Western systems of conception of the cosmos in the context of colonialism (see Prakash, 1992; 1999; Raina and Habib, 2004).

In the 'science in colony' scholarship, engagement between Europeans and Indians has been largely understood more as a process of philosophical rationalisation reconciling old and new forms of knowledge, whereas recent scholarship stresses cross-cultural negotiations within Indian responses to Western science. Minkowsky (2001; 2004) for example, examines the attempts by Benaras pandits to modify the cosmologies of the purāṇas and siddhāntas and how they sought to produce a synthetic cosmology that would fit in with the Copernican model of modern astronomy. Both the Jesuit savants and the savants of the Enlightenment saw 'native' society as being back-ward and steeped in superstition. Drawing on the work of the French astronomer Bailly, Raina (2000: 276) says the framework adopted by such scholars was in the mode of "... classical diffusionist theory of transmission of knowledge ..." and gave an image of Europe as the "... home of scientific truth ... [while the] non-West was the vast continent of darkness and superstition." On the other hand, Bayly (2000) argues that the eclectic engagement between European and Indian scholarship led to a reassertion of pride in the Indian tradition during the late colonial period.

Nonetheless, one of the key limitation has been an over-emphasis on engaging with the relationship between traditional knowledge claims and modern science, and the concomitant process of philosophical rationalisation. The 'practical' aspects of modern science are given scant attention. Refreshingly Joydeep Sen (2014: 192) shows that the engagement during the colonial period was both "... philosophical and practical." After all, according to Themistius, who was Aristotle's commentator, ultimately, "... that which exists does not conform to various opinions, but rather the correct opinions conform to that which exists." (cited in Rescher, 1987: 131). Whatever may be the issues connected with philosophical reconciliation, the practical superiority of modern astronomy in accurately computing celestial phenomena in advance, as compared to the traditional methods, have to be factored into any understanding of the encounter of modern science by native *literati* in a colonial setting.

As an astronomer well versed in modern astronomy, its theory, instrumentation and so on, Ragoonatha Charry had to face twin challenges, philosophical and practical, in order to reconcile the progress of modern astronomy and the dismal state of traditional computations. Firstly, computational methods of pañcāṅkam had to be improved to give desired levels of accuracy with respect to the planetary positions and predicttions of celestial events such as eclipses. Secondly, the primitive purāṇic cosmology, that held the Earth to be a flat disc, the Moon to be twice as far away as Sun, and so on—directly in contradiction to modern astronomy—somehow had to be reconciled.

When Ragoonatha Charry wrote pamphlets in vernacular languages on phenomena like eclipses or the 1874 transit of Venus, his employer and patron N.R. Pogson commented that they were

> . . . well calculated to instruct and at the same time to dispel the superstitious fears of the ignorant native masses, while it goes further and by its quotations from the puranahs, and other weighty arguments show that the absurd notions which render eclipses so alarming are not authorized by their own religious writings.

Furthermore, Pogson (1871) commented that when Ragoonatha Charry compared the computations of the traditional pañcāṅga-makers and modern methods, he showed

> . . . by comparison of results, the vast inferiority and great inaccuracy of the calculations of Hindu astronomers and [therefore] urges them to abandon their worthless methods and antiquated tables and avail themselves of modern improvements.

Thus, reading Ragoonatha Charry’s efforts as aligned with the civilising mission of the Colonial Government, Pogson recommended that the Government provided support by extending their funding. But in the eyes of colonial officials, Ragoonatha Charry’s mission may have seemed radical, as it aimed at breaking away from the past and directing native society into a future conceived by the colonial imagination. However, close examination of Ragoonatha Charry’s actions seems to suggest that what he wished was not replacement of the ‘traditional’ by ‘colonial’, but a rejuvenation of the rational components of Indian tradition, and thereby an endeavour to reform it from within. While the observatories like the ones at Madras remained in effect ‘alien outposts of a foreign science’ serving primarily the British science (Ansari, 2011), it was the efforts of people like Ragoonatha Chary that led to their utility go beyond colonial, enabling domestication.

The Dṛg (thirukanitha) advocated by Ragoonatha Charry was not conjured up out of thin air, but had a glorious history in Indian astronomy. The Dṛggaṇita system had its origin in medieval Kerala, where between the fourteenth and sixteenth centuries a group of teachers, astronomers and mathematicians popularly referred to as the ‘Kerala school of Mathematics’ by present-day historians of science today attempted to solve problems in astronomy. In order to achieve this they created sophisticated mathematics, including power series and pre-calculus (see Joseph, 2009; Sarma, 1963).

It was well known that there was always a small margin of error in the astronomical constants given in traditional texts, hence over time the calculated planetary positions or celestial events (such as the rising time of the Moon) no longer matched the observed planetary positions. But because of the great authority of texts such as the *Sūrya Siddhānta* or the *Āryabhaṭīya*, traditional people were hesitant to change the astronomical constants given in them. Thus, for example, the parahita system of calculations used in Kerala state in southern India, promoted by Haridatta, was based directly on the astronomical constants given in the *Āryabhaṭīya*. About 800 years later, obviously the computations and the observations had perceptible deviations.

Parameśvara (ca. AD 1360–1465), one of the astronomer-mathematicians belonging to the Kerala School of Mathematics, was aghast at such deviations introduced in the Dṛggaṇita system, which incorporated corrections based on observations.

Parameśvara's Dṛggaṇita theory was a development that took place in the light of his continuous comparison of computations and observations. A resident of Ālattūr, near the river Bhāratappuzha, he embarked on a massive observational quest of eclipses from Saka 1315 (AD 1393) and made careful observations of more than thirteen eclipses between 1393 and at least 1448. He used his observational data that spanned about 55 years to illuminate his computational theory of eclipse prediction, and his Dṛggaṇita system (see Sarma, 1963).

Upon examining the works of Nīlakaṇṭha Somayāji (AD 1444–1545), Narasimha (2007) observed that the keywords deployed to describe the works included parīksā, anumāna, gaṇita, yukti, nyāya, siddhānta, tarka and anveṣa*n*a. Thus, the School appeared to "... put great value on careful observation and skill in development of algorithms and use of computation ..." (Narasimha, 2007: 521), rather than displaying blind adherence to tradition. Thus, it was not the case that Indian astronomers were unaware of the limitations of the systems such as vākyas. Having realised the limitations of the traditional computational algorithms, the Veṇvāroha and Sphuṭacandrāptiḥ of Madhava and Saṇgamagrāma composed around AD 1350 (Sarma, 1956, 1973) and the karaṇapaddhati of Putumana Somayaji composed around AD 1732 (Koru, 1953) provided better methods for computing the true positions of celestial bodies. However, these developments were not taken into account by the traditional pañcāṅga-makers, and did not help revise the vākyakaraṇa in actual use. What is more, steeped in the belief of the divine revelation of the vākyas, most pañcāṅga-makers in the Tamil region were not even aware of these developments.

Perhaps the burgeoning need for pañcāṅgan or gani (as pañcāṅga-computers were known in the medieval southern India) and the need for an easy tool for computation prompted astronomers like Vararuci and Sundararaja to write karaṇa works like the vākyakaraṇa and the vākya panchadhyayi in the first place. The agricultural and administration expansion under the Chola reign during the tenth to fourteenth centuries required time-keepers, thus pañcāṅga-makers. The vākyas (karaṇa) were perhaps prepared to serve as handbooks for the local pañcāṅga-computers. The vākyas system that evolved in southern India through these works was merely an easy tool for computations, and was not expected to work forever. Many centuries later, pañcāṅga computing had largely been reduced to memorising the vākya and blindly computing celestial events like eclipses or tithis or making predictive astrology about, for example, rainfall. Most were not aware of the history of the system nor the mechanisms behind the vākya method. Hence most of the traditional pañcāṅga-makers took an orthodox position in the debate during the nineteenth century as they were not familiar with the spirit of the Dṛg school of Kerala, which formed the basis of the vākya system in the first place.

Perhaps unknowingly, Ragoonatha Charry drew on the rational ethos of Kerala’s Dṛg School[23] when he asserted that as far as exact sciences like astronomy went, the only observational conformation was the pramāna (acceptable epistemological evidence). The *Parameśvara* emphatically stated that the positions of

> . . . the planets derived according to the Parahita [system of computation] are found to be different [from their actual positions] as seen by the eye. And, in authoritative texts [śāstras], it is said that [only] positions as observed [should be taken] as the true ones . . . [and further, the positions of the planets] are the means of knowing the times specified for [the performance of] meritorious acts . . . [and] times calculated from incorrect [positions of planets will not be auspicious for those] acts. (Sarma, 1972: 2).

Further Ragoonatha Charry seems to have been highly influenced by a ‘traditional’ text that had been ‘discovered’ during his lifetime. This was the *Bījopanaya*, a Sanskritic manuscript in the possession of Saraswati Bhandar of Melukote. Initially this was mistaken for the *Bījagaṇita* (*Text on Algebra*) by Aufrecht in his catalogues of Sanskrit and was subsequently found to be an independent work on astronomy attributed to Bhāskara II.[24] This work, with a commentary called *Vāsanābhāṣya*, was first published in 1876 by Ragoonatha Charry and T Venkatakrishna Raya in Madras. Subsequently, in 1926, Ekendranath Ghosh brought out an edition with an Introduction. Both the editions had a short work called *Tithiṇirnayakārikā* by Srinivasa Yajvan, as an Appendix. Both editions asserted from the colophons in the manuscript, that the author of the work was Bhāskarācārya II.

The *Bījopanaya* enunciated two corrections that should be applied to the calculated value of the longitude of the Moon by applying the usual equation of the centre, to make it more accurate. Of these two corrections, the first makes up for the deficiency in the equation of the centre when compared with the correct one, and the second is an equivalent of the inequality called variation which, when applied to the Moon, will take it nearer to its true position in longitude (Mukhopadhyaya, 1930). Thus, the corrections that Ragoonatha Charry desired in the traditional pañcāṅga computation of tithis could be seen to have been sanctioned by the authority of the *Bījopanaya*.

Bhāskarācārya II states his *raison d’être* for (allegedly) writing the *Bījopanaya*:

> I wrote the [Siddhānta Śiromani] following the ancient texts alone. But this is not sufficient to give the correct positions of the planets in order to find the auspicious moments for the

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[23]The texts of the Kerala School had by then been ‘discovered’, but they were not recognised and went into oblivion for many years (see Whish, 1835). The works of the Kerala school were only edited, published and studied by historians of astronomy since the 1960s when K.V. Sarma began publishing critical editions of some of the important works—see Sriram (2010) for a brief sketch of Sarma’s contribution towards the rediscovery of the ‘Kerala School’. Thus arose the often-cited claim that after Baskara II, Indian astronomy and mathematics ‘stood still’ (e.g. see Parameswaran, 1992).

[24]However Sastri (1958) refutes the authorship by Bhāskara II, largely due to the apocryphal style of presentation as well as errors, and he believes it to be a later composition. In his *Siddhānta Dharpana*, Samantha Chandrasekhara also cites the *Bījopanaya*, implying that it was a text known to traditional astronomers during the nineteenth century (see Uphdyaya, 1998(II): 329).

> different rites enjoined by the śāstrass. So I am writing the [Bījopanaya]. (cited in Sastri, 1958: 401).

The *Bījopanaya* asserted that tithis got after applying the corrections were more appropriate, as they provided a much more accurate position of the Moon. Furthermore, the *Vāsanābhāṣya* averred that

> In mathematical sciences (such as astronomy) holy tradition is authority, only in so far only as it agrees with demonstration … whichever agrees with present observation must be admitted. (cited in Charry, 1868a: 4).

These could be interpreted to support pañcāṅga reform. In particular the verse that says "If the Gaṇita of the country does not give the necessary dṛksphuṭa there is nothing wrong in taking the almanac of another country …" (cited in Sastri, 1958: 409) makes it amply clear that Bhaskaracharya could use the *Nautical Almanac* to compute the dṛk pañcāṅga.

During 1850s pundits from Benaras College such as Bapudeva Sastri were becoming popular among Indian reformers and Indian intellectuals (Gosha, 1881: 453–455). Schooled by Lancelot Wilkinson, a colonial official and enthusiastic student of Sanskrit astronomy, these select traditional pundits were well versed in Indian mathematics and astronomical literature, and they tried to bridge the gap between modern heliocentric astronomy and geocentric traditional Indian astronomy on the one hand and the virodha (inconsistency) between a spherical Earth in the Siddhāntas and the flat-circular Earth in the Purāna on the other (Minkowski, 2001; Sarma, 1995–1996). Inspired by the pragmatic enlightened orientalism of Wilkinson (1834), that to effect modernity, one must first invoke antiquity, these pundits drew specifically on Bhāskara's traditions of scientific rationality, in particular his insistence that in matters of śāstras such as astronomy, observation prevailed over authority. Consequently, works of Āryabhaṭa and Bhāskara II were celebrated and published approvingly by Hall and Bapu (1859) and Sastri and Wilkinson (1861). Along with Wilkinson, they were convinced that the

> … distance from Bhāskara to Copernicus, from geocentrism to heliocentrism, was scientifically insignificant, and that progress could be effected from within the scientific traditions of India without rejecting India's antiquity for Europe's modernity. (Young, 2008: 57).

The dogma of the orthodoxy, seen to adopt literal interpretations of the sacred texts and retain popular cosmology—which besides being geo-centric also perpetuated a notion that the Earth was a flat circular plane—was seen as the main hurdle for revitalisation and modernisation of Indian astronomy. Ragoonatha Charry appears to have been in correspondence with him and cites him approvingly (see Shylaja, 2009, 2012).

Ragoonatha Charry's intentions were not confined to publishing pañcāṅga on his own or giving out franchises to others, and reaching out to other regions of India and other sects. He set himself the task to replicate what Varacuci and Sundararaja did during fourteenth century for the pañcāṅga computation. In a public lecture in 1874 he confided that he had already begun writing a treatise (to be styled the *Jyothisha Chinthamany*), "… containing rules, formulae, and tables based on the English methods of calculation for the guidance of our Siddhāntis." (Charry, 1874: vii). This manual, or handbook, was to have modern astronomical computations,

> . . . together with what is proper to retain from our own works, and thus to construct a manual accessible to Hindu astronomers, and sufficient for all the purposes to which Astronomy is applied in our social and religious practices. (Obituary, 1881: 180).

His intention was to go beyond philosophical re-conciliation and provide practical revitalisation of the traditional computation methods.

But Ragoonatha Charry went beyond merely wanting to write a modern version of the karaṇa handbook. He also aspired to establish an observatory, and a school to train Indians in positional astronomy. He was even willing to give his own astronomical instruments for such an institution, if and when it was established (Charry, 1874: postscript vi). As these projects needed to be funded, he formed a society with the Honourable V. Hamienger, C.S.I., as the President and R. Raghunatha Rao as the Secretary. Others who enrolled as members included: Sir T. Mathava Rao, K.C.S.L.; T. Moothoosawmy Iyer, B.L.; P. Chentsal Rao; M. Venkatsawmy Naidu; M. Ramaswamy Naidu; Y. Venketramiah; and D. Sashiengar. However, nothing seems to have come from Ragoonatha Charry's efforts, and the idea of a society and an observatory appears to have died with him in 1880. Meanwhile, the *Jyothisha Chinthamany* was never published, but the manuscript was lodged with the Government Oriental Library, Madras.[25] These tables were be a handbook for pañcāṅkam-computers to prepare an error-free calendar, and rather than containing mnemonic sentences and algorithm for computation, as per the vākya karaṇas, these tables were available anytime for easy consultation.

8 Concluding Remarks

Ragoonatha Charry's call for pañcāṅga reform, inspired by modern astronomy, cannot be seen as the work of a 'colonial mind', but as revitalizing reform. Although he did not fall down the slippery slope of dogma and orthodoxy, Ragoonatha Charry was able to make positive evaluations of Indian astronomical tradition. The 'modernity' that he fabricated was not an extension of the colonial project expounded by Lord Macaulay, of "Indian in blood and colour; English in tastes, in opinions, in morals and in intellect." (cited by Sharp, 1965: 116). Nor was it a repulsion and rejection of the 'modern' or 'science' as mleccha (i.e. foreign, and alien to the culture). The appropriation of the modern was not passive, and the popular science material prepared by Ragoonatha Charry was not merely a translation of English works into a local language. Even the illustrations in the eclipse diagrams were in the Siddhāntic idiom. Times of events were given in the length of the shadow of the

[25] See the manuscript No 13431 (Dṛggaṇitam) by Raghunātha of Nungambakam and manuscript No 13429 (Dṛggaṇitam) by Taḍakamalli Kṛṣṇarāyar in the Telugu script for the tables prepared for the computation of Dṛggaṇita computations.

changu (gnomon), with which traditional pañcāṅkam-makers would be familiar. Devoid of excessive jingoism, Ragoonatha Charry's local publications readily acknowledged that European nations were excelling in astronomy and that India was way behind. However, unlike the colonial ideologue, he did not see the 'backwardness' of India as an intrinsic feature of its native culture, or as an Orientalist symptom of the 'other worldly Indian mind'. He squarely identified material factors as the cause for the comparative backwardness of Indian science and astronomy during the 1850s.

In a public lecture for the comparative backwardness of Indian given at the Pacheappah's Hall in Madras on 13 April 1874 Ragoonatha Charry's plea for a 'native observatory' reflected this:

> In Europe, excluding Russia, there now exists fifty-four public and ten private observatories spread over an area of less than two million square miles. In India with a surface of one and half million miles we have but one wholly supported by the State. I recommend no more than modest but thorough place of instruction and study should be founded where the theoretical knowledge can be united to actual practical work. Such places exist in hundreds in Europe, but nowhere is the need for them greater than in India. Not much money, a little zeal, a little steadfastness of purpose, wed these to a regard for science, and soon would the metropolis of southern India be graced with an Institution which would be an honour to the country. (Charry, 1874: post script i–vi).

India's 'backwardness' was rightly seen in terms of deprivation, and although Ragoonatha Charry did not specifically point the finger at the Colonial Government for the dispiriting state of higher education in the country, it is clear that he saw redemption in the establishment of institutions of learning and research. If the Colonial Government would not come forward enthusiastically, he would advocate self-help. In this matter, Ragoonatha Charry's clarion call seemed to echo Dr. Mahendra Lal Sircars' establishment of the Indian Association for Cultivation of Science in 1876, which also was outside the colonial system, and promoted research and higher education in the sciences in Calcutta, with subscription from native donors (see Biswas, 2003).

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Our History in Our Traditions: A Reminder

K. Sinha

Abstract The arrival of the Europeans in the Indian Sub-continent, the British in particular, also heralded new vistas: to know and explore the region. Already they had heard of people with only one eye, with a dog's head, and without a head. There could be flying snakes, flying lions and other strange animals, birds, insects, etc. Also, there could be men and women with huge leaf-like legs, who used these as umbrellas, and so on!

A conscious effort to study the literature and the people, soon yielded the important result that although the Sanskrit language contained nothing that could be called 'history', there were books describing events of true historical importance and these were presented in the form of drama etc. Several lost manuscripts, scriptures, and writings on stones were discovered. Excavations lead to a discovery of evidence of lost civilizations.

What is known today is mainly through the writings of such travellers as Hiuen Tsang, Fahyan Megasthanes, Al Biruni and others. The Greeks providing an insight into the reign of Chandragupt. However, clinching evidence in support of what existed earlier, before Buddha for example, continues to be elusive. Astronomy, too, has been invoked to date events in the *Ramayana* and the *Mahabharata*, but with conflicting results.

Taking a cue from the fact that we still continue to observe mythology based festivals and traditions, supported additionally by the modern-day TV serials, it is felt that a close study of these festivals and traditions, but with a modern perspective and the help of things like of computer software, may lead to new discoveries. Consider the description of the skies at the birth of Sri Rama, the demise of Bhishm etc. If Sri Rama was exiled for exactly 14 years around Rama Navami day (i.e. around his birthday), and if the citizens of Ayodhya celebrated his return with Deepawali, why should today there be a difference of around five and a half months between the two festivals? We do not know when and how the lunar, solar and lunisolar calendars were respectively introduced into India and by whom. The emergence of different religious sects at different times often clearly marked epochal

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changes in society. Can we reliably date this societal evolution through a study of religious practices?

These topics, and others, are discussed in the present study.

1 Introduction

The British, in particular were in a habit of recording events in chronological order and this could be in the form of writing diaries and/or making notes. It additionally resulted in recording the events of the state. So, once they arrived in India, finding no such records, it was easy for them to surmise that the country had no history and it lived in myths and superstitions. But again, thanks mainly to the British who formed the Asiatic Society for Researches and the Archaeological Survey of India, some very highly motivated individuals worked tirelessly to unravel the wonders and grandeur of the ancient civilization that was India. However, to depend entirely on the writings of foreign travellers such as Megasthenes, Ptolemy, Pliny, Hiuen Tsang, Al Biruni and others, would be a virtual negation of what India had to offer to the world prior to the visits of these people, or that of Alexander the Great.

As Indians, we do precious little to preserve our heritage, be it in the form of manuscripts, monuments, structures or something similar. It is no wonder therefore that as late as 1834 the Secretary (actually *de facto* Director) of the Sanskrit College in Calcutta, Captain Anthony Troyer (d. 1865; Stein, 1940) wrote in the *Journal of the Asiatic Society of Bengal* that he knew almost nothing about Samudragupta and Chandragupa (and therefore the Gupta Empire). Meanwhile, Kautilya's *Arthshastra* (see Brosche, 2002), an important second century BCE socio-political treatise written in Sanskrit, was influential until the twelfth century BCE, then it was lost, only to be rediscovered by the Mysore Oriental Librarian, Rudrapatnam Shamashastry as recently as in 1905.

In the olden days, the remnants of old fallen structures were used in the construction of new buildings, and precious old gold and silver coins were melted down and converted into valuable jewellery. It needed an order from the British Army Engineer and Director-General of the Archaeological Survey of India, Alexander (later Sir Alexander) Cunningham (1814–1893; Fig. 1; Iman, 1966) to stop Dewan Jagat Singh excavating the Dhamek Stupa in Sarnath and using the bricks to construct a house (Kejriwal, 1998: 9). These activities by Cunningham resulted in the beginning of the process of preservation of the India's architectural and religious heritage. However, without an adequate knowledge of the local culture, traditions and rituals, interpretations of findings were biased.

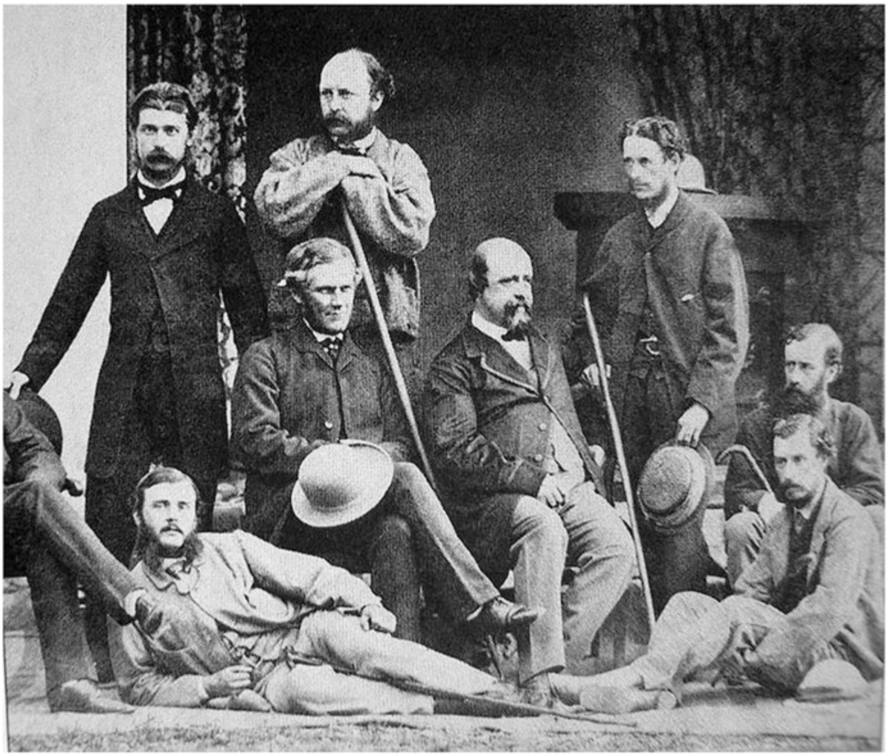

Fig. 1 An undated photograph showing Alexander Cunningham (fourth from right), the founding Director-General of the Archaeological Survey of India (en.wikipedia.org)

2 The Indian Way of Recording History

We had probably been in the habit of glorifying and emulating the feats of great people who served humanity, partly through folklores and rituals performed at different times of the year. One may like to note here that as a hard-core Indian, one may like to ignore the contribution of a Briton, Major-General Robert Clive (1825–1874; Harvey, 1998), Commander-in-Chief of British India, in popularizing the annual Hindu *Durga Pooja* Festival, but not the Indian Bal Gangadhar Tilak (1856–1920; Tahmankar, 1956), the first leader of the Indian Independence Movement, who will always be remembered for the beginning of the *Ganesh Chaturthi* celebrations. However, a study of these two great Indian festivals reveals the important dates when and why these celebrations began.

But what is more interesting, in my opinion, is that elements of Indian history are recorded in yet another way, i.e. in important religious celebrations. But which calendar needed to be followed?

To digress, I wish to make an important point here: a calendar is nothing more but a record of celestial events and their association with happenings here on the Earth, such as the seasons! Here, it is amply clear and must be borne in mind that whereas astronomy deals essentially with the science of celestial events and bodies, astrology deals with the *art* of interpreting the impact or influence of some such events on human life! It is no wonder that the development of the calendar also depended upon the development of our understanding of objects in the sky.

Because of their huge apparent sizes in the sky the Sun and the Moon immediately attract our attention. If the Sun freed the living beings from the uncertainties of the deathly dark night, the Moon served as a clear crusader in the background, along with point-like asterisms shining as diamonds, serving as markers and beckoning the approaching dawn. Continuous rigorous observations showed the repetitive path of the Moon. It was realized that the Moon took 29.5 days to go round the Earth and 12 such orbits were enough to mark a year—which was almost the same time that the Sun rose in the beginning of the year. But later on it became clear that the arrival of seasons, which were so important for agriculture, had to be associated with the heliacal rising of different stars. This led finally to a 365.25 day solar year instead of the previous 354 day lunar year. However, any discussion of the refinements in the calendar lie beyond the scope of this research paper.

It may be remarked here that planetary movements served as a sufficiently accurate clock. We know that Jupiter takes about 12 years to orbit the Sun, and Saturn does the same in 30 years. Therefore, any relative position of these two cannot be repeated before the passage of a good 60 years. This is akin to saying that the hour and minute hands of a clock do not repeat their relative positions before the passage of 12 h! Now add to the planetary movements the motion of, say, Mars (1.88-year period) and Venus (0.615-year period). Thus, instead of making the picture complicated, here we actually make it fascinating and end up with a system that is precise, self-sustaining and valid for years to come. The moment we add the motion of the vernal equinox to this system we get a calendar for approximately 26,000 years, with the planetary movements serving as the many hands of a conceptual clock (Bhatnagar, 2004).

Now, let us see how the above can be utilized to put our history in chronological order. It is not precisely known when the practice of preparing horoscopes began in India. We note in particular that initially Buddhists did not believe in astrology and when Buddhism became weak Greek influence probably took over and the occult had its way (Kay, 1924: 97).

3 The Date of Birth of Rama

In the first millennium BCE epic Indian poem *Ramayana*, written by Valmiki (see Fig. 2), the position of the planets at the time of birth of Sri Rama is given as follows:

> Sun (Surya) in Aries (Mesh), Saturn (Shani) in Libra (Tula), Jupiter (Brihaspati) in Cancer (Kark), Venus (Shukra) in Pisces (Meen), Mars (Mangal) in Capricorn (Makar), lunar month of Chaitra, nineth day after New Moon (Shukla Paksh, Navami Tithi), Moon near Pollux in Gemini (Punarvasu in Mithun), Cancer as Lagna or Cancer rising in the East, and Jupiter above the horizon (see Goldman, 1990).

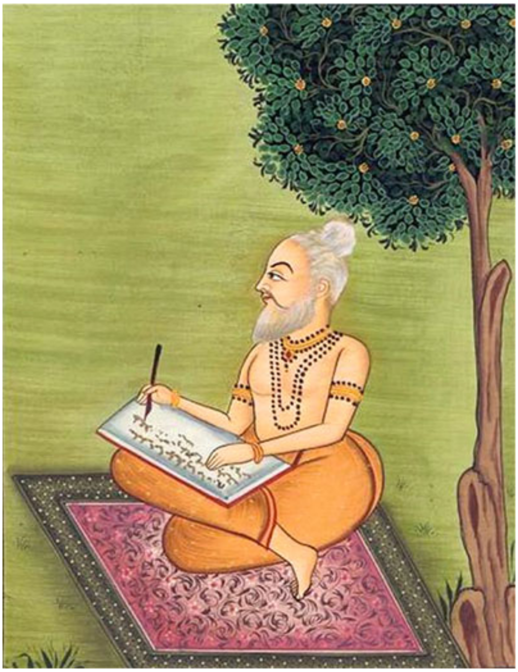

Fig. 2 A painting of Valmiki scribing the *Ramayana* (en.wikipedia.org)

Using the above details and with the help of the Planetarium Gold software, P. Bhatnagar (2004: 23–24) found the date of the birth of Sri Rama as 10 January 5114 BC. Yet another factor that is also clearly brought out by Bhatnagar is that owing to the precession of the equinoxes, back in 5114 BC the lunar month Chaitra fell between 15 December and 15 January (instead of between 15 March and 15 April, as at present). Later, A.K. Bhatnagar (2012: 55–80) showed that using different computer software did not affect the result. However, at an earlier date Vartak (1999: 46) had carried out calculations without the aid of computer softwares and using a different astronomical approach, found 4 December 7323 BC as the birth date of Rama. The appreciable difference between the two dates for the birth—both derived from astronomical data—provides scope for further research.

4 Use of the Lunar Calendar

The above also leads us to an interesting aspect. In the *Ramayana* epic, Sri Rama was exiled for 14 years on his 21st birthday, i.e., on one of the days of *Ra*m *Navami*, a Hindu spring festival. Obviously, his return to Ayodhya should have been on or close to a *Rama Navami* day, but instead the occasion was marked by *Deepawali* celebrations (during the autumn Hindu ‘festival of lights’). Why, then, do we celebrate *Deepawali* in October–November and *Ram Navami* in March–April?

The answer is not too difficult to find. If we assume that the lunar calendar was in vogue during the *Vedic* period, then a short-fall of 11 days every year would make it 154 days, or 5 months and about 6 lunar days, over a 14-year period. This conveniently fills the gap between October-November and the following March–April.

A similar controversy in the *Mahabharata*, the other great prehistoric Indian Sanskrit epic text, relates to the exile of the Pandavas (the five sons of Pandu) and whether they completed the stipulated 13-year period of exile. The controversy is similar to the above example, and was resolved by Bhishma in favor of the Pandavas (see Mishr 1930: 306–311). This may be taken to mean that although the lunar calendar was being used during the *Mahabharata* period, a solar calendar was not unknown and probably it was in the ascendancy. If we agree to this, the important question to be answered is who introduced the lunisolar calendar to India and when?

We thus see clearly how a horoscope and a precise mention of the celestial objects can be utilized to obtain important dates in history!

5 *Maha Shivratri* and Some Other Festivals

Another interesting aspect relates to the annual Hindu festival *Maha Shivratri*, that occurs in late Winter (February/March) in honor of the god Shiva. When was it first observed or celebrated?

It is well known that every New Moon day (Amavasya) is a Shivratri. Obviously, the day when the night or the Amavasya is the longest is *Maha Shivratri*. But such a night occurs on 22/23 December whereas the festival is celebrated in February or March. Abhyankar (2007: 51–53) has explained this apparent discrepancy. Accounting for 1 day every 71 years he goes on to illustrate that the practice of observing the festival began in 3000 BC. Also, on the basis of the visibility of the star Canopus (Agastya), Abhyankar (ibid: 197–202) arrives at the period 5000–4000 BC for when the revered Hindu sage Agastya crossed the Vindhya, a topographically-challenging region in west-central India typified by mountain ridges, hill country, high-lands and plateau escarpments. The author is inclined to believe that the practice of *Makar Sankranti* celebrations (around 14 January every year) in India was started by a very knowledgeable and influential person whose name and contribution currently remains unknown.

6 Kumbh Celebrations

It is well known that after every 12 years the *Kumbh Mela* festivals are organized in Prayag, Haridwar, Nasik and Ujjain. A very popular story is also told about why it is celebrated. For the festival, the planetary positions are: the Sun in Capricorn and Jupiter in Taurus for Prayag; Sun in Aries and Jupiter in Aquarius for Haridwar; Sun and Jupiter in Leo for Nashik and Sun and Jupiter in Scorpio for Ujjain. The questions that needs answers are: why do such dissimilar combinations of Sun and Jupiter exist for the North and the South of the country, who began these festivals and at what date. The answers, difficult ones, when available, may be expected to throw considerable light on our heritage.

7 Naming the Planets

While quoting Bentley, Max Muller (1862: 28–29) recalled the story that the 27 daughters of *Daksh* were given to the Moon, and he surmised that the union of the Moon with these daughters in the shape of a planetary occultation in an asterism yielded beautiful progenies. Thus Mercury is called Rohineya, Venus is Maghabhu, Mars is Ashadhabhava and Jupiter is Purvaphalgunibhava. Further, Bentley found that such occultation occurred between 17 April 1424 BC and 19 August 1425 BC. However, I have found that no such occultation took place in the stated period, so the reasons for thus naming the planets should be sought elsewhere. This calls for further investigation.

8 Stone Alignments

Kameswara Rao et al. (2011: 211–220) mention stone alignments constructed between 1400 and 1000 BC at Murardoddi in Mahbubnagar district of Andhra Pradesh. Observations show that the rows of the stones are aligned to the directions of sunrise and sunset on calendrically important events like equinoxes and solstices. Sunrise and sunset observations and the patterns of the shadows of stones were used to measure time, days and fractions of the day. Archaeological studies to accurately date the stone alignments are required.

9 Conclusions

The above examples illustrate very clearly how the astronomical facts recorded in our epics, in folklore and/or even in traditions and culture can go on to establish our golden heritage and our place in history. In this context efforts to know when a certain tradition or ritual began and who started it might lead to new discoveries.

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Part V
The Emergence of Astrophysics and Radio Astronomy in Asia

K.D. Naegamvālā: The Founder of the First Astrophysical Observatory in India

S. M. Razaullah Ansari

Abstract Kavāsjī Dādābhāi Naegamvālā was born in 1857, and belonged to an illustrious family of Parsi contractors. He was educated at Elphinstone College in Bombay, where he studied for B.A. and M.A. before being appointed a Lecturer at the College in 1882. Six years later he shifted to the College of Science in Poona, as their founding Professor of Astrophysics, and in 1900 became the Director of the new Takhtasinghji Observatory in Poona. He remained at the College until his retirement in 1912, and the Observatory was then closed and its astronomical instruments transferred to Kodaikanal Observatory. Naegamvālā died in 1938.

In this paper I relate briefly the tremendous efforts of Naegamvālā to educate himself in 'celestial spectroscopy and astronomical physics', first with the aid of Father Lafont (Calcutta) and later at European observatories in Rome, Potsdam and South Kensington, before he established India's first astrophysical observatory in Poona. For this he procured what, at the time, was the most modern astronomical equipment in India. In his endeavours, Naegamvālā was helped in particular by the Astronomer Royal, Sir William Christie. I then end this paper by examining Naegamvālā's observations of the 1898 total solar eclipse. This paper is based largely on archival records and family papers (I had the privilege to meet Nowrojee in 1976 at Poona, when he was in his mid-80s. I was also fortunate then to meet Professor Naegamvālā's grand-daughter, Dr. Silloo M. Vacha, grandson, Mr. J.-P. Naegamvala, and the mother of Dr. Vacha, who were very kind in letting me study the Family Papers, containing Professor Naegamvālā's publications, hand-written drafts and typescripts. They are referred to here as 'Family Papers'. Records concerning Professor Naegamvālā's work and Takhtasingji Observatory are extant also in the Maharashtra Government Archives (Mumbai) and in the Education Department (1882–1899), which I refer to here simply as 'Bombay Archives' (and then cite the No. and the Year).).

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1 Introduction

The second half of the nineteenth century was a time of rapid development in Indian astronomy, as the Subcontinent accommodated local and international solar eclipse and transit of Venus teams in 1868, 1871, 1874, and 1898, and responded to international developments in astrophysics and especially solar physics (e.g. see Ansari 2000, 2011; Kapoor 2014; Kochhar 1993; Kochhar and Orchiston 2017). This was the era when India saw the establishment of two different astrophysical observatories, one by the Jesuit scientist Father Eugene Lafont at St. Xavier College in Calcutta and the other by K.D. Naegamvālā at the College of Science in Poona.

In this paper we focus on the second of these observatories, and after briefly reviewing Naegamvālā's life we examine the scientific equipment that he assembled at his Takhtasingji Observatory, the research that he carried there, and his observations of the solar chromosphere and corona from Jeur, western India, during the 22 January 1898 total solar eclipse. I regard this meticulously planned expedition as Naegamvālā's most remarkable achievement.

2 A Brief Life Sketch

Kavāsjī Dādābhāī Naegamvālā (1857–1938; Fig. 1) belonged to an illustrious family of Parsi contractors. His grandfather Jamsetjee Dorabjee Naigaumvala (1804–1882) had been a pioneer Contractor of Railways in India, as praised by the Assistant Secretary to Railways in Bombay. K.D. Naegamvālā was educated at Elphinstone College in Bombay, where he obtained a B.A. degree in 1876 and an M.A. in Physics and Chemistry in 1878, in the latter year winning the Chancellor's Gold Medal. In 1882 he was appointed a Lecturer in Experimental Physics at the College.

Fig. 1 The photograph of K.D. Naegamvālā on the cover page of the April 1939 issue of the Gujrati English magazine *Hindi Graphic* (Bombay)

Then in 1888 he joined the College of Science in Poona (presently the College of Engineering) as a Professor of Astrophysics, and in 1900 he was appointed Director of Takhtasingji Observatory at the College.

I may mention here that from the 1880s, Naegamvālā was in active correspondence with the British Astronomer Royal, William Christie (1845–1922; Dewhirst 2014); Norman Lockyer (1836–1920; Meadows 1972), the founder of the solar observatory at South Kensington in England; William Huggins (1824–1910; Becker 2011) from Tulse Hill in England; Edward W. Maunder (1851–1928; Baum 2014; Kinder 2008) from the Royal Observatory in England and a one-time Vice-President of the British Astronomical Association; Hermann Carl Vogel (1841–1907; Frost 1908), Director of the Potsdam Astrophysical Observatory in Germany; and the American, George Ellery Hale (1868–1938; Adams 1939). Through these contacts Naegamvālā became known internationally, and he was elected a Fellow of the Royal Astronomical Society in 1885 (see Ansari 1985: 36–40).

In 1912 Naegamvālā took early retirement from the College of Science, and he died in 1938. Subsequently, a detailed biography of him was written by his son Nowrojee K.D. Naigamvalla (1946), and this is listed in full here in the References section of this paper.[1]

3 The Establishment of Takhtasingji Observatory

It is reported that the Maharaja Takhtasingji of Bhavanagar (1858–1896) visited Bombay University in October 1882, when Naegamvālā suggested to him as follows:

> . . . that adequate means for the pursuit of spectroscopic investigation did not exist in any of the Colleges affiliated to the Bombay University and that Elphinstone College would be prepared to organise a spectroscopic laboratory, if provided with a sum sufficient for the purpose. (Bombay Archives, No. 4906, 2 November 1882).

As a result, the Maharaja offered a sum of Rs. 5000 and also hoped for a matching grant by the Bombay Government to establish such a laboratory. His motivation was twofold:

> On one hand I [the Maharaja] have the satisfaction of knowing that I had done something to supply a very desirable means for [the] study of an important branch of science. I shall, on

[1]I had the privilege to meet Nowrojee in 1976 at Poona, when he was in his mid-80s. I was also fortunate then to meet Professor Naegamvālā's grand-daughter, Dr. Silloo M. Vacha, grandson, Mr J.P. Naegamvala, and the mother of Dr. Vacha, who were very kind in letting me study the Family Papers, containing Professor Naegamvālā's publications, hand-written drafts and typescripts. They are referred to here as 'Family Papers'. Records concerning Professor Naegamvālā's work and Takhtasingji Observatory are extant also in the Maharashtra Government Archives (Mumbai) and in the Education Department (1882–1899), which I refer to here simply as 'Bombay Archives' (and then cite the No. and the Year).

> the other hand, have the gratification of thinking that it was permitted me to perpetuate the memory of my present visit . . . (Raja's letter of offer in Bombay Archives, No. 738, 1882).

It is clear that the main spirit behind this establishment of the laboratory was the young lecturer K.D. Naegamvālā, who rightfully claimed, later, that he was responsible for the establishment of Takhtasingji Observatory (Naegamvala 1899). In this context, it is interesting to note that after he founded a spectroscopic laboratory in Bombay, Naegamvālā established an astrophysical observatory in Poona (modern Pune).

4 The Acquisition of Spectroscopic and Astronomical Physics

Obviously Naegamvālā planned to acquire knowledge about astrophysics from spectroscopic laboratories or observatories so that he could use the spectroscopic apparatus. The only spectroscopic laboratory in India at that time was at St. Xavier College Observatory in Calcutta, where the Director, the Jesuit astronomer Father Eugene Lafont (1837–1908; Fig. 2; Biswas 1994, 2003; Udias 2003), was engaged in solar and stellar spectroscopy using 9-in (22.9-cm) and 7-in (17.8-cm) refracting telescopes (Chinnici 1995/96). As Naegamvālā noted, Lafont's work consisted of

> . . . delineation of the forms of the Solar prominences and spots with the object of supplementing . . . similar observations . . . [at] the College Romano . . . (Bombay Archives, Vol.10, No. 244, 1884).

Naegamvālā is referring here to the College Romano in Italy, where Father Angelo Secchi (1818–1878) had been the Director of the Observatory, and had founded the Società degli Spectroscopisti Italiani in 1867. To note here is that Father Lafont had been in close contact with Father Secchi up until his death just 4 years earlier, and that at this time planetary and stellar spectroscopy also were being carried out by William Huggins in England and H.C. Vogel in Germany.

Fig. 2 Father Eugene Lafont (https://en.wikipedia.org)

Through Father Lafont's influence, it was natural that Naegamvālā's interest shifted from a spectroscopic laboratory to an astrophysical observatory. After convincing Principal Wordsworth of Elphinstone College, Naegamvālā used recommendations from Father Lafont and Father Deckmann (Professor of Physics at St. Xavier College) to request funding so that he could visit various observatories and laboratories in Europe (Bombay Archives). This trip was approved.

Naegamvālā received a grant of Rs. 10,000 to purchase equipment, and after visiting Father Lafont's Laboratory in Calcutta he proceeded to Europe. However, Elphinstone College decided to grant him leave without pay, so presumably Naegamvālā was able to use part of the grant for his daily living expenses, but especially meals and local travel. Once in Europe, Naegamvālā visited the College Romano in Rome, the Astrophysical Observatory in Potsdam, the Observatory of Astronomical Physics at Meudon in Paris and Sir Lockyer's Solar Physics Observatory at South Kensington in England, where he trained himself in handling the new spectroscopic and photographic apparatus (Bombay Archives, No. 244 (1884) and No.441 (1886)). After visiting the above mentioned European observatories Naegamvālā felt confident about establishing an astrophysical observatory in India.

5 Equipment for the New Observatory

Naegamvālā compiled a list of suitable instruments, had this approved by the Astronomer Royal, Sir William Christie, and then returned to India.

Initially Naegamvālā worked in his spectroscopic laboratory in Bombay, then he shifted to the College of Science (the present-day College of Engineering) in Poona where he established Takhtasingji Observatory (for these and other localities mentioned in this paper see Fig. 3). He began as a Lecturer in Astronomy and Curator of the Observatory (Draft dated 28 May 1888 in Family Papers, Bombay Archives, No. 1464, Aug. 10, 1888). By the end of 1888 the Observatory was complete (Naegamvala 1888), and Naegamvālā sent Sir William Christie a list of its instruments, which included:

A 20-in (50.8-cm) Grubb reflector
A 6-in (15.2-cm) Cooke equatorial
An 8-in (20.3-cm) achromatic lens, 12-in (30.5-cm) siderostat and solar grating spectroscope
A large stellar spectroscope
A 3-in (7.6-cm) transit instrument
A standard clock.
A chronograph

Naegamvālā was conscious of the excellent quality of this equipment, which at the time was not available elsewhere in India, even at Madras Observatory, and he wrote to the Astronomer Royal:

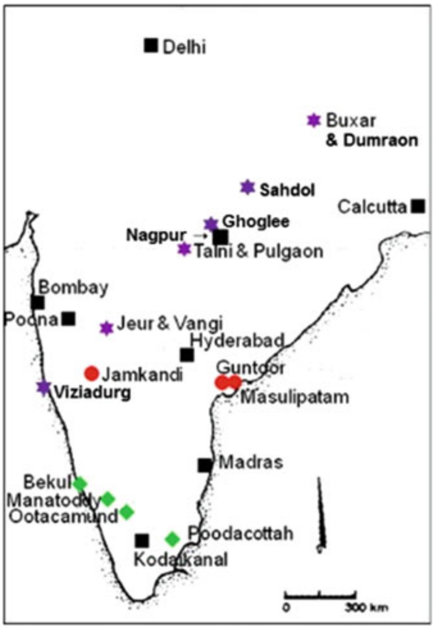


Fig. 3 Map of India showing Bombay, Calcutta, Delhi, Kodaikanal, Madras, Poona, and the principal observing sites used during the total solar eclipses of 1868 (red dots), 1871 (green diamonds) and 1898 (purple stars). Jeur is the most southerly of the 1898 eclipse observing sites, and is located between Poona and Hyderabad (map: Wayne Orchiston)

> My earnest desire is that this splendid equipment that I have managed to bring together should not lie idle and that I may be put in a position to make use of it. (Naegamvala 1896).

In reply, Sir William suggested:

> It is very desirable that the fine equipment of the observatory . . . should be fully utilized as such valuable work might be done with it at a station like Poona near the Equator where observations of the Sun, Moon Planets etc. could be made under much more favourable conditions than in our Northern observatories. India seems to be peculiarly marked out for observations of the Sun, especially spectroscopic . . . (Christie 1897).

Following Christie's advice, Naegamvālā started working in the field of astrophysics and solar physics. This research had culminated in his observations of the total solar eclipse of 22 January 1898.

6 The Astrophysical Work

According to the list of publications available to me, the details of which are given in the References section, Naegamvālā published nine different research papers between 1891 and 1902 (inclusive), following his first publication, in 1888, which merely announced the establishment of Takhtasinghji Observatory in Poona. Thereafter Naegamvālā typically published one paper or short communication per year, mainly in *Monthly Notices of the Royal Astronomical Society*. These ranged from spectroscopic studies of the Orion Nebulae (Naegamvala 1891b), the sunspot group of February 1892 (Naegamvala 1892), NGC 6595 (Naegamvala 1895), a nebula and 43 Virginis (Naegamvala 1897) and nova 1901 in Perseus (Naegamvala 1901), together with observations of the 9 May 1891 transit of Mercury (Naegamvala 1891a).

7 The Total Solar Eclipse of 1898

However, Naegamvālā's most remarkable research was carried out during the 22 January 1898 total solar eclipse, from Jeur (see Fig. 3) in western India.

India had already made a remarkable contribution to solar physics, through the 1868 total solar eclipse (see observing sites in Fig. 3). This 'watershed event' was the first eclipse to be subjected to detailed spectroscopic analysis, and resulted (eventually) in the identification of a new element, helium (see Nath 2013).

Overseas and local observing teams also congregated in India for the 1871 total solar eclipse (see Fig. 3), when further advances were made in solar physics (see Kochhar and Orchiston 2017).

With the advent of the 22 January 1898 eclipse, India was again host to international research teams, from England (Christie 1898a; Grove-Hills and Newall 1898; Maunder 1899), Japan (Terao and Hirayama 1910), Scotland (Copeland 1898) and the USA (Burckhalter 1898; Campbell 1898, 1900; cf. Orchiston and Pearson 2017), and these positioned themselves at eight different observing sites in central India (see Fig. 3). Apart from Naegamvālā's team, India also supplied another 'local' eclipse team, this time from St. Xavier's College in Calcutta and led by the Jesuit, Father V. de Campigneulles (1899; Udias 2003; cf. de Campigneulles and Josson 1898). In addition, Evershed and Michie-Smith from Kodaikanal Observatory participated in one of the British expeditions (Maunder 1899).

Naegamvālā chose to observe from Jeur, adjacent to the American Lick Observatory compound, and we can cite his own words to highlight the difficulties he faced in planning an expedition in the interior of the Indian countryside at the end of the nineteenth century:

> The country in the vicinity of Jeur was . . . flat, almost devoid of trees except a few scraggy babuls and the supply of water was not plentiful. Plague had also appeared in Karmala, the chief town of the taluka [sub-district], but had not yet spread to the surrounding villages . . . (Naegamvala 1902: 3).

One can understand how difficult it would have been to transport the fine and delicate instruments Naegamvālā employed for his spectroscopic observations. For these he relied on the horizontal photoheliograph shown in Fig. 4.

The sky was cooperative on 22 January 1898, and all of the observing teams located at Jeur successfully observed the eclipse. Naegamvālā then analysed his team's observations and began writing them up. First he prepared a short communication for the *Astrophysical Journal*, on his successful photograph of the 'flash spectrum', which is shown here in Fig. 5. The editor of the *Astrophysical Journal* pointed out to readers that the reproduction ". . . failed to bring out all the fine lines

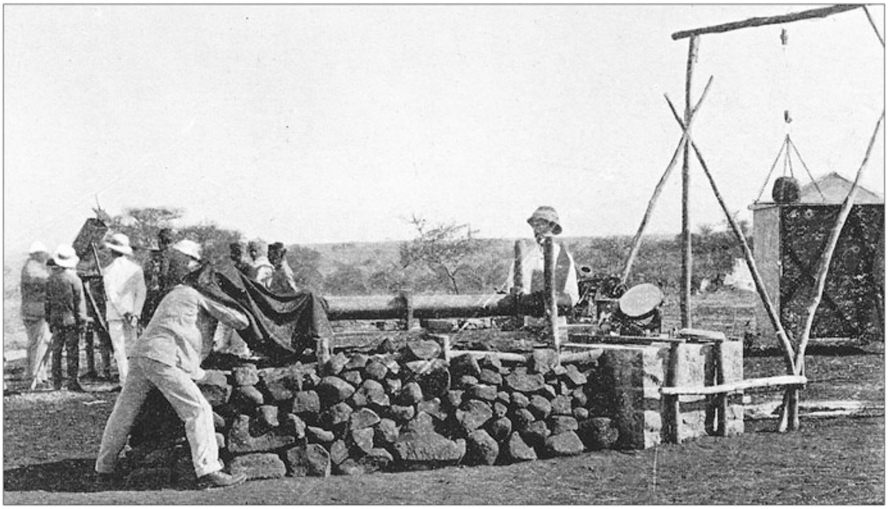


Fig. 4 A photograph of Naegamvālā's horizontal photoheliograph, showing the heliostat that was driven to track the Sun, and the tube that led to the spectrograph, which was located under the black cloth cover (after Maunder 1899: 81)

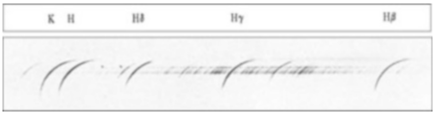


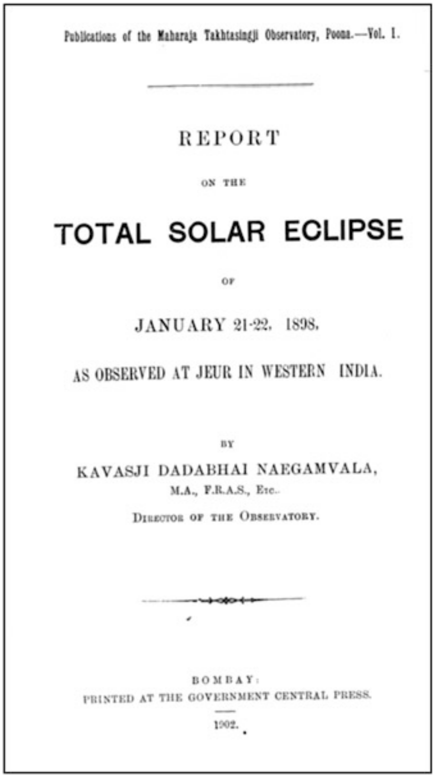
Fig. 5 The photograph of the 'flash' spectrum published in the Astrophysical Journal (after Naegamvala 1898)

shown on the original." He also commented that perhaps the most interesting feature of the photograph was the prominence that was shown in two lines, H and Hδ, but was invisible in the H and K and the hydrogen lines (Naegamvala 1898: 121).

Naegamvālā then proceeded to prepare a monograph on the expedition, and this was published in 1902. The front cover is shown in Fig. 6 and the Contents are listed in Table 1.

A copy of this book is available in the Library of the Indian Institute of Astrophysics in Bangalore, a pdf copy of which can be used online, and is available through the website of the National Digital Library of India (NDL).

The Contents list in Table 1 obviously is not comprehensive. However, it gives an idea about the hard work done by K.D. Naegamvālā in managing the programme and eventually in compiling this Report. The list of his co-observers contains also many students, along with his son, (Master) P. Naegamvala and presumably his brother or cousin, R.D. Naegamvala. The most important sections of the Report are those about the 'flash' spectrum and the coronal photographs. Here I may cite his opinion:



Publications of the Maharaja Takhtasingji Observatory, Poona.—Vol. I.

REPORT

ON THE

TOTAL SOLAR ECLIPSE

OF

JANUARY 21-22, 1898,

AS OBSERVED AT JEUR IN WESTERN INDIA.

BY

KAVASJI DADABHAI NAEGAMVALA,

M.A., F.R.A.S., Etc.

Director of the Observatory.

BOMBAY:

PRINTED AT THE GOVERNMENT CENTRAL PRESS.

1902.

Fig. 6 The front cover of Naegamvālā's Report on Solar Eclipse of 1898 (courtesy: Dr. Silloo M. Vacha (Poona) et al.)

> From the first I had proposed to concentrate powers of the expedition in the spectroscopic lines, assigning a secondary place to the subjects of observations . . . but for the late arrival of the instruments and the programme . . . finally was adopted as follows. (Naegamvala 1902).

On pages 6 and 7 in his Report Naegamvālā lists 14 important aspects of the observations. Of special interest is his drawing of the corona, shown here in Fig. 7 (cf. Fig. 8).

Finally, I may add the following. The importance of this particular total solar eclipse, particularly for coronal photography can be gauged from the fact that a Joint Eclipse Committee of the Royal Society and Royal Astronomical Society was set up—headed by the then Astronomer Royal Sir William Christie—to take an expedition to India for the eclipse, but also to report on the status of Indian observatories. Christie toured India to gain first-hand knowledge of the observatories at Bombay, Madras and Kodaikanal (and he also successfully observed the eclipse). His Report, which was printed in 1898, is 17-pages long and contains nine sections (Christie 1898a). Meanwhile, an abbreviated version was published in the *Proceedings of the Royal Institution* (Christie 1898b).

Table 1 Table of contents of Naegamvālā's report

Table
Outline of Contents of K.D. Naegamvala's Report on the Total Solar Eclipse of 1898
Prefatory Remarks: "...Regarding the delay in publishing the report of Eclipse", signed by K.D. Naegamvala, November 1,1901
Contents: List of XXXII Sections from p. 1 to p. 67.
List of 44 Illustrations, contains also list of Plates from I to XXX.
Chapter I: Preliminary Preparation, Sections I to VI.
Chapter II. Eclipse Observations, starting from Sec. VII, for instance,
………………
Sec. X. Personnel and Programme of Work, containing list of 14 instruments, Issued to various observers.
Sec: XVIII. The Flash Spectrum,
Section XXI. The Coronal Spectrum, containing list of previous observations of 13 years (1868? 1900), furnished with references.
Section XXIII. The Coronographs: Photography of the Corona,...
Section XXX. Meteorological Observations.
Appendix. Instructions for observing the Total Eclipse of the Sun, at Jeur on Jan. 22,1898.
………………
Plate VI. Photograph of the Observing Party, with printed list of names of 52 members.
Plate IX. Spectrum of the Flash with Figs. 1 and 2.
Plate XXVI. Sketch of the Corona made by Rev. A. Abbott.

Fig. 7 A composite drawing of the corona based on photographs (after Naegamvālā 1902)

Christie's reports reveal that there were actually four official British observing parties:

1. Sir Norman Lockyer and Alexander Pedler (1849–1918), Director of Public Instructions in Bengal, led a team that observed the eclipse at Viziadurg, from a British ship.
2. William Christie and Oxford University's Professor H.H. Turner (1861–1930) were based at Sahdol.
3. Soldier-astronomer Captain E.H. Grove-Hills (1864–1922) and Cambridge University's H.F. Newall (1857–1944) were at Pulgaon.
4. The party led by Astronomer Royal of Scotland, Dr. Ralph Copeland (1837–1905) was based at Ghoglee (for all localities see Fig. 3).

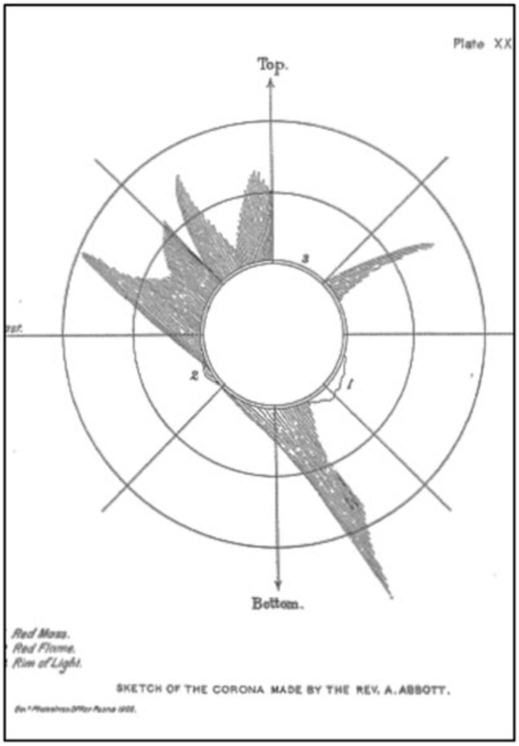


Fig. 8 A sketch of the corona by the Reverend A. Abbot (after Naegamvala 1902: Plate XXVI)

In addition to these parties sponsored by the Royal Society and Royal Astronomical Society,

> The British Astronomical Association (BAA) mounted an ambitious expedition, using two observing sites, and in a copiously-illustrated 184-page book, Edward Maunder (1899) provides a detailed account of this venture by some of Britain's leading amateur astronomers . . . (Orchiston and Pearson 2017).

The large BAA party split into two teams. One of these was based at Buxar and carried out photographic observations, while the second, led by Edward W. Maunder and based at Talni, focussed on spectroscopic observations. John Evershed (1864–1956) and Michie-Smith from Kodaikanal Observatory joined Maunder's team (see Maunder 1898, 4–28).

All this underscores the significance of the eclipse of 1898, when an Indian team headed by Naegamvālā contributed substantially.

8 Discussion

8.1 Working Conditions

As to the working environment, Naegamvālā had been researching in difficult conditions. He had to hold a teaching position at the College of Science, and he worked simultaneously as the Director of the Observatory. In fact he confessed to Astronomer Royal Christie:

> As long as I am required to teach Physics . . . it would be idle to expect me to have energy or time to accomplish anything . . . (Naegamvala 1896).

This did not turn out to be exactly true, for despite his double appointment he was engaged in preparations for the 1898 solar eclipse, which he specifically mentioned in his Report (Naegamvala 1902: 1–2). On 23 February 1896, he approached the Government of Bombay to convince it of the importance of the total solar eclipse of 1898, and to secure a grant so that he could view the total solar eclipse on 9 August 1896 from Norway (in order to familiarise himself with the correct observing techniques), and so that he could acquire modern equipment for the Indian eclipse of 1898. Fortunately, the Government approved his request.

However, despite of his best efforts and capabilities, Naegamvālā could not secure a graded Government post, even up to 1899, although back in 1887 the Government had already recognised that he was "... practically qualified for a graded appointment." (Naegamvala 1899: 6).

Noteworthy here is another Report on Indian Observatories by the Director of the Solar Physics Observatory at South Kensington, Sir Norman Lockyer (FRS), which was compiled at the request of the India Office in London. In this, Lockyer (1898: 32–33, 37) depreciated the non-astronomical routine work carried out at these observatories and recommended strongly that the astronomers should be free to spend more time on pure research. An important outcome of this Report was that Naegamvālā be relieved of teaching duties so that he could devote all his time to research at Takhtasingji Observatory, and that he would communicate the results of his solar observations to Lockyer. And

> If Lockyer had had his way, he would have appointed Naegamvala the director of the proposed Solar Physics Observatory at Kodaikankal. (Kochhar and Narlikar 1995: 18; cf. The observatories of India 1899: 309).[2]

However, the successful applicant was Madras Observatory Director, Charles Michie-Smith.

[2]Cf., also, page 2 in a three-page printed Memorial in Family Papers.

8.2 Naegamvālā's International Standing

Naegamvālā's spectroscopic and photographic observations brought him worldwide recognition. In his book, *The Indian Eclipse of 1898*, Edward W. Maunder (1899) mentions Naegamvālā's research, and he also is cited by Agnes Clerke (1842–1907; Brück 2002) in her masterful tomes *A History of Astronomy during the Nineteenth Century* (1893: 302) and *Problems in Astrophysics* (Clerke, 1903: 46, 94). Naegamvālā (1899: 3–4) was particularly proud of this first citation.

Meanwhile, the famous Indian astronomer M.K. Vainu Bappu (1927–1982), founding Director of the Indian Institute of Astrophysics in Bangalore and the inspiration behind the Vainu Bappu Observatory at Kavalur, had this to say: "Naegamwala's solar work is the first complete Indian efforts of its kind on record." (Bappu 1974–75: 9). He also praised Naegamvālā's solar eclipse observations:

> The report of this successful expedition indicates the great care and thoroughness that went into the planning of the expedition. (Bappu 1974–75: 13).

Much earlier, Sir Norman Lockyer (1898: 21) had voiced a similar opinion when he evaluated Naegamvālā's spectroscopic observations of the 1898 solar eclipse, describing him as

> . . . the only person in India at that time who was well qualified to carry out worthwhile investigation into solar physics.[3]

8.3 Naegamvālā, Michie-Smith and the Founding of the Kodaikanal Observatory

It is appropriate here to say a few words about the establishment of the Solar Observatory at Kodaikanal.

Despite his extensive international connections, it is known that Naegamvālā did not have contact with other astronomers working in India, so initially he may have been completely unaware of the developments that led to the establishment of the first solar physics observatory in India, particularly the efforts by Madras Observatory Director Norman Pogson (1829–1891), and after his retirement in 1891 by Charles Michie-Smith (1854–1922)—who was actually the main spirit behind the establishment of Kodaikanal Observatory (see Ansari 1985: 26–28). In a recent paper Kameswara Rao et al. (2014b) trace the developments that led eventually to the actual establishment of the observatory at Kodaikanal, between 1892 and 1895. In fact, as I pointed out previously:

> The Indian Observatories Committee by its resolutions on 26 Oct.1892 (Chairman Lord Kelvin) and on 20 July 1893 (Chairman President of RAS) approved the establishment of a

[3]In addition, an unattributed remark in the Bombay Archives (No. 799, dated 23 June 1899), states that "Naegamvala earned a name in three continents."

> Solar Physics Observatory at Kodaikanal under the directorship of Michie Smith. (Ansari 1977: 255).

In October 1895, the foundation of the new Observatory was laid by the Governor (Kameswara Rao 2014b: 457–458).

It is possible that Naegamvālā only learnt of these developments when he discussed the future of solar astronomy in India with William Christie and newly knighted Sir Norman Lockyer at Jeur in 1898, but by this time it was 'too little too late', so at least he might have thought to secure the status of Takhtasingji Observatory as an astrophysical observatory in order to ensure that it would survive after his retirement. But he did not do this.

Perhaps Naegamvālā was unhappy—even bitter—about the Kodaikanal appointment for it is significant that after the 1902 solar eclipse monograph appeared he published no more research papers, and he seems to have made little use of the 20-in telescope or the other facilities at Takhtasinghji Observatory (Kochhar and Orchiston 2017).

8.4 *The Fate of Takhtasingji Observatory and Its Instruments*

It was fateful irony that the Government of India decided, after Naegamvālā retired in 1912, that Takhtasingji Observatory would be closed and the instruments transferred to the Solar Observatory at Kodaikanal (Sohini 1951: 5–7). Thus, a purely Indian initiative to promote astrophysics in an Indian educational institution was nipped in the bud. Note, in this context, that Nizamiah Observatory at Osmania University (in Hyderabad) was founded in 1901, but only became fully operational in 1908.

The Government directive was carried out, and all of the Takhtasingji Observatory instruments were transferred to Kodaikanal Observatory in 1912. When the 20-inch reflector reached Kodaikanal it finally fulfilled a longstanding dream of former Madras Observatory Director, N.R. Pogson, to install such a telescope at a hill station:

> It was the largest telescope in the country at that time and served as the principal instrument for stellar observations for a long time. (Bhattacharyya and Vagiswari 1985, 413–414).

Later it was renamed the Bhavnagar Telescope, and has been described by Kameswara Rao et al. (2014a) as "... the most widely travelled telescope in the country." As they noted, after arriving at Kodaikanal Observatory

> It took different forms and configurations ... From Kodaikanal it went to Kavalur and then to Leh and back to Kodaikanal [where it remains]. (Kameswara Rao et al. 2014a: 619).

Unfortunately, there are no photographs of this famous historic telescope in its Grubb 16.5-in or a Grubb/Common 20-in Takhtasingji Observatory configurations, but there is an image of it taken during the 1980s, when it was located at Leh for site-testing, and this is reproduced here in Fig. 9.

Fig. 9 A photograph of the 20-in Bhavnagar Telescope when it was at Leh between 1984 and 1988 (adapted from Kameswara Rao et al. 2014a: 619)

9 Concluding Remarks

On the basis of original records extant in Bombay Archives and Family Papers of Naegamvālā, I have tried in this paper to relate the story of the first astrophysical observatory in India and of its Director, K.D. Naegamvālā.

However, I need to record here that the first brief preliminary report on Takhtasingji Observatory in Poona was published by me already in 1977 as a short section in a general history of the early development of Western astronomy in India, which was actually the topic of my talk at the Tercentenary of the Royal Greenwich Observatory, held at Greenwich (14–18 July 1975). I then tried to update this on the basis of original archival records available at the Maharashtra Government Archives (Bombay) and Family Papers of K.D. Naegamvālā, on the occasion of the General Assembly of International Astronomical Union that was held in New Delhi in 1985 (see Ansari 1985: 36–40). I collected and included in my account data drawn from records in the Royal Greenwich Observatory Archives, which were later moved to Herstmonceux Castle. However, I do not claim to have conducted a definitive search, as far as the available Indian and international archival records are concerned.

To my mind the following questions require answers, if we are to understand the early history of the development of observational astrophysics in India:

1. Why didn't Naegamvālā keep up-to-date with the general development of astronomical physics in India during the last decade of the nineteenth century?
2. Since Naegamvālā's work was recognised by famous foreign astronomers, why didn't he establish formal connections with relevant British Government officials in New Delhi, either directly himself or through Norman Lockyer?
3. Why didn't Naegamvālā hire any assistant to help him increase his observations and the output of publications?
4. What did he do after retirement in 1912? He only passed away in 1938 (more than two and a half decades later)?

I hope that some young historian of astronomy under the supervision of a senior astronomer may be motivated to collect further relevant data from records in England, at the India Meteorological Department in New Delhi and at the archives at Kodaikanal Observatory, and thereby study more thoroughly Naegamvālā's contribution to Indian and international astronomy.

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The Emergence of Radio Astronomy in Asia: Opening a New Window on the Universe

Wayne Orchiston and Govind Swarup

Abstract Some countries in the greater Asian area, namely Australia, China, India, Japan and New Zealand, played important roles in the early development of radio astronomy from the 1940s through into the 1960s. In this paper—which is based on the Public Lecture that we presented in Pune during the ICOA-9 conference—we trace these early developments. We then finish this review paper by briefly surveying the exciting new radio astronomical developments that are currently occurring throughout the greater Asian region.

1 Introduction

Radio astronomy is one of the newest specialist areas of astronomy, and was founded less than a century ago. Between 1930 and 1933 the American physicist and radio engineer Karl Guthe Jansky (1905–1950; Fig. 1), working at Bell Telephone Laboratories field station near Holmdel, New Jersey, used the 'merry-go-round' antenna shown in Fig. 2 and a receiver tuned to 20.5 MHz to investigate 'anomalous propagation' that turned out to be radio emission from our Galaxy (Sullivan, 1984b). After writing several research papers on this unusual discovery Jansky was assigned to another project, and so ended his all-too-brief sojourn in what would 15 years later would become the new field of 'radio astronomy'. Fig. 3 shows the electromagnetic spectrum, and the location of the broad 'radio window' (in red) relative to the narrow optical window, which is marked in yellow.

One of the few individuals who took an avid interest in Jansky's publications was Grote Reber (1911–2002, Fig. 4), a young American radio engineer living in

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Fig. 1 Karl Guthe Jansky. (en.wikipedia.org)

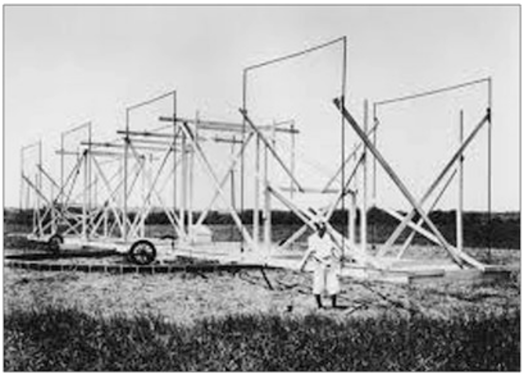

Fig. 2 Jansky's 'merry-go-round' antenna. (Courtesy: National Radio Astronomy Observatory)

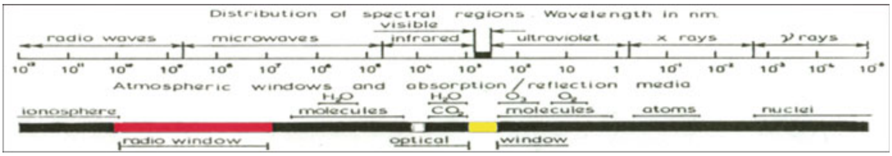

Fig. 3 The electromagnetic spectrum, showing the location of the 'radio window'. (Modifications: Wayne Orchiston)

Wheaton, Illinois, who went on to build the world's first dedicated radio telescope, a 9.75-m 'dish' (Fig. 5) and use this to investigate galactic radio emission at 160 MHz (Kellermann, 2005).

If Jansky was the 'discoverer' and Reber the 'founding father' of radio astronomy, it was World War II that acted as the nursemaid that allowed this new field of astronomy to blossom, thanks largely to the development of radar technology (see Lovell, 1977; 1983).

Fig. 4 Grote Reber. (Courtesy: National Radio Astronomy Observatory)

Fig. 5 Reber's 32-ft (9.75-m) parabolic antenna built at Wheaton in 1937. (Courtesy: National Radio Astronomy Observatory)

Solar radio emission was first detected during the War (among other places, in New Zealand and Australia), but it was other later discoveries that fundamentally changed our perception of the Universe. These include:

- Pulsars (evidence of neutron stars)
- The Cosmic Microwave Background (the Big Bang Theory)
- Molecules in Space (Star-formation; ingredients of life)
- Rotation curves of galaxies (evidence of Dark Matter)
- Magnetic fields in galaxies (galaxy evolution)
- Radio Galaxies and Quasi-Stellar Objects (black holes in galactic nuclei)

These discoveries, and others, rest on firm historical foundations.

2 The Emergence of Radio Astronomy in the Greater Asian Region

In this Section countries are considered in the chronological order in which they first began serious research in radio astronomy. Surprisingly, the first of these countries was New Zealand.

2.1 New Zealand

New Zealand's first encounter with radio astronomy occurred in 1945 when the Head of the Department of Scientific and Industrial Research's Wellington-based Radio Development Laboratory, British-born geologist and physicist Dr. Elizabeth Alexander (1908–1958; Fig. 6; Harris, 2018), investigated anomalous increases in 200 MHz 'radio noise' observed at the Norfolk Island radar station between 17 March and 1 April. This was dubbed the 'Norfolk Island Effect'.

Fig. 6 Dr. Elizabeth Alexander, the world's first female radio astronomer. (Courtesy: Mary Harris)

Fig. 7 A map of New Zealand showing early radio astronomy sites mentioned in the text, including the five RNZAF radar stations: (1) Norfolk Island; (2) North Cape; (3) Whangaroa; (4) Maunganui Bluff; (5) Piha. (Map: Wayne Orchiston)

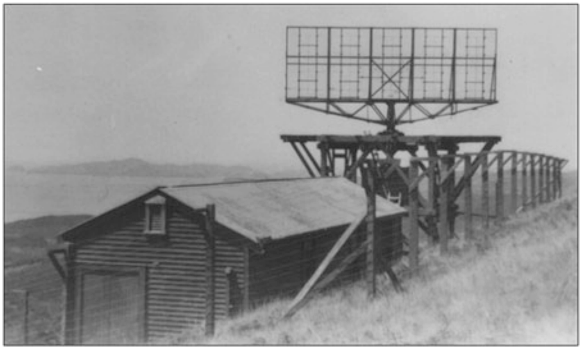

Fig. 8 The WWII Whangaroa radar station, showing the 200 MHz broadside antenna and the associated technical hut. (Orchiston Collection)

Alexander arranged to monitor this anomalous radiation from 10 to 23 April 1945 with the Norfolk Island antenna and four other identical Royal New Zealand Air Force radar units located in the northern part of the North Island of New Zealand. Their geographical distribution is indicated in Fig. 7 (along with other New Zealand localities mentioned in this paper) and one of the radar stations is shown in Fig. 8. Table 1 shows the results of this investigation, where the anomalous radiation was detected on almost all days when monitoring occurred.

Alexander concluded that "… at sunrise and sunset a detectable amount of noise over and above normal noise is received from a direction roughly that of the sun." (Alexander, 1945: 4). She stressed that while the observations were crude "… they do seem to indicate that more energy is sometimes radiated from the sun on 200 Mc/s

Table 1 Days when solar monitoring took place (●) and when solar radio emission was detected (⦿) at the different RNZAF radar stations

Radar station	Date in April 1945													
	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Norfolk Island			⦿	●	⦿	●	●	●	●	●	⦿	⦿	●	⦿
North Cape		⦿	●	⦿	●	●	●	●						
Whangaroa			●	●	⦿	⦿	⦿	⦿	⦿					
Maunganui Bluff		●	⦿	●	⦿	⦿	⦿	⦿						
Piha	●	●	●	⦿	●	●	●	●	⦿	⦿				

than would be expected on black body theory." (ibid.); in other words, the emission was non-thermal. Because of wartime security issues these results were only shared with staff at the Council of Scientific and Industrial Research's Division of Radiophysics in Sydney, Australia, which also was involved in radar development and research.

In order to investigate this solar emission further, Alexander then arranged for Royal New Zealand Air Force, Army and Navy radar units to monitor the Sun from July to December 1945, and on 5 October ". . . violent surges of noise were observed at regular intervals. These surges were of momentary duration and sent the noise meter needle hard over."

With the war now over in the Pacific the New Zealand radar stations were soon closed down as was Dr. Alexander's Radio Development Laboratory, and after publishing a brief report on this work (Alexander, 1946) she joined her husband, Professor Norman Alexander, and they eventually returned to Singapore and she to her pre-war research on local geology. It was only through a strange set of war-time circumstances that she ended up being the world's first female radio astronomer, but after WWII she never again carried out research in this field (Orchiston, 2016a).

It turned out that Alexander's research was the catalyst that encouraged other solar radio astronomy projects in New Zealand in the immediate post-war years. In 1947–1948 a young physics graduate student named Alan Maxwell carried out research using 100 MHz twin Yagi antennas at Auckland University College for an M.Sc. (Maxwell, 1948). His was surely among the earliest radio astronomy post-graduate theses completed anywhere in the world (Orchiston, 2017). Maxwell then left New Zealand to embark on a Ph.D. in England, and went on to become a respected Harvard University Professor, founder of the Fort Davis radio astronomy field station, and authority on solar radio emission (Thompson, 2010). Although he published prolifically after leaving New Zealand, Maxwell never published material from his Master thesis.

Another solar research project, also carried out during 1947–1948, was conducted by Bob Unwin (Elizabeth Alexander's former colleague) and Ivan Thomsen, the Director of Carter Observatory in Wellington. They used a 97.5 MHz ex-WWII radar antenna and receiver sited at Wakanui Beach, and later nearby Ashburton

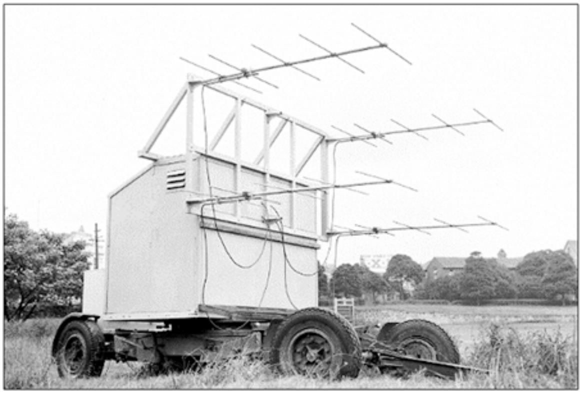

Fig. 9 The mobile 4-Yagi sea interferometer used for the New Zealand observations. (Courtesy: CRAIA). (CRAIA = CSIRO Radio Astronomy Image Archive, which is now under the care of CASS (CSIRO Astronomy and Space Sciences) at Marsfield in Sydney)

Airport to search for solar emission immediately after sunrise and before sunset. Although they detected many solar bursts, again no publications derived from this investigation.

Almost as if to make amends, in 1948 Ivan Thomsen published a paper in *Nature* on the correlation between optical feature on the Sun (based on New Zealand observations) and solar radio emission (Thomsen, 1948). To our knowledge, this was the first time that a resident New Zealand astronomer published in *Nature*.

This flurry of activity in 1948 brought New Zealand's intensive four-year foray into solar radio astronomy to an abrupt end, as Alexander and Maxwell enjoyed new lives in Singapore and England, Unwin began research on radio-meteorology and Thomsen concentrated on optical investigation of the Sun.

However, this was not the end of New Zealand involvement in radio astronomy *per se*, as two scientists from Australia, John Bolton and Gordon Stanley, spent 2 months near Auckland in June–August 1948 observing 'radio stars' with the small mobile radio telescope shown in Fig. 9 while the third member of the research team, Bruce Slee, continued parallel observations from Dover Heights in Sydney (see Orchiston, 1993). Their objective was to obtain accurate positions for a number of so-called 'radio stars' so that they could see if any of these had optical correlates. As it turned out, the New Zealand expedition was a resounding success: the Taurus A radio source turned out to be associated with the Crab Nebula (Fig. 10), and Centaurus A and Virgo A with two unusual galaxies (Figs. 11 and 12), which were later shown to be extragalactic objects. What the New Zealand observations showed, more than anything else, was that these discrete radio sources were not connected with stars—that the term 'radio stars' was a misnomer (Orchiston, 2016c; Robertson et al., 2014).

After this illustrious start, nearly half a century would elapse before New Zealand would once again begin to contribute to international radio astronomy (e.g. see Head, 2010). In contrast, during this period radio astronomy thrived in neighbouring Australia (see Sullivan, 2009).

Fig. 10 Taurus A was associated with the Crab Nebula, the remains of a supernova that exploded in AD 1054. (Courtesy: Jeff Hester and Paul Scowen, Arizona State University, and NASA/ ESA)

Fig. 11 Centaurus A was associated with the galaxy NGC 5128, with its unusual dark dust lane. (Courtesy: Eric Peng, Herzberg Institute of Astrophysics, and NOAO/AURA/NSF)

Fig. 12 Virgo A was associated with NGC 4486, a giant elliptical galaxy with an unusual optical jet. (en.wikipedia.org)

2.2 Australia

2.2.1 Introduction

Radio astronomy in Australia had its origins in the founding in 1940 of the Commonwealth Scientific and Industrial Research's Division of Radiophysics (henceforth RP), that was charged with developing radar during WWII. In August 1945 Dr. Elizabeth Alexander sent RP her report on the 'Norfolk Islands Effect' and this inspired the Australians to replicate her work, using radar antennas sited near Sydney (Orchiston, 2016a). At this time RP was reviewing research fields to pursue following the War, and the promising results from their study of solar radio emission between October 1945 and January 1946 justified the selection of radio astronomy as one of these fields (Sullivan, 2017).

While RP was conducting this research, unbeknown to them a young Royal Australia Air Force radar operator named Bruce Slee independently detected solar radio emission from near Darwin (see details see Orchiston and Slee, 2002a). Soon he was invited to join RP, where he remained throughout his career, and built an international reputation (see Orchiston, 2004a).

From this start, radio astronomy developed rapidly at RP, as the following review will reveal, but for a short time in the late 1940s there also were small but very active radio astronomy groups at Mt. Stromlo Observatory, near the Australian capital city, Canberra, and in the Physics Department at the University of Western Australia in Perth, on the far side of the continent (Orchiston et al., 2006). For Australian localities mentioned in this paper see Fig. 13).

In the mid-1950s a second major centre of radio astronomy emerged in the island state of Tasmania, to the south of the Australian mainland, where Professor Graeme ('Bill') Ellis from the Physics Department at the University of Tasmania (in Hobart, the state capital city) and the radio astronomy pioneer, Grote Reber—who had relocated from the USA—built a succession of low frequency arrays (see George et al., 2015), culminating in the world's first 'square kilometre array' at Bothwell (George et al, 2017). Because research on these Tasmanian developments is ongoing, and is being published in a succession of papers by Martin George for his Ph.D., it is premature to include this important Tasmanian work in the following Australian review.

2.2.2 The RP Field Stations

At the end of WWII Dr. Joe Pawsey (1908–1962; Fig. 14; Lovell, 1964), the dynamic Head of Radio Astronomy at RP, decided to set up a number of field stations in or near suburban Sydney. By the early 1960s these field stations and associated remote sites had mushroomed in number, eventually totalling twenty. Their geographical distribution is shown in Fig. 15, which also includes the Radiophysics Building, located in the grounds of the University of Sydney, where high frequency solar and lunar observations were made in the late 1940s using a small dish located at the very top of the building.

Fig. 13 Australian localities mentioned in the text. (Base map: https://forums.envata.com/t/Australia-map-vector-hard-rejected/72230; Map modifications: Wayne Orchiston)

Fig. 14 Dr. Joseph Lade Pawsey. (Courtesy: CRAIA)

In the interests of space, not all of the RP field stations shown in Fig. 15 are included in the following review. Those excluded are sites 1, 8 and 13 in Fig. 15, i.e. Badgerys Creek (Orchiston and Slee, 2017), Georges Heights (Orchiston, 2004b) and Murraybank (Wendt et al, 2011b) respectively. See, also, Robertson (1992).

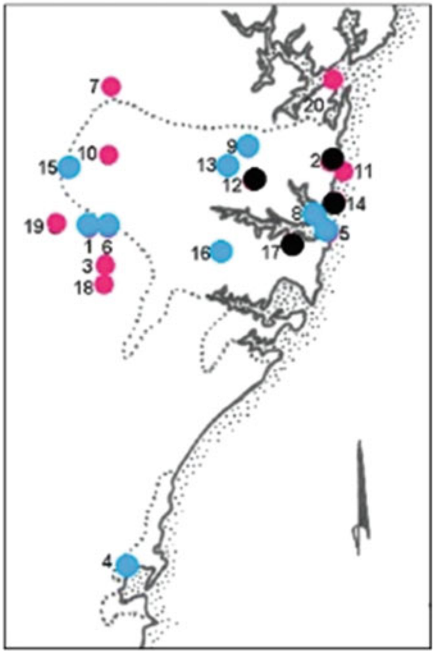

Fig. 15 Radio astronomy localities in the Sydney-Wollongong region; the dotted outlines show the current approximate boundaries of Greater Sydney and Greater Wollongong. Key. Field stations: blue; remote sites: red; other sites: black. 1 = Badgerys Creek, 2 = Collaroy, 3 = Cumberland Park, 4 = Dapto, 5 = Dover Heights, 6 = Fleurs, 7 = Freeman's Reach, 8 = Georges Heights, 9 = Hornsby Valley, 10 = Llandilo, 11 = Long Reef, 12 = Marsfield (ATNF Headquarters), 13 = Murraybank, 14 = North Head, 15 = Penrith, 16 = Potts Hill, 17 = Radiophysics Laboratory (Sydney University grounds), 18 = Rossmore, 19 = Wallacia, 20 = West Head. For scale: from Dapto (site 4) to Dover Heights (site 5), as the crow flies, is 88 km. (Map: Wayne Orchiston)

2.2.3 Dover Heights

Dover Heights field station (site 5 in Fig. 15) was located on the coast just south of the entrance to Sydney Harbour, and was a former WWII radar station. Radio astronomy was carried out here from 1946 (when the site was released by the Army) until 1954, and the leading scientists there were John Bolton (1922–1993; Robertson, 2017), Gordon Stanley (1921–2001; Kellermann et al., 2005) and Bruce Slee (1924–2016).

Their research was mainly non-solar, and focussed on discrete sources after Hey et al. (1946) reported the discovery in England of a strong localised variable radio source in the constellation Cygnus. Bolton, Stanley and Slee used cliff interferometers for their observations, and after confirming the existence of Cygnus A they searched for other sources, and by the end of 1947 had found five more. The cliff interferometer operated like a Lloyd's Mirror, with one incoming signal from the radio source arriving directly, while the other was reflected off the sea, giving a sinusoidal interference pattern (see Fig. 16). These interference fringes provided the position and upper limit to the size of a source, but to improve these much higher cliffs than at Dover Heights were called for.

This is why Bolton and Stanley made the trip to New Zealand in 1948, referred to earlier, where the 300-m cliffs were a vast improvement of the 79-m cliff at Dover Heights. As we saw, this excursion produced positions that led to the first optical identifications of these sources. Most of the early observations were made at 100 MHz with simple 2- or 4-Yagi antennas, but from 1949 increasingly more sophisticated Yagi arrays were constructed, culminating in the 12-Yagi sea interferometer shown in Fig. 17. A survey with this instrument revealed 104 discrete radio sources, scattered over the whole of the sky that was visible from Dover Heights (Fig. 18).

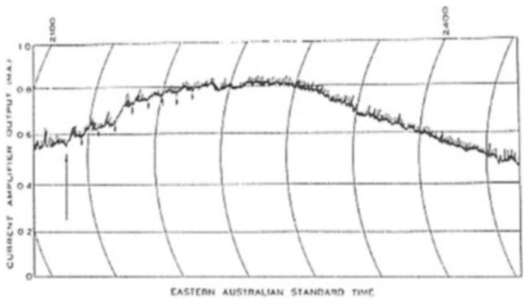

Fig. 16 The 6 November 1947 discovery chart record of Taurus A; the small arrows indicate the interference fringes. (After Slee, 1994: 522)

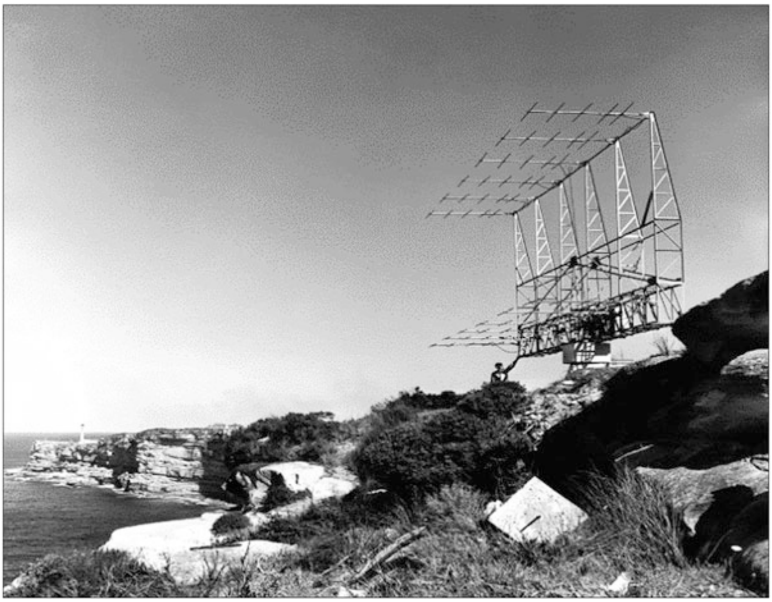

Fig. 17 The 12-Yagi sea interferometer which was constructed in 1952, replaced earlier 8-Yagi and 9-Yagi antennas. (Courtesy: CRAIA)

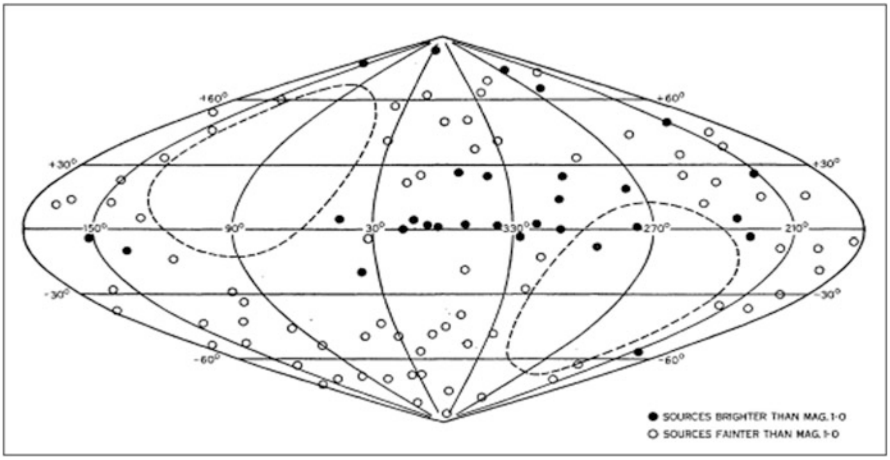

Fig. 18 The 104 discrete sources detected with the 12-Yagi radio telescope. (Bolton et al., 1954: 126)

The final Dover Heights project we will describe is the remarkable 'hole-in-the ground' radio telescope. In 1951 John Bolton was unsuccessful in obtaining funding for a new much larger sea interferometer, so he decided that they would construct a new radio telescope themselves. Over a 3-month period, Bolton and Slee spent their lunchtimes excavating a 72-ft (21.9-m) diameter parabolic hole in the sand, lined this with thin metallic reflecting strips, installed a mast with a dipole, attached this to a 160 MHz receiver, and succeeded in detecting galactic emission. With the concept proven, they received funding support from RP to expand the antenna to 80 ft. (24.4 m), concrete the surface of the parabola, and install a 400 MHz receiver.

Obviously this was a transit instrument that looked at the zenith, and relied on the rotation of the Earth to monitor the sky, but the declination band surveyed could be changed by altering the tilt of the aerial mast—and hence the position of the dipole (see Fig. 19). Using this ingeniously-conceived radio telescope, Stanley, Slee and a newcomer to Dover Heights, Dick McGee, mapped a strip of sky, recording 14 discrete sources. The strongest of these was located at the position of the centre of our own Galaxy (Goss and McGee, 1996), and was assigned the name Sagittarius A (Fig. 20). A detailed account of the Dover Heights 'hole-in-the-ground' radio telescope is provided by Orchiston and Slee (2002c).

2.2.4 Hornsby Valley

Hornsby Valley field station (site 9 in Fig. 15) was located on a farm in a secluded radio-quiet valley on the northern outskirts of Sydney (Fig. 21). Radio astronomy was carried out here from 1948 until 1955, and the scientists involved were Frank Kerr (1918–2000; Westerhout, 2000), Ruby Payne-Scott (1912–1981; Goss, 2013) and Alex Shain (1922–1960; Pawsey, 1960).

Fig. 19 The 80-ft ‘hole-in-the-ground’ antenna at Dover Heights. Gordon Stanley is using a theodolite to record the tilt of the aerial mast. (Courtesy: CRAIA)

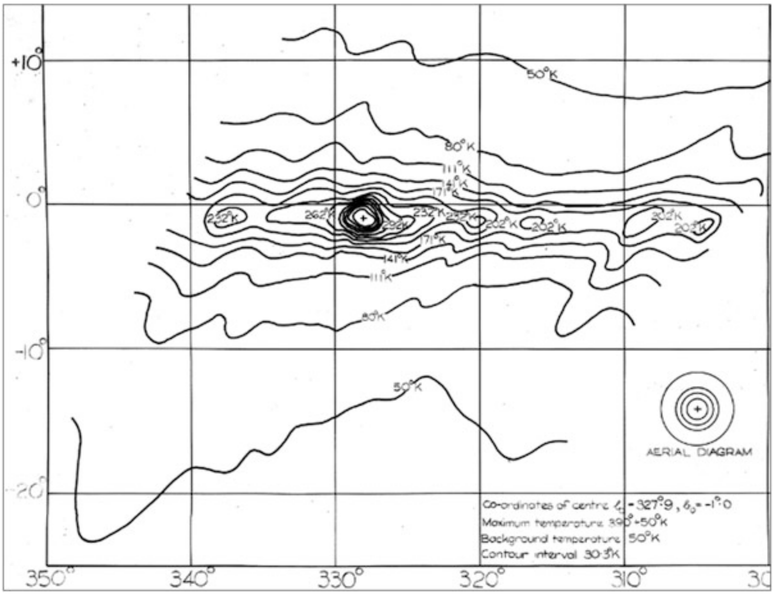

Fig. 20 A plot of 400 MHz radio emission along the Galactic Plane showing the strong source, Sagittarius A, at the Galactic Centre. (Courtesy: CRAIA)

Fig. 21 The Hornsby Valley field station. (Courtesy: CRAIA)

The first research carried out at Hornsby Valley was in radar astronomy, when Frank Kerr and Alex Shain investigated the Earth's ionosphere by recording low frequency radio signals bounced off the Moon. In the process they learned something about the surface structure of the Moon.

After Frank Kerr transferred to Potts Hill field station, Alex Shain and his assistant Charlie Higgins, built Hornsby Valley into RP's principal low frequency radio astronomy facility. Their first radio telescope consisted of dipoles suspended between power poles attached to an 18.3 MHz receiver, and they used this in 1949 and 1950 to survey the sky—the first such survey since Jansky's pioneering observations at about the same frequency. Shain and Higgins produced an isophote plot of 18.3 MHz emission and a map of discrete sources discovered (see Fig. 22).

After rewiring their array, in 1951–1952 Shain and Higgins then carried out a survey of the sky at 9.15 MHz, the lowest frequency ever attempted up to that time (though a few years later Ellis and Reber in Tasmania would dip way below this), but this was near the limit of ionospheric transmission and there also were problems with manmade interference. Nonetheless, they did produce some results.

For a short time, Hornsby Valley also was associated with solar radio astronomy. At the end of 1947 Australia's pioneering female radio astronomer, Ruby Payne-Scott, transferred from Dover Heights to the Valley, and carried out solar observations, mainly at 60 and 85 MHz, before mimicking Frank Kerr and transferring to Potts Hill.

One of the unexpected outcomes of the Hornsby Valley research occurred in 1956 when the American pair of Burke and Franklin reported the discovery of decametric burst emission from Jupiter. This led Shain to contemplate the many instances of

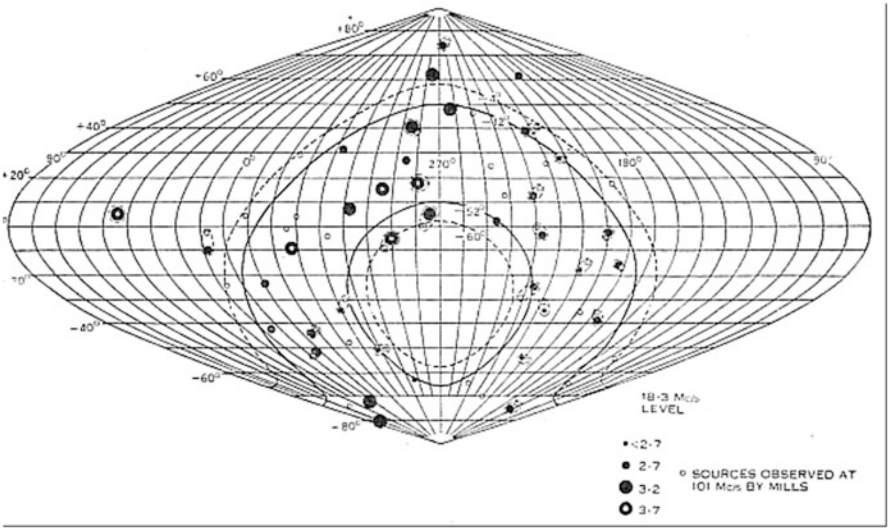

Fig. 22 The galactic distribution of discrete sources detected at 18.3 MHz. (After Shain and Higgins, 1954: 142)

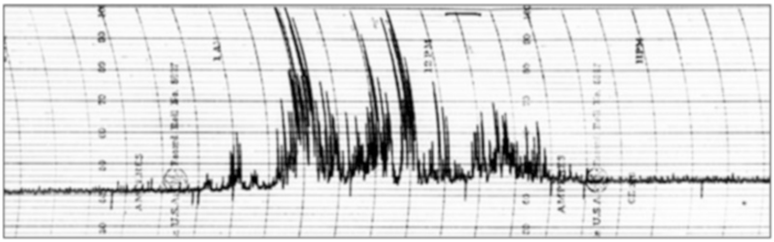

Fig. 23 An example of Jovian bursts detected at 18.3 MHz on 17 October 1950. (Adapted from CRAIA)

annoying 'interference' he and Higgins had to contend with back in 1949 and 1950, and when he investigated these he found many examples of Jovian emission (e.g. see Fig. 23).

For a detailed account of the Hornsby Valley field station see Orchiston et al. (2015b).

2.2.5 Potts Hill

Potts Hill field station (site 16 in Fig. 15) was located at a Sydney metropolitan water reservoir facility in what was then a far western suburb of Sydney (Fig. 24). Radio astronomy was carried out here from 1949 until 1963, and the main scientists involved were 'Chris' Christiansen (1912–2007; Wendt et al., 2011a), Frank Kerr,

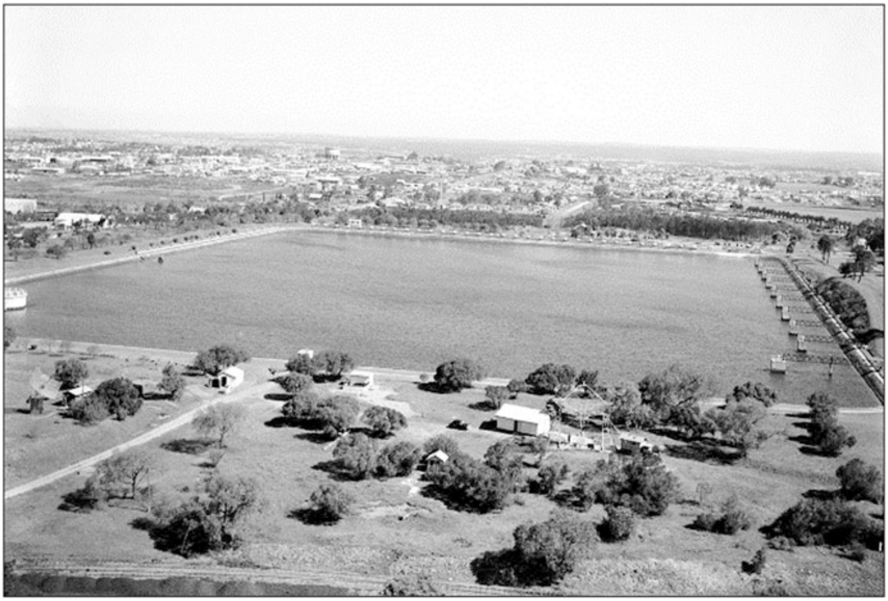

Fig. 24 A view looking south across the easterly of the two Potts Hill water reservoirs. At one time or another radio telescopes were set up along the southern and eastern edges of the water reservoir, and on the flat land in the foreground to the north of the reservoir. (Courtesy: CRAIA)

Jim Hindman (b. 1919); Alec Little (1925–1985); Bernie Mills (1920–2011; Frater et al., 2013), Harry Minnett (1917–2003; Thomas and Robinson, 2005), Ruby Payne-Scott, Jack Piddington (1910–1997; Melrose and Minnett, 1998) and Brian Robinson (1930–2004; Whiteoak and Sim, 2006).

Solar, galactic, extra-galactic and hydrogen-line research all were carried out at Potts Hill, which featured a wide variety of different radio telescope types (e.g. see Orchiston and Wendt, 2017).

Multi-wavelength observations using a number of different radio telescopes were carried out from Potts Hill during the 1 November 1948 partial solar eclipse. These revealed the positions of the various sources of radio emission at this time (see Orchiston et al., 2006).

Two innovative solar-related developments then occurred. In 1949 Payne-Scott and Little installed a 3-Yagi position interferometer along the northern margin of the water reservoir. The first of its kind in the world, this operated at 97 MHz and allowed the positions and polarisation characteristics of solar burst to be quickly determined.

Soon afterwards, Christiansen constructed the world's first solar grating interferometer, which was designed to probe the locations of 1.42 GHz emitting regions in the solar corona. The array was set up in 1952 along the southern edge of the reservoir, and consisted of 32 solid-metal dishes each 1.8-m (66-in) in diameter (Fig. 25). It produced strip-scans of the Sun, which showed the development and

Fig. 25 A view looking east along the first solar grating array, with Chris Christiansen in the foreground. (Courtesy: CRAIA)

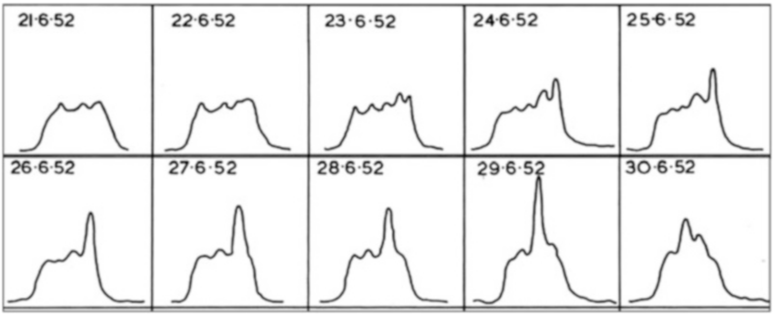

Fig. 26 A succession of daily strip-scans from 21 to 30 June 1952 showing the rapid growth and motion of a conspicuous radio plage. (Courtesy: CRAIA)

motion of radio plages in the corona (see Fig. 26). In 1953 a N-S array of larger mesh dishes was erected along the eastern margin of the water reservoir, and when the strip scans from both arrays were analysed they revealed that the 1.42 GHz radio Sun was elliptical (not circular) and exhibited equatorial limb-brightening (see Fig. 27). For further details of the grating arrays see Wendt et al., 2008a).

Potts Hill also was involved in significant non-solar radio astronomy. Between 1948 and 1950 Jack Piddington and Harry Minnett (1951) carried out surveys of the

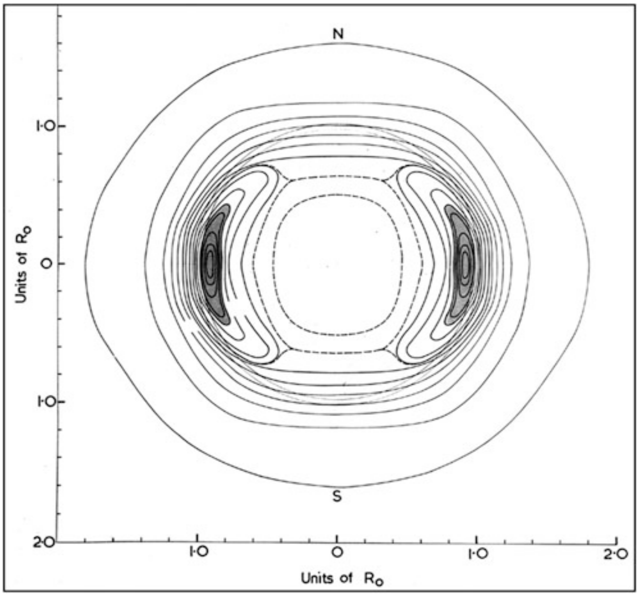

Fig. 27 The quiet Sun at 1.42 GHz showing equatorial limb-brightening. (Courtesy: CRAIA)

sky at 1.21 and 3 GHz. Undoubtedly their most important discovery was the Sagittarius A radio source at the Galactic Centre, several years *before* this was detected by the Dover Heights 'hole-in-the-ground' radio telescope and then publicised widely through the paper that McGee and Bolton (1954) published in *Nature*. Meanwhile, Piddington and Minnett's earlier 1951 paper languished in the *Australian Journal of Scientific Research* that, at the time, was still in its infancy and was little known to international astronomers (see Sullivan, 2017).

Undoubtedly the most important non-solar research carried out at Potts Hill was on 21-cm (1.421 GHz) hydrogen line emission. Following Ewen and Purcell's 25 March 1951 prepublication announcement of their detection of the line, Christiansen and Hindman cobbled together a primitive receiver, attached this to the ex-radar antenna shown in Fig. 28, and confirmed the existence of the H-line (Kerr, 1984). Christiansen and Hindman then proceeded to use this radio telescope to carry out the world's first all-sky H-line survey. They found that the neutral hydrogen was concentrated along the plane of our Galaxy.

This emphasis on the H-line demanded a new dedicated radio telescope. This took the form of an 11-m transit 'dish' (Fig. 29), which was constructed in 1952–1953 along with the world's first multi-channel H-line receiver. Christiansen then returned to solar work (with his grating arrays), and it was left to Kerr, Hindman and Robinson to continue the H-line program. First they carried out an examination of the Large and Small Magellanic Clouds—the first time neutral hydrogen was

Fig. 28 This antenna was originally at RP's Georges Heights field station, and had started life as an experimental radar aerial. At Georges Heights it was modified for radio astronomy and used for solar observations at 600 MHz and 1.2 GHz. In 1948 is was transferred to Potts Hill in time for the 1 November solar eclipse, and then was used by Piddington and Minnett for their all-sky surveys before serving as the initial H-line antenna. (Courtesy: CRAIA)

Fig. 29 The 11-m H-line antenna. (Courtesy: CRAIA)

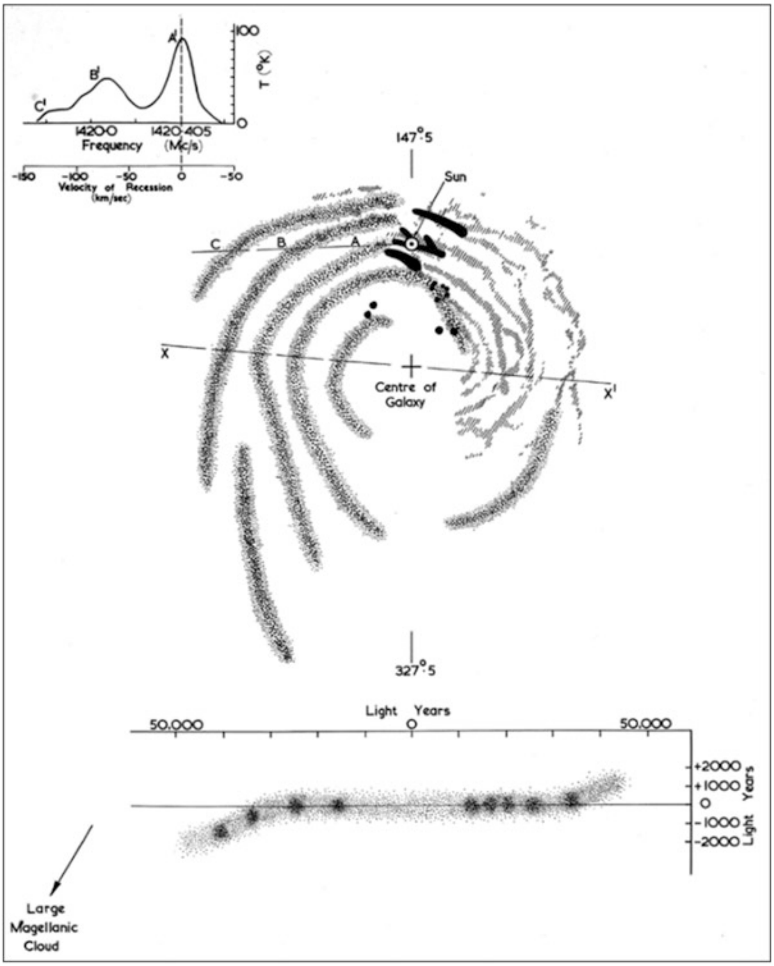

Fig. 30 H-line evidence of the spiral structure of our Galaxy, and the warping at the ends of the galactic plane. (Courtesy: CRAIA)

detected in extra-galactic objects—looking at the relative masses, dust contents and rotational properties of the two Clouds.

Kerr, Hindman and visiting Cornell University radio astronomer Martha Stahr ('Patty') Carpenter (1920–2013) then teamed up with Dutch colleagues to investigate the spiral structure of our Galaxy, using the distribution of neutral hydrogen to map the positions of the spiral arms. They also discovered that our Galaxy was warped (see Fig. 30), which was attributed to the tidal effect of the Large Magellanic Cloud. For further details of Christiansen's H-line work see Wendt et al. (2008b).

The final new radio telescope from Potts Hill we wish to introduce is the Mills Cross prototype. This unique radio telescope (Fig. 31) was invented by Bernie Mills in response to the quest for improved resolving power and consisted of a cross-

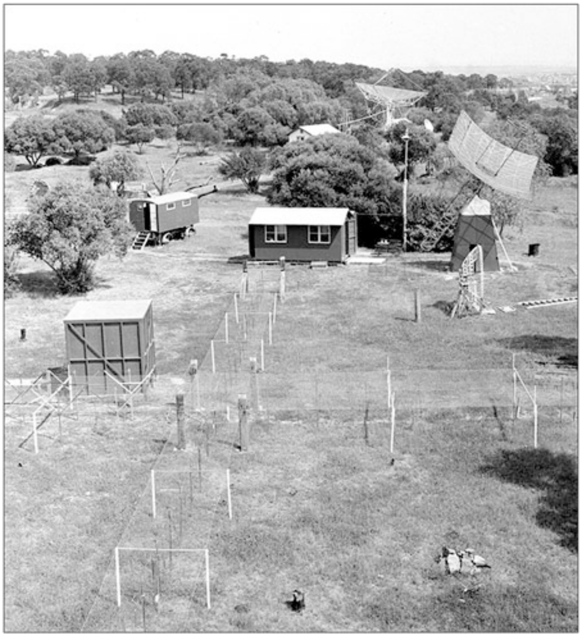

Fig. 31 The central area of the Mills Cross prototype in the foreground, with the ex-Georges Height and 11-m H-line antennas in the background. (Courtesy: CRAIA)

shaped antenna with 120-ft (36.6-m) N-S and E-W arms, each containing 24 half-wave E-W aligned dipoles. This prototype Cross produced an 8° pencil beam, and although it was a transit instrument, different areas of sky could be scanned as the Earth rotated by changing the phase of the dipoles in the N-S arm. As we shall see, the success of the Potts Hill prototype led to the construction of three much larger more sophisticated RP cross-type radio telescopes.

For further details of Potts Hill field station see Davies (2005, 2009) and Wendt et al. (2011c).

2.2.6 Fleurs

Fleurs field station (site 6 in Fig. 15) was located adjacent to an old WWII airstrip 40 km WSW of central Sydney, and was home to three different cross-type radio telescopes (Fig. 32). Radio astronomy was carried out here from 1954 until 1963, and the main scientists involved were Alan Carter, 'Chris' Christiansen, Eric Hill, Norman Labrum (1921–2011), Alec Little, Bernie Mills, Dick Mullaly (d. 2001), Alex Shain, Kevin Sheridan (1918–2010) and Bruce Slee (see Orchiston and Slee, 2002b).[1]

[1]This field station has special meaning to the first author of this paper, who began his career in radio astronomy there in November 1961, at first working as Bruce Slee's Research Assistant using the Shain Cross, and later operating the Chris Cross and producing the daily isophote maps of 1.42 GHz solar radio emission under the watchful eye of Richard F. ('Dick') Mullaly.

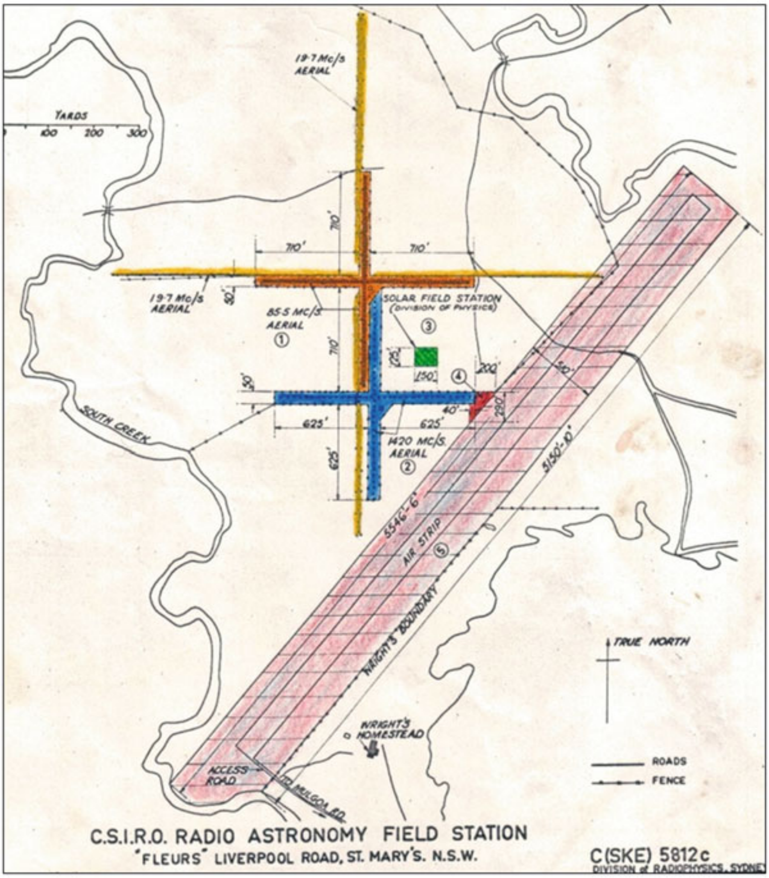

Fig. 32 A map showing Fleurs field station to the north of the WWII airstrip, and between South Creek and Kemps Creek. The three radio telescopes, in chronological order of construction, are the Mills Cross (brown), Shain Cross (yellow) and Chris Cross (blue). (Courtesy: CRAIA)

The first radio telescope at Fleurs was the 85.5 MHz Mills Cross constructed in 1953–1954 (Fig. 33). This had 460-m long N-S and E-W arms and a pencil beam of 49′ (regarded at the time as remarkable). As with the smaller Potts Hill prototype, this also was a transit instrument, with phasing of the dipoles in the N-S arm allowing different strips of the sky to be scanned.

The main research program of the Mills Cross was an all-sky survey, which was carried out by Mill, Slee and Hill between 1954 and 1957 and revealed ~2000 discrete sources, far more than any previous survey at around this frequency. When compared with sources recorded during the Cambridge 2C survey in England, the Fleurs results created international controversy because of their differing cosmological implications. This caused 'bad blood' between the RP and Cambridge astronomers for many years (Mills, 1984). After Mills left RP and joined the University of Sydney in 1960, Slee diversified the range of research programs involving the Cross,

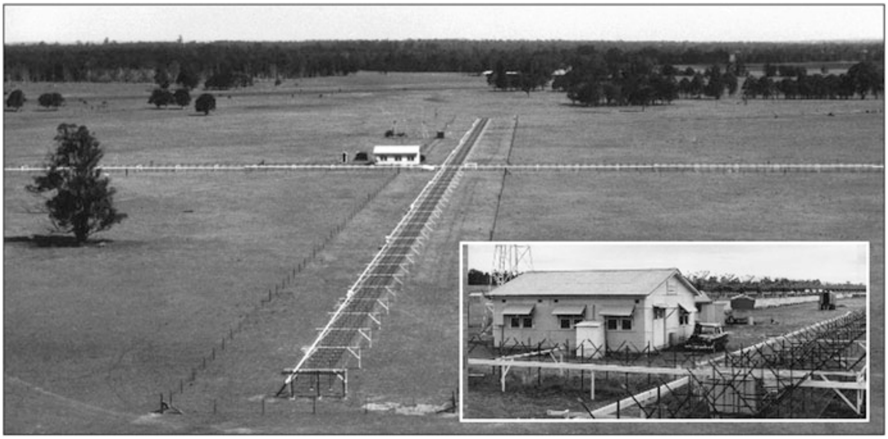

Fig. 33 An aerial view looking south along the N-S arm of the Mills soon after construction, also showing the receiver hut and part of the E-W arm. The inset, taken several years later, shows individual dipoles at the centre of the Cross, adjacent to the receiver hut. (Courtesy: CRAIA)

and it was used for studies of a comet, discrete source sizes and the solar corona (see Orchiston, 2005; Orchiston and Slee, 2017: Section 19.2.7).

In 1956 Fleurs gained its second major radio telescope with the completion of the 19.7 MHz Shain Cross (Orchiston et al., 2015a). This had a 1151-m N-S arm and 1036 E-W arm, with the dipoles 4 m above the ground and suspended between telegraph poles, and a beam of 1.5° (see Fig. 34). Shain and Higgins used this instrument to survey the Galactic Plane, noting that there was absorption caused by a band of HII regions (see the inset in Fig. 34). Shain also planned to research Jovian emission, but his untimely death in 1960 prevented this. Instead it was Slee, aided by Higgins, who used the Shain Cross and remote 19.7 MHz antennas located at Dapto (site 4 in Fig. 15), Jamberoo (south of Dapto) and at Heaton north of Fleurs (see Fig. 13), to investigate the location and size of the emitting region(s) generating the Jupiter bursts. From 1961, Slee also used the Shain Cross in conjunction with the Mills Cross and newly-commissioned 64-m Parkes Radio Telescope to investigate radio emission from flare stars (e.g. see Fig. 35), and along with Sir Bernard Lovell must be credited as the first radio astronomer to detect a genuine ‘radio star’.

The third cross-type radio telescope erected at Fleurs was the ‘Chris’ Christiansen’s Chris Cross, which became operational in 1957. This comprised 433-m long E-W and N-S arms, each containing 32 equatorially-mounted parabolic dishes 19-ft (5.8-m) in diameter (see Fig. 36). The Chris Cross combined the principles of the Mills Cross and Christiansen’s earlier Potts Hill grating interferometers. Electronically combining the signals from the two arms produced a network of pencil beams at the junction points of the fan beams. Each pencil beam was 3′ in diameter and was separated from its neighbours by 1°, so the Sun could never be in more than one pencil beam at any time.

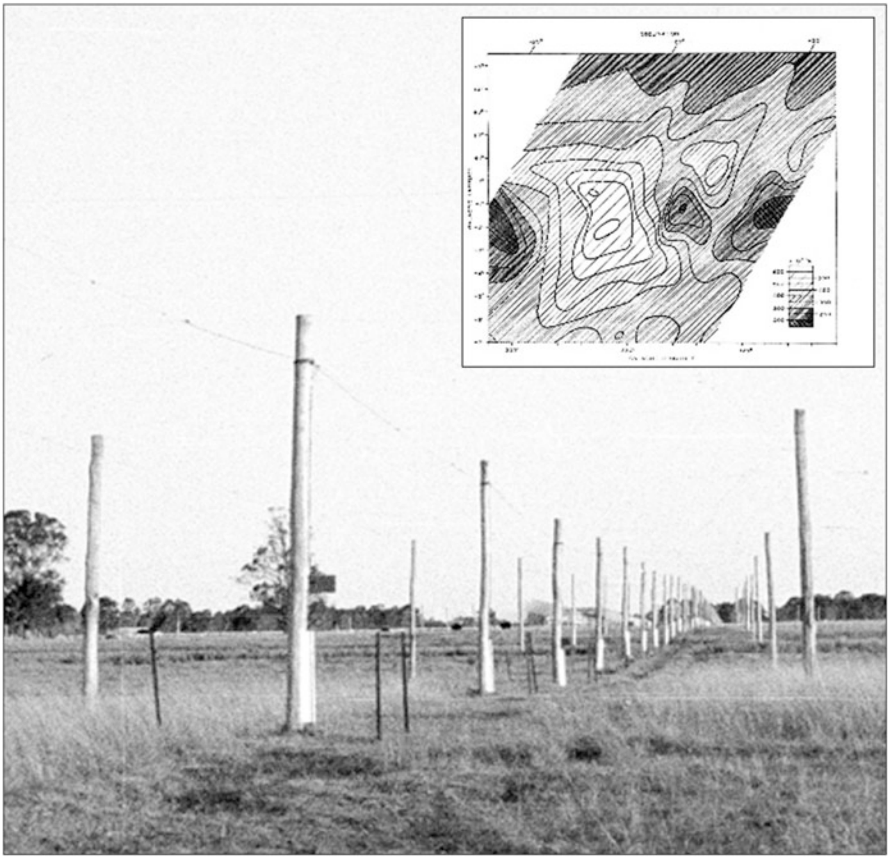

Fig. 34 A view looking west along the E-W arm of the Shain Cross. The inset isophote plot shows 19.7 MHz radiation in absorption at the Galactic Centre. (Courtesy: CRAIA)

The Chris Cross operated at 1.42 GHz and was designed to investigate the nature and evolution of radio plages. Driving the array across the Sun in the course of a day's observations produced a succession of strip scans, and these were then analysed to provide daily isophote maps of solar emission (Fig. 37). For a detailed review of the Chris Cross see Orchiston and Mathewson (2009), while Christiansen's very substantial overall contribution to RP radio astronomy is summarised by Wendt et al. (2011a).

2.2.7 Penrith and Dapto

Penrith field station (site 15 in Fig. 15) was located 50 km west of central Sydney at the foot of the Blue Mountain. In 1948–1949, Paul Wild (1923–2008; Stewart et al., 2011b) used a simple rhombic aerial and a swept-frequency receiver to investigate

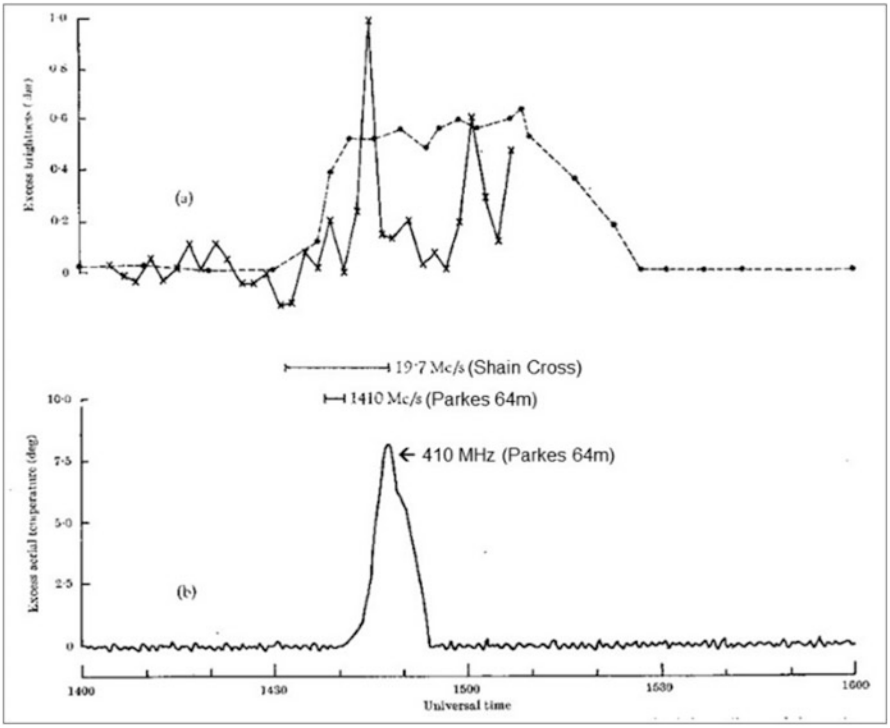

Fig. 35 Detection of radio emission at 19.7and 410 MHz and 1.41 GHz during an optical flare of V371 Orionis on 30 November 1962. The top plots show visual and photographic observations of the flare. (Adapted from Slee et al., 1963: 993)

Fig. 36 A view looking south along the N-S arm of the Chris Cross from near the centre of the array. (Courtesy: CRAIA)

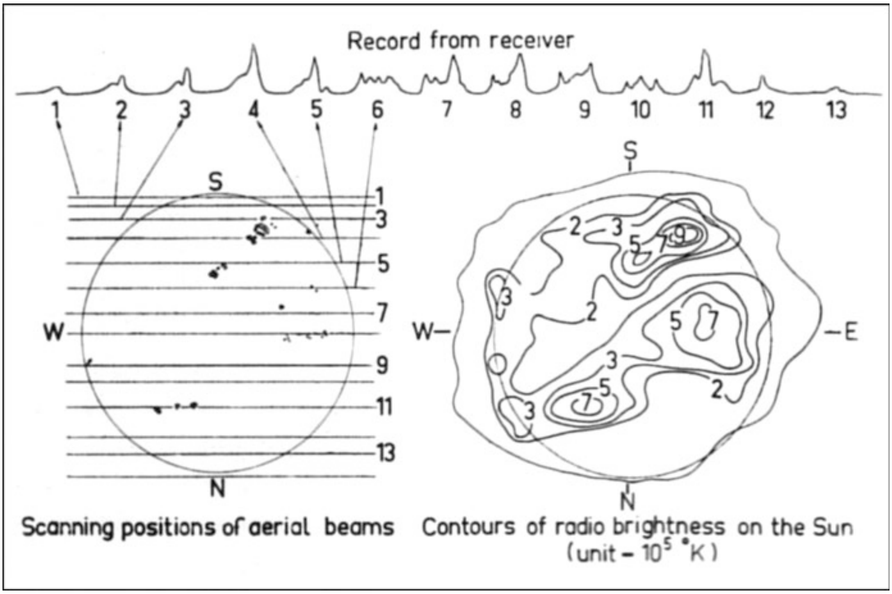

Fig. 37 A diagram showing 13 successive strip scans across different heliocentric latitudes of the Sun (top and left), and the resulting 1.42 GHz isophote plot. This includes three coronal radio plages, all of which correlate in position with photospheric sunspot groups. (Courtesy: CRAIA)

the nature of solar bursts in the 70–130 MHz frequency range. Wild quickly established the existence of three distinct spectral types of burst emission (named Type I, Type II and Type III), thereby justifying the expansion of this project, but at a more expansive radio-quiet location.

Wild's selection was a dairy farm, near the city of Wollongong, to the south of Sydney, and from 1952 to 1965 the Dapto field station (site 4 in Fig. 15) would play a leading role in international solar radio astronomy. Apart from Wild, other well-known radio astronomers who worked there, or analysed the Dapto solar observations back in Sydney, were Don McLean, John Murray, Jim Roberts, Kevin Sheridan, Steve Smerd (1916–1978; Wild, 1980), Ron Stewart, Shigamasa Suzuki (1920–2012) and Alan Weiss.

Initially Dapto field station featured three crossed rhombic aerials (Fig. 38) that could record the polarisation and intensity of solar emission over the frequency ranges of 40–75, 75–140 and 140–240 MHz. Between 1958 and 1963 the frequency range was increasingly expanded with the addition of new rhombic antennas and a 10-m parabola with a log-periodic feed until it extended from 5 MHz to 2 GHz. The Dapto radio astronomers quickly added Type V bursts and 'Reverse Drift Pairs' to the three earlier types that they had identified at Penrith (Fig. 39). They also observed Type IV noise storms, which were first reported by French radio astronomers (see Pick et al., 2011).

In 1957 two new instruments were installed at Dapto: a position interferometer that recorded real-time changes in the positions and sizes of the burst sources over

Fig. 38 A view of the Dapto field station showing the original three rhombic antennas and the receivers building. (Courtesy: CRAIA)

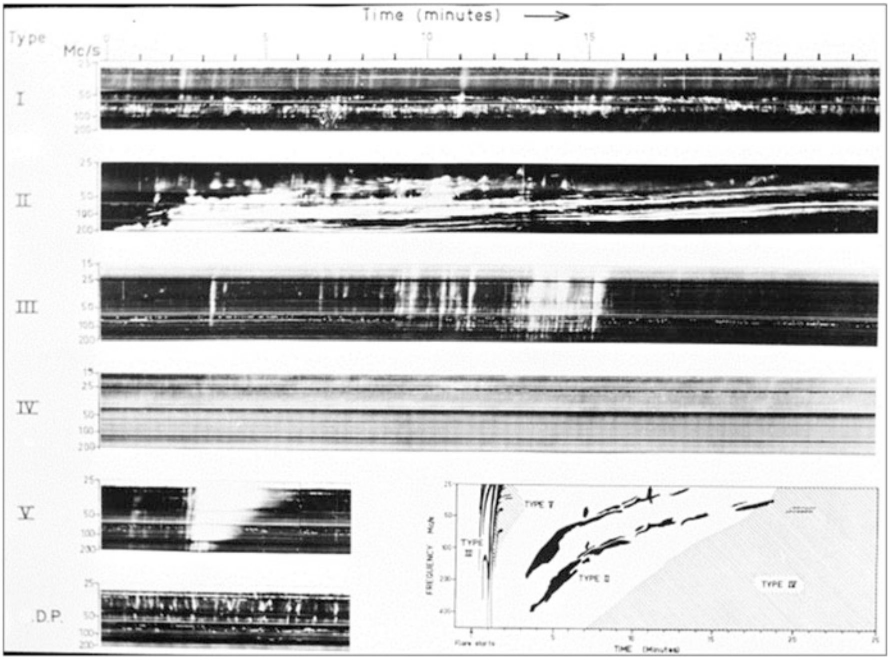

Fig. 39 Typical examples of the six different spectral types of solar bursts, five of which were first identified at Penrith or Dapto. The schematic at the lower right summarises their relative features. (Courtesy: CRAIA)

the frequency range 40–70 MHz, and a crossed rhombic antenna that simultaneously recorded the polarisation of the bursts. Elsewhere the late Bruce Slee and I reported that

> Members of RP's illustrious Solar Group then used data from the radio spectrographs, the position interferometer and the polarimeter to produce a succession of seminal research papers on the properties of the different types of solar bursts, and this is surely Dapto's greatest legacy. For more than a decade this field station was at the forefront of international solar radio astronomy, and through its innovative instrumentation ... was able to provide important new information on coronal properties, solar burst generation, and the association between solar radio emission and photospheric and chromospheric events and features ... (Orchiston and Slee, 2017: 546).

For details of the Penrith and Dapto field stations see Stewart et al. (2010, 2011a).

2.2.8 Parkes, Culgoora and the Demise of the Field Stations

For the 20 years following WWII Australia was the undisputed leader in radio astronomy (Sullivan, 2009), thanks largely to a relatively large pool of brilliant scientists, the innovative antennas and receivers designed by people like Bolton, Christiansen, Hindman, Little, Mills, Shain and Wild, and the special opportunities the RP field stations offered for fundamental research.

All this changed in November 1961 with the commissioning of the 64-m Parkes Radio Telescope (see Robertson, 1992), and all non-solar projects quickly were reassigned to this instrument and the associated field stations were closed. The same happened to Dapto not much later, when the Culgoora Radioheliograph, near Narrabri, began observations (see Wild, 1967). These monumental changes in the research philosophy at RP—the move from small locally-designed and -manufactured radio telescopes, each dedicated to a specific type of research problem, to 'Big Science', and the massive, extremely expensive instruments at Parkes and Culgoora—had its inevitable fall-out at RP, with the defection of certain key staff members to other institutions (see Sullivan, 2017 for details). With the close-down of all of the RP field stations, radio astronomy in Australia entered a new and very different era.

2.3 Japan

2.3.1 Introduction

Japanese radio astronomy began in 1948, but because of the immediate post-war situation, accessing scientific and electronic equipment was particularly difficult. Nonetheless, by 1951 there were already active radio astronomy groups at Tokyo Astronomical Observatory, and in Hiraiso, Toyokawa and Osaka (Ishiguro et al., 2012; Orchiston and Ishiguro, 2017). See Fig. 40 for Japanese localities mentioned in this paper.

2.3.2 The Yagi Antenna

Before beginning this Japanese review, we should pay tribute to Shintaro Uda (1896–1976) and his Professor, Hidetsugu Yagi (1886–1976), at Tohoku Imperial University in Sendai (Fig. 40) who in 1925 invented what is now widely known as the 'Yagi Aerial' (although it should, more correctly, be termed the 'Uda-Yagi Aerial'). This antenna played a critical role in the early development of international radio astronomy, in the years immediately after WWI and throughout the 1950s.

2.3.3 The University of Tokyo

The first Japanese to carry out radio astronomical observations was Koichi Shimoda (b. 1919; Fig. 41), a young University of Tokyo graduate who worked at the Aeronautical Research Institute. In 1948 he used a 2-m pre-war metallic parabola and a 3 GHz radar receiver to try and record the 9 May partial solar eclipse. It is not clear whether his observations were successful. For further details see Shimoda et al. (2013).

2.3.4 Osaka University and Osaka City University

In November 1949 Minoru Oda (1923–2001) and Tatsuo Takakura (b. 1925) from the Physics Department at Osaka University observed solar noise at 3.3 GHz with a hand-made metallic horn on a search-light mounting. Later they moved to Osaka City University (Fig. 40), where the horn was replaced by a small parabolic dish. Starting in April 1950, they monitored solar radio emission for the next 15 months,

Fig. 40 Japanese localities mentioned in the text. Key: 1 = Sendai; 2 = Hiraiso; 3 = University of Tokyo, and Tokyo Astronomical Observatory (Mitaka); 4 = Nobeyama; 5 = Toyokawa Radio Observatory; 6 = Nagoya; 7 = Osaka. (Map: Wayne Orchiston)

Fig. 41 Koichi Shimoda, Japan's first radio astronomer. This photograph was taken in 1947, 1 year before he observed the solar eclipse. (Courtesy: Koichi Shimoda)

and published one short paper on their work (Oda and Takakura, 1951). Oda then turned to cosmic ray research, and Takakura joined the vibrant solar radio astronomy group at Tokyo Astronomical Observatory. For further details of the Osaka solar radio astronomy projects see Orchiston et al. (2016), while the 1950 Osaka proposal to build the world's first solar grating array is discussed by Wendt et al. (2017).

2.3.5 Tokyo Astronomical Observatory

Radio astronomy began at Tokyo Astronomical Observatory (henceforth TAO) in the Tokyo suburb of Mitaka (Fig. 40) in September 1949, led by Professor Takeo Hatanaka (1914–1963), who was assisted by Fumio Moriyama (b. 1927) and Shigamasa Suzuki (1920–2012) who later emigrated to Australia.

The first radio telescope at Mitaka was the 200 MHz 5-m × 2.5-m broadside array shown in Fig. 42, which was installed in 1949. Soon after, 60 and 100 MHz Yagi antennas were erected and multiwavelength observations of solar bursts began. This program was expanded in 1952 when a 100–140 MHz spectrometer became operational, and at the same time the radio telescope that Shimoda had used during the 1948 eclipse was set up at Mitaka for observations at 3 GHz.

Further radio telescopes were added in 1953: two more rhombic antennas (thereby allowing solar spectral observations from 200 to ~700 MHz), and a equatorially-mounted 10-m parabolic dish (Fig. 43) that could operate at both 200 MHz and 3 GHz. The following year, Suzuki installed at 4-element interferometer (using broadside arrays) to investigate the positions of solar burst sources at 200 MHz.

Finally, in 1955 and 1957 in preparation for the International Geophysical Year (1957–1958) the following new radio telescopes were installed at Mitaka: 67 and 100 MHz interferometers, a 250–900 MHz radio spectrograph and a 9.5 GHz polarimeter with a 1.2-m parabolic dish.

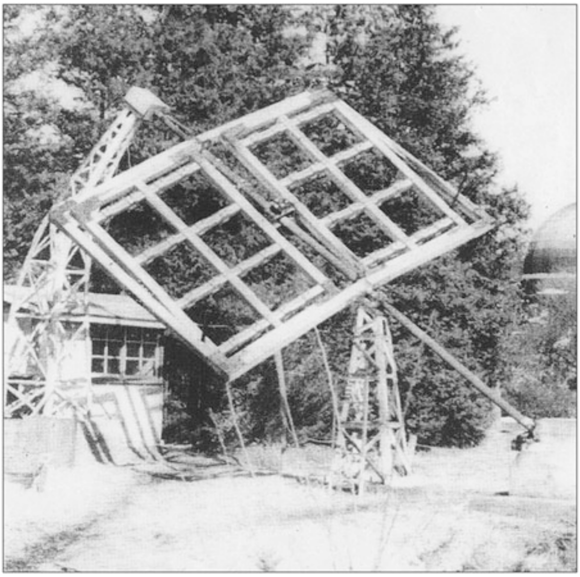

Fig. 42 The broadside array set up at Mitaka in 1949, which was used to observe solar bursts at 200 MHz. (Courtesy: National Astronomical Observatory of Japan Archives—henceforth NAOJA)

Fig. 43 This 10-m parabolic radio telescope installed in 1953 was used for solar monitoring at 200 MHz and 3 GHz. (Courtesy: NAOJA)

Fig. 44 A slightly cropped version of a photograph taken during at Toyokawa Observatory during the 1954 meeting of the Japanese National Commission V of URSI. Seated in front (left to right) are Professor A. Kimpara (Director of the Research Institute of Atmospherics at Nagoya University) and Professor Y. Hagihara (Director of TAO). Standing behind them (left to right) are K. Akabane (TAO), T. Takakura (TAO), T. Kakinuma (Toyokawa), H. Tanaka Toyokawa), S. Suzuki (TAO) and Professor T. Hatanaka (TAO). (Adapted from Tanaka, 1984: 345)

The initial research at 200 MHz by the TAO radio astronomers focussed on the relationship between solar bursts and sunspots and calcium plages and the polarization of these bursts. The research then looked at the positions and heights of the sources responsible for the 200 MHz bursts, and from 1961 investigated specific spectral types of solar bursts, with emphasis on the characteristics, polarization parameters and source heights of Type 1, Type III and Type IV emission. Meanwhile, observations conducted at 3 and 9 GHz centred on long-term variations in solar emission at these higher frequencies, and also included observations of a partial eclipse in 1955 that produced a model for the region assumed to be responsible for the emission. By 1960 about ten TAO staff were actively studying solar radio emission, and some of these are shown in Fig. 44.

After 20 years of fruitful solar research at Mitaka, the TAO shifted its solar radio astronomy programs to Nobeyama (150 km north-west of Tokyo—see Fig. 40), where a new 160 MHz compound interferometer was constructed in 1969.

For details of the solar radio astronomy instrumentation and research programs at TAO, prior to their transfer to Nobeyama, see Nakajima et al. (2014).

2.3.6 Toyokawa Observatory

Radio astronomy at Nagoya University began in June 1949 when the Research Institute of Atmospherics established a field station at Toyokawa, a former naval arsenal and radio-quiet site 60 km south-east of Nagoya (see Fig. 40). The plan was to observe the Sun at high frequencies in connection with the ionospheric disturbances that impacted on radio communications and terrestrial radio noise.

At the end of 1949 Haruo Tanaka (1922–1985) was appointed to lead a radio astronomy group, and nearly one and a half years later he was joined by Takakiyo Kakinuma (b. 1925). In 1951 the first Toyokawa radio telescope was completed: a 2.5-m dish connected to a 3.75 GHz receiver that operated as a total power radiometer.

Tanaka (1984: 339) describes what happened next:

> After the completion of our first radiometer at 3750 MHz, we designed a one-dimensional grating interferometer and applied for funds for construction in 1951. The frequency of the interferometer was 4000 MHz . . . The budget was partly approved in 1952, and the first 5-element interferometer was completed in March 1953 . . .

The solid-metal dishes were 1.5 m in diameter (see Fig. 45). The following year this interferometer was expanded to eight elements (Fig. 46). It is important to remember that this grating interferometer was planned and built quite independently of the one at Potts Hill in Sydney which was constructed by Christiansen at about the same time (see Wendt et al., 2008b). In 1954, polarization screens were added to the Toyokawa dishes (and these are shown in Fig. 46).

The next phase in the development of the Toyokawa Observatory involved the construction of three dishes with diameters of 3 m, 2.2 m and 1.2 m, which operated at 1, 2 and 9.4 GHz respectively. These were used as total power radiometers in

Fig. 45 The 5-element E-W grating interferometer in 1953, with the original Toyokawa antenna in the background. (Courtesy: Tanaka Family)

Fig. 46 The expanded 8-element solar grating array, complete with polarisation screens, and behind it the four total power radiometers that monitored the Sun at 1, 2, 3.75 and 9.4 GHz. (Courtesy: Tanaka Family)

conjunction with the original 2.5-m dish (which continued to record at 3.75 GHz). These four radiometers are shown in Fig. 46, behind the 8-element grating array.

The final phase in the development of the pre-1961 instrumentation at Toyokawa occurred in 1959 when another 8-element grating array was constructed, but this one utilized 1.2-m dishes and operated at 9.4 GHz. During the 1960s, a two-dish antenna, another grating array, two compound interferometers and a radioheliograph were constructed, but these lie outside the chronological bounds of this paper.

The Toyokawa radio telescopes were used to study the characteristics of radio plages at 4 and 9.4 GHz and the intensity and polarization of bursts at these two frequencies and at 1 and 2 GHz. Multi-frequency observations also were made of the partial annular solar eclipse of 19 April 1958 to examine the brightness distribution over the solar disk. International collaborative programs also were undertaken with Australian, Canadian, Indian and U.S. colleagues. By 1960 there were eleven staff members and a few students from the Faculty of Engineering at Nagoya University involved in radio astronomical research at Toyokawa.

In 1990 the Toyokawa Observatory solar radio astronomers combined with those at Nobeyama to form a new group, and the 17 GHz Nobeyama Radioheliograph was constructed 2 years later.

2.3.7 Hiraiso Radio Observatory

The Hiraiso field station on the east coast of Japan about 150 km northeast of Tokyo (see Fig. 40), was run by the Radio Research Laboratories of the Ministry of Posts and Telecommunications, and monitored solar noise in connection with Japan's international telecommunications network. In 1950 an experimental broadside array was installed, but in 1952 this was replaced by a new 200 MHz array modelled on the one at Mitaka (shown in Fig. 42), and regular solar monitoring began. However, there was a utilitarian rationale for these observations, so very few research papers about solar radio emission were published.

2.3.8 Radio Astronomy and the Development of Optical Astronomy in Japan

In other parts of the world, following an initial period of caution—even mistrust—of radio astronomers by optical astronomers (e.g. see Jarrell, 2005; Sullivan, 2009), at a national level the growth of radio astronomy and astrophysics often went hand-in-hand. This was not the case in Japan, where the emergence of radio astronomy appears to have occurred in comparative isolation, with little if any inspiration from developments that were occurring in Japanese optical astronomy at the time (Nakamura, 2017; Tajima, 2017). This aspect if discussed further by Ishiguro et al. (2012: 223–224).

We can conclude that through the combined efforts of the early Mitaka and Toyokawa solar radio astronomers during the 1950s Japan was able to dramatically increase its international visibility in solar physics at a time when most Japanese optical astronomers were still struggling to break free from the long-entrenched shackles of classical astronomy and embrace astrophysics.

2.4 India

2.4.1 Introduction

The early development of radio astronomy in the Indian Subcontinent is intimately associated with the initiatives of one of the authors of this paper (GS), so what follows is my personal perspective. For Indian localities mentioned in the text see Fig. 47).

Indian interest in radio astronomy first emerged when Dr. K.S. Krishnan (1898–1961; Fig. 48), the Director of the National Physical Laboratory (NPL) in New Delhi, attended the 1952 URSI Congress in Sydney and returned to India full of admiration for what the CSIRO Division of Radiophysics (henceforth RP) radio astronomers in Sydney had been able to achieve in the short interval since WWII. Dr. Krishnan's talk

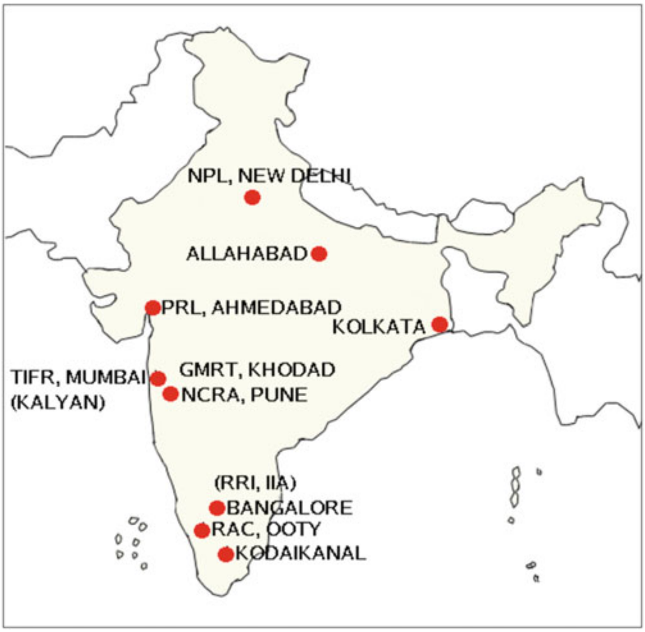

Fig. 47 Indian localities mentioned in the text. (Map: Govind Swarup)

Fig. 48 Dr. K.S. Krishnan, Director of the National Physical Laboratory, New Delhi. (Courtesy: National Physical Laboratory)

> . . . caught my imagination. I then visited the NPL library, where I studied some of the thirty papers that had been published by the RP scientists in the *Australian Journal of Scientific Research* and in *Nature* describing these discoveries. I was told that these were almost half of the papers on radio astronomy that had been published worldwide up to that time. I, too, was fascinated (Swarup, 2006: 22).

Krishnan was keen to initiate radio astronomical research at the NPL but lacked staff with relevant training, so he arranged for me to spend 2 years at RP (under a Colombo Plan Fellowship)—see Fig. 49.

Fig. 49 Govind Swarup (left) and the other Indian Colombo Plan student who went to RP, R. Parthasarathy (right), at Potts Hill field station in 1954, posing in front of the ex-Georges Heights experimental radar antenna. (After *Illustrated Weekly Times of India*, 14 September 1954)

2.4.2 The Australian Sojourn

In March 1953 I arrived at RP and Dr. Joe Pawsey (Fig. 14), the dynamic Head of the Radio Astronomy group suggested that I work for 3 months each in the research groups led by W.N. Christiansen, J.P. Wild, B.Y. Mills and J.G. Bolton. As we already saw in Sect. 2.2, above, by this time all four were acknowledged world leaders in their respective fields. Then, after the first year, Parthasarathy and I would select a joint project. What a great opportunity for initiation into the new field of radio astronomy!

For the first 3 months, I assisted Chris Christiansen and Joe Warburton to make the two-dimensional map of the quiet Sun shown in Fig. 27 (see Swarup, 2008). Then I spent 3 months in Paul Wild's Solar Group, and Jim Roberts and I developed a 45 MHz receiver that was then used at the Dapto field station. After this, I spent 3 months developing a phase shifter for the prototype Mills Cross shown in Fig. 31, and for the final 3 months of the first year I worked in John Bolton's group and made a highly stable D.C. power supply.

In 1954, Christiansen went to work at Meudon Observatory (France) for a year so the Potts Hill grating interferometers were not going to be used for regular observations. After discussions with Pawsey, Parthasarathy and I converted the Potts Hill EW grating array (Fig. 25) from 1.42 GHz to 500 MHz, to see whether the quiet Sun exhibited limb-brightening at that frequency. This was predicted by RP's Steve Smerd, but conflicted with observations made at Cambridge University. Our results agreed with Smerd's prediction (Swarup and Parthasarathy, 1955; 1958). For us, this was a wonderful experience: building dipoles, a transmission line network and a

Fig. 50 W.N. Christiansen (left) and T Krishnan (right) at Fleurs field station beside one of the Chris Cross antennas. (Krishnan Collection)

receiver system; making the observations; and finally, carrying out data reductions and writing up the two research papers.

Upon his return from France in early 1955, Christiansen decided to build a new solar cross-type antenna array at RP's Fleurs field station (see Orchiston and Mathewson, 2009), so I suggested to Joe Pawsey that RP gift the Potts Hill E-W grating array to India. He readily agreed to this, as did Dr. 'Taffy' Bowen, Chief of the Division of Radiophysics, and the CSIRO authorities in Canberra.

2.4.3 From India to the USA

I returned to New Delhi in mid-1956, and although Dr. Krishnan was enthusiastic about starting radio astronomy at the National Physical Laboratory there were various delays, and towards the end of the year I decided to go to the USA for a year or two. Parthasarathy had also joined the NPL in 1956 but he, too, decided to leave, and he moved to Alaska. Another to join the NPL in 1956 was T. Krishnan, after studying radio astronomy in Cambridge, but he went to RP in 1958 to work with Christiansen (Fig. 50). In that same year M.R. Kundu (1930–2010) joined the NPL after completing a Ph.D. in radio astronomy in France (see Orchiston et al., 2009), but he soon moved to the USA. Two others to join the NPL in 1956 were M.N. Joshi and N.V.G. Sarma, after finishing M.Sc. degrees in India, and later Joshi

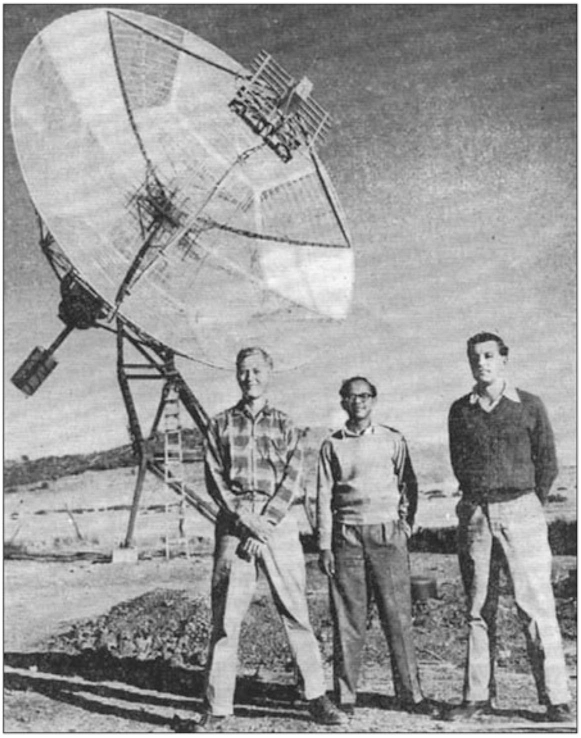

Fig. 51 Alan Maxwell, Govind Swarup and Sam Goldstein (left to right) posing in front of the 28-ft dish at the Fort Davis field station in Texas. (Swarup Collection)

went to France to study for a Ph.D. and Sarma went to Leiden Observatory to build radio receivers. Both subsequently returned to India and rejoined the NPL.

Upon arriving in the USA I joined Harvard Observatory's Fort Davis Radio Astronomy Station in Texas (Thompson, 2010). This field station had been set up by the New Zealander, Dr. Alan Maxwell, and a 28-ft dish (Fig. 51) and swept-frequency receiver were used to record the spectra of solar bursts over the frequency range 100–600 MHz. In December 1956 I discovered the Type U solar burst.

Early in 1957, I decided to study for a Ph.D. degree in the USA and after receiving favourable responses from Harvard, Caltech and Stanford, I chose Stanford, where the radio astronomy group was led by the visionary Australian Ron Bracewell (1921–2007; Thompson and Frater, 2010). At the time, Bracewell was in the process of building a cross-grating interferometer (Bracewell, 2005) that—just like the Chris Cross—would be used to generate daily solar maps. Fig. 52, which was taken in about 1960, shows the two of us examining solar records obtained with the Stanford Cross. On 1 January 1961, soon after obtaining my Ph.D. degree, I joined the University as an Assistant Professor.

While I was at Stanford I sometimes talked with two other Indian radio astronomers also working in the USA when we were at meetings. One was Dr. T.K. Menon (Fig. 53), who did his Ph.D. at Harvard University and was working at the National Radio Astronomy Observatory, and the other was Dr. M.R. Kundu (Fig. 53), in Fred

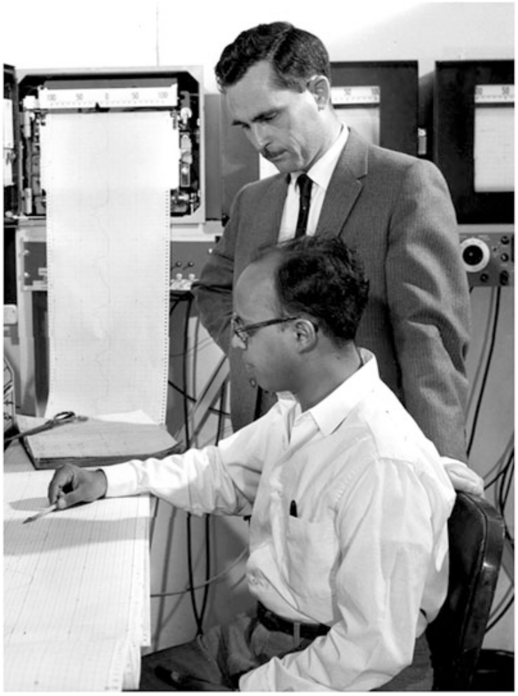

Fig. 52 Ron Bracewell and Govind Swarup examining solar records. (Courtesy: Stanford University News Service)

Fig. 53 T.K. Menon (left) and M.R. Kundu (right) at the Berkeley General Assembly of the International Astronomical Union in 1961. (Menon Collection)

Haddock's solar radio astronomy group at the University of Michigan. On several occasions the three of us discussed the possibility of returning to India and forming a major radio astronomy group. When I put the idea to Chris Christiansen, Frank Kerr and Joe Pawsey they were enthusiastic. Chris suggested that the three of us, and Krishnan, "… should get together for a united attack on the monolith of Indian bureaucracy …" (Christiansen, 1960). The four of us met in Berkeley in August 1961 during the General Assembly of the IAU and we discussed returning to India. We then prepared a detailed proposal outlining our plan to start solar observations

Fig. 54 Dr. Homi Bhabha, founding Director of the Tata Institute of Fundamental Research. (Courtesy: TIFR Archives)

using the thirty-two dishes already donated by RP to the NPL (which had still not been used), and thereafter to set up "… a very high resolution radio telescope of a novel design would be the next step in our programme … certain types of radio telescopes would be cheaper to build in India due to lower labour cost … such as a Mills Cross operating at low frequencies …" (Menon et al., 1961).

In September 1961 we sent this to five different Indian institutes and agencies. All replied, but the most encouraging and highly supportive was from the great visionary scientist and dynamic organizer, Dr. Homi J. Bhabha (1911–1966; Fig. 54), Director of the Tata Institute of Fundamental Research (TIFR) in Mumbai. He sent a cable to all four of us on 20 January 1962: "We have decided to form a radio astronomy group stop letter follows with offer…" (Bhabha, 1962).

2.4.4 Radio Astronomy and the Tata Institute of Fundamental Research

I resigned from Stanford, and returned to India on 31 March 1963. This was the start of TIFR radio astronomy. In August 1963 I was joined by two recent graduates, V.K. Kapahi (1944–1999) and J.D. Isloor, and two scientific assistants. The following year N.V.G Sarma and M.N. Joshi resigned from the NPL and joined the TIFR. After completing 1 year of coursework in physics at the Atomic Energy Establishment Training School R.P. Sinha joined the TIFR in 1964. Another newcomer that year was D.S. Bagri, a fresh M.Tech graduate from Birla Institute of Technology and Science in Pilani. Mukul Kundu returned from the USA in 1965 to join the TIFR, but he went back to the USA in 1968. T.K. Menon joined the TIFR radio astronomy group in 1970 and returned to the USA after several years.

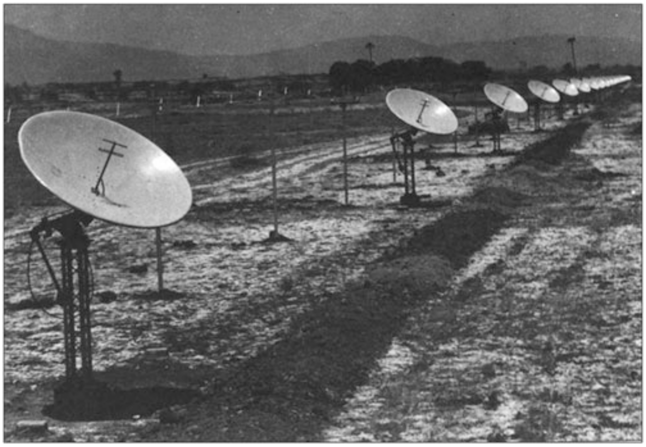

Fig. 55 A view along the east-west arm of the Kalyan grating array. (Courtesy: TIFR Archives)

2.4.5 The Kalyan Array

Our first task was to set up a solar radio telescope, and the NPL and CSIR authorities had transferred the thirty-two 1.8-m diameter Potts Hill dishes to the TIFR by mid-1963.

By April 1965 we had set up a grating array at Kalyan near Bombay, consisting of twenty-four of them placed along a 630-m east-west baseline (Fig. 55) and the remaining eight along a 256-m north-south baseline. This was India's first 'cutting edge' radio telescope, and it was used to investigate properties of the quiet and active radio Sun at 610 MHz from 1965 to 1968. We found that the Sun showed considerable limb brightening at 610 MHz (confirming our earlier Potts Hill observations at 500 MHz), and that the solar corona had a temperature of around 10^6 K.

2.4.6 Cosmology Models, the Ooty Radio Telescope and Synthesis Radio Telescope

In June 1963 there was a raging controversy between the Steady State and Big Bang cosmologies and I came across a paper by Cyril Hazard (b. 1928) about his observations of a lunar occultation of the radio source 3C273 made with the 64-m Parkes Radio Telescope, and a companion paper by Maarten Schmidt (b. 1929), concluding that the enigmatic spectrum of the blue stellar object identified with 3C273 was best explained by an object with a redshift of 0.17. This marked the discovery of quasars (see Kellermann, 2014), and has revolutionized our understanding of the Universe.

Fig. 56 The Ooty Radio Telescope. (Courtesy: TIFR Archives)

While reading the two papers, a thought flashed through my mind: that the lunar occultation method could provide accurate positions and angular size measurements of a large number of radio sources, much weaker than those in the 3C catalogue, and thus distinguish between competing cosmological models. Since India could not afford to build a large parabolic dish of more than 120-m diameter, as required by the occultation program, it occurred to me that the solution would be to construct a large cylindrical radio telescope located on a suitably inclined hill in southern India so as to make its axis parallel to the Earth's axis, and thus take advantage of India's close proximity to the Equator. In August 1963 I discussed this idea with Professor M.G.K. Menon (1928–2016), Dean of the Physics Faculty, who responded enthusiastically. Next I met with Dr. Bhabha who grilled me for over 2 h and then gave his approval.

In early 1965, after an extensive search Sinha and I located a suitable hill at Ooty, in the picturesque Nilgiri Hills, for the proposed equatorial radio telescope. The Ooty Radio Telescope (ORT) was completed in December 1969, and it is still in operation. It consists of a 530-m long and 30-m wide parabolic cylindrical antenna (Fig. 56), located on a north-south hill with a slope equal to the latitude of the station (+11.35°). It is, therefore, possible to track celestial radio sources continuously every day for up to 9.5 hours by a simple mechanical rotation of the telescope along its long axis. Along its 500-m long focal length is placed a phased array consisting of 1024 dipoles operating in the RF band of 322–328.6 MHz.

The first occultation observations were made on 18 February 1970 and by the end of the following year the radio astronomy group at the TIFR had grown to seventeen scientists (including T.K. Menon), plus engineers and technical staff.

During the 1970s we observed lunar occultations of more than 1000 radio sources and provided independent support for the Big Bang cosmological model. Detailed physical properties of many galactic and extragalactic sources also were derived, and we also made important observations of pulsars.

By 1984 we had set up the 4-km long Ooty Synthesis Radio Telescope (OSRT), consisting of six small parabolic cylindrical antennas measuring 23 m × 7.5 m, a seventh measuring 100 m × 7.5 m and the large ORT itself, with the three nearby antennas joined by coaxial cables and the four other antennas located at a distance of 4 km with rather cumbersome radio links. The OSRT provided a resolution of ~45 × 50 arc seconds at 327 MHz. The most significant scientific contributions made by the ORT and the OSRT during the first 20 years are described in Swarup et al. (1991).

2.4.7 From Giant Equatorial Radio Telescope to the Giant Metrewave Radio Telescope

Following the success of the equatorially mounted ORT, a proposal was developed between 1976 and 1978 to construct a Giant Equatorial Radio Telescope (GERT) at a suitable site on the Earth's Equator in either Kenya or Indonesia. This would consist of a 2-km long and 50-m wide cylindrical radio telescope. For various reasons this never eventuated (see Swarup, 2017).

By 1982, revolutionary methods of phase and amplitude closures and self-calibration allowed radio astronomers to obtain radio maps of celestial sources of high quality even in the presence of phase and amplitude variations caused by electronics, the ionosphere or the atmosphere. It also seemed feasible to connect the elements of an interferometer using lasers and optical fibres. We then investigated the type of radio telescope needed to study the postulated condensates of neutral hydrogen existing at very high redshifts prior to the formation of galaxies in the Universe.

> To pursue this interesting problem, which is still a major challenge for radio astronomy, it became clear to us that a major new instrument was needed in order to fill the existing gap in radio astronomical facilities at metre wave-lengths. (Swarup, 2017: 834).

This was the genesis of the Giant Metrewave Radio Telescope (GMRT), which I proposed on 1 January 1984. This project was approved by the Government of India in March 1987.

Instead of building a 2-km long and 50-m wide cylindrical antenna we ended up building 30 parabolic antennas each 45-m in diameter and joined by optical fibres to form a synthesis radio telescope of about 25-km in extent. Fourteen antennas are placed somewhat randomly in a central array of about 1 km × 1 km, while the other sixteen dishes are situated along three 14-km long arms, making a Y-shaped array (Fig. 57). The GMRT operates at five frequency bands between ~110 MHz and 1.43 GHz. A close-up of one of the antennas in the compact array is shown in Fig. 58.

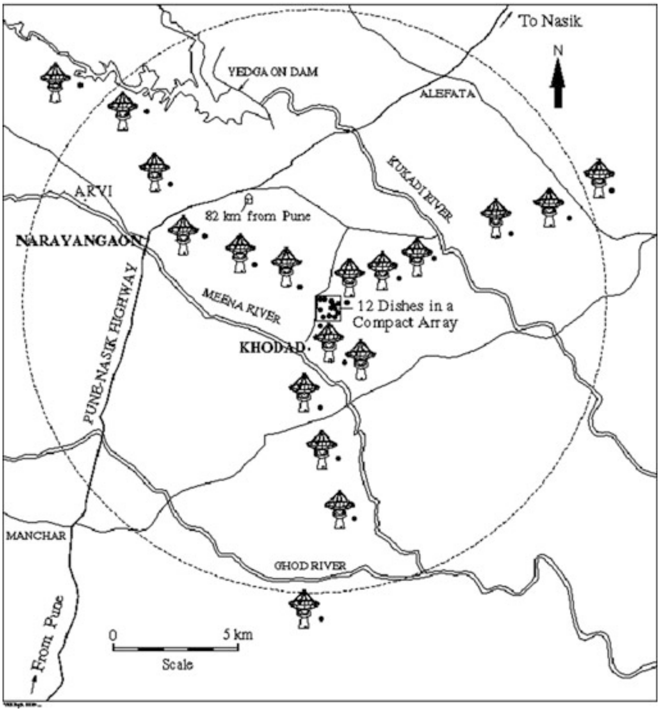

Fig. 57 A map showing the locations of the 30 dishes in the GMRT. (Courtesy: TIFR Archives)

The GMRT became operational in 2000, and is still the world's largest metre radio telescope. It has been used by Indian astronomers and overseas astronomers from >31 countries. Among the many research highlights, let me mention just three:

1. Observations made with the GMRT have led to the discovery of the new and interesting double-double radio galaxy (J1453 + 3304) (Saikia et al., 2006), which is shown in Fig. 59. The outer-most lobes are remnants of an earlier epoch of the radio source when the supply from the central engine was stopped; millions of years later the central engine was activated again, giving rise to another double radio source.
2. The GMRT is being used to search for giant radio galaxies and probe the intergalactic medium. The giant radio galaxy J1420-054 (shown in Fig. 60) is identified with an optical galaxy at $z = 0.3067$, and has a projected linear size of 4.69 Mpc (15 million light years). This is currently the largest known radio galaxy (see Machalski et al., 2007).

Fig. 58 A close up of one of the 45-m antennas, with eight others in the background. (Courtesy: TIFR archives)

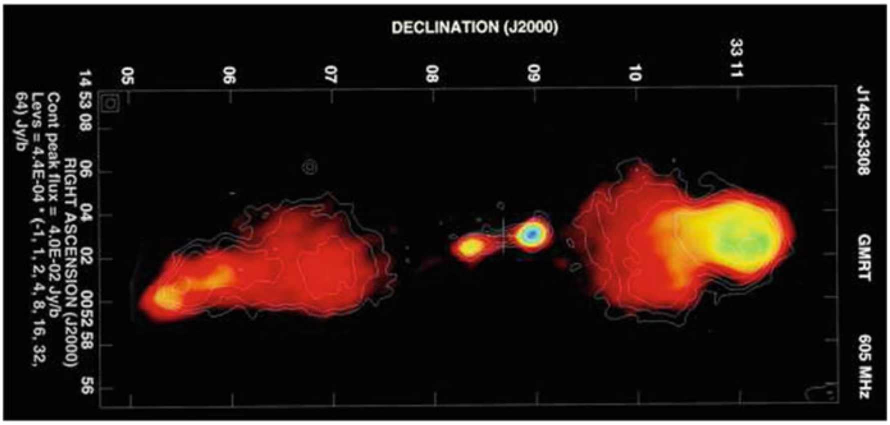

Fig. 59 A false-colour image of the unusual radio galaxy J1453 + 3304. (Courtesy: TIFR Archives)

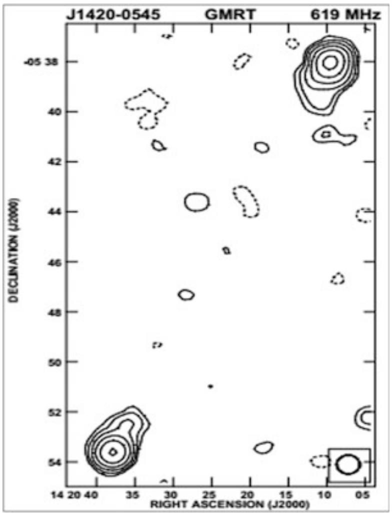

Fig. 60 The radio source J1420-054, bottom left, is currently the largest-known giant radio galaxy. (Courtesy TIFR Archives)

3. A recent outstanding result relates to the formation of structure in the Universe by the merging of galaxies and clusters of galaxies, and is the discovery of a giant double radio relic in the Planck Sunyaev-Zel'dovich Cluster (Fig. 61).

For further details of the development of radio astronomy in India see Swarup (2014, 2017).

2.5 China

In his reminiscences of early developments in Chinese radio astronomy Professor Wang Shouguan recalls how in the early 1960s China was still isolated from the West, and the local electronics industry was in its infancy. Beijing Observatory had a field station in the Beijing suburb of Shahe, where the radio astronomy group was based.

Wang and his colleagues had decided to build a replica of the Chris Cross that W.N. Christiansen had constructed at Fleurs, near Sydney, in 1957 (see Sect. 2.2.6, in this paper), but they had no knowledge of the technical specifications of the transmission lines. Then they were thrilled to learn that Christiansen would pay them a visit:

> . . .it was like a happiness that had fallen from heaven . . . [We] had been cut off from the West for more than a decade, as though we were sealed inside an hermetic wall. And this was the first time that a small door would open in this wall, and who should come through that door but the very man we most wanted to meet, Professor W.N. Christiansen. (Wang, 2017: 246–247).

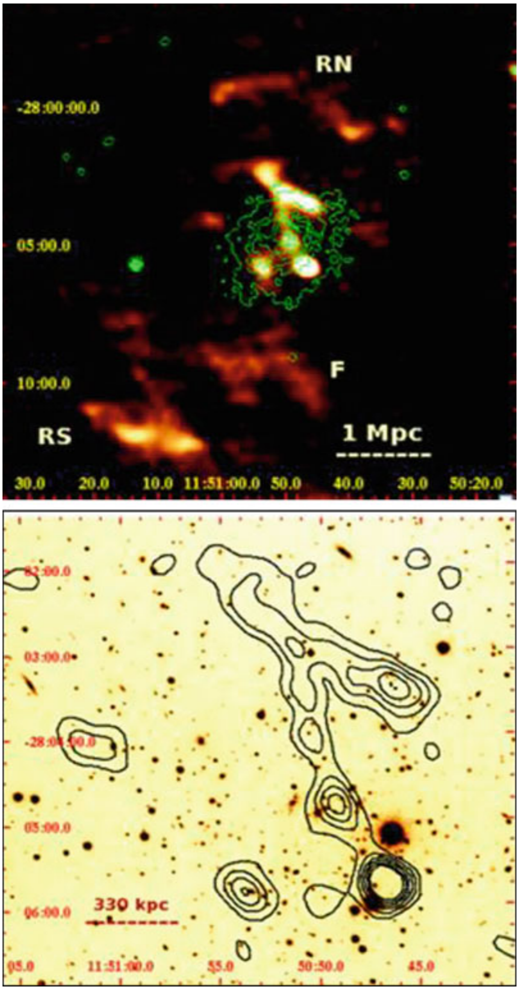

Fig. 61 Top: XMM-Newton contours in X-rays (green) superimposed on the 150 MHz GMRT radio map of the cluster (orange and yellow). Bottom: The 150 MHz GMRT radio map near the cluster centre, superimposed on the R-band optical image. (After Bagchi et al., 2011: 3)

This was to be the first of many visits Christiansen (known affectionately as 'Prof Ke') made to China, and his support was crucial in the early days of Chinese radio astronomy—bringing not only knowledge and advice, but even electronic components.

With Christiansen's guidance, Wang Shouguan's group established a 4-element interferometer at the Shahe site in 1965 (Fig. 62), but the internal unrest in China meant that it would be another two decades before the next-generation radio telescope, the Miyun Metre Wave Aperture Synthesis Telescope was constructed and operational (see Fig. 63).

As Professor Wang (2017: explained: 249, 251):

> The making of the Miyun Aperture Synthesis Telescope was a gradual process. We started at a very low point, when the material conditions were difficult and the technological base was

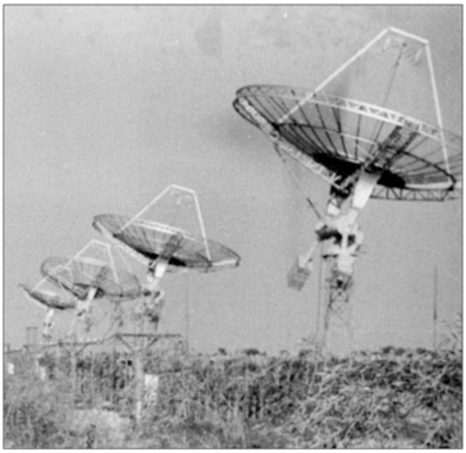

Fig. 62 Shahe and its four 6-m parabolas. (After Wang, 2017: 248)

Fig. 63 The Miyun 28-element Meter Wave Aperture Synthesis Array. (Courtesy: Beijing Astronomical Observatory)

weak. But we had made preparations beforehand, and our target was clearly defined (as during the earlier Shahe period), so by making the best of a very difficult situation and bringing out our hidden potential we were able to keep forging ahead.

From these difficult and humble beginnings Chinese radio astronomy has made remarkable strides, as the following Section will confirm.

3 Recent Radio Astronomical Developments in the Greater Asian Region

3.1 Introduction

After the foregoing historical background material, in this short section we will briefly review the current status of Asian radio astronomy on a project-by-project and country-by-country basis.

3.2 International Projects

3.2.1 The SKA

The Square Kilometre Array (SKA) is a major international initiative involving a consortium of eleven countries. Four of these are Asian nations: Australia, China, India and New Zealand.

The SKA is being constructed in South Africa and Australia, with the first phase due for completion in 2022 at a cost of 650 million Euros.

Once operational, the SKA will be 100 times more powerful than any existing radio telescope.

3.2.2 ALMA

The Atacama Large Millimetre Array (ALMA) is a large millimetre array in the Atacama Desert in Chile (Fig. 64), which became operational in 2013.

This is also a major international initiative, and three Asian nations (Japan, South Korea and Taiwan) are partners.

3.3 National Initiatives

3.3.1 Australia

Apart from its involvement in the SKA, Australian radio astronomers now have their own new low frequency radio telescope, the Murchison Wide-field Array (Fig. 65), which became operational in 2013.

Fig. 64 The ALMA array. (Curtesy: ESO/NAOJ/NRAO)

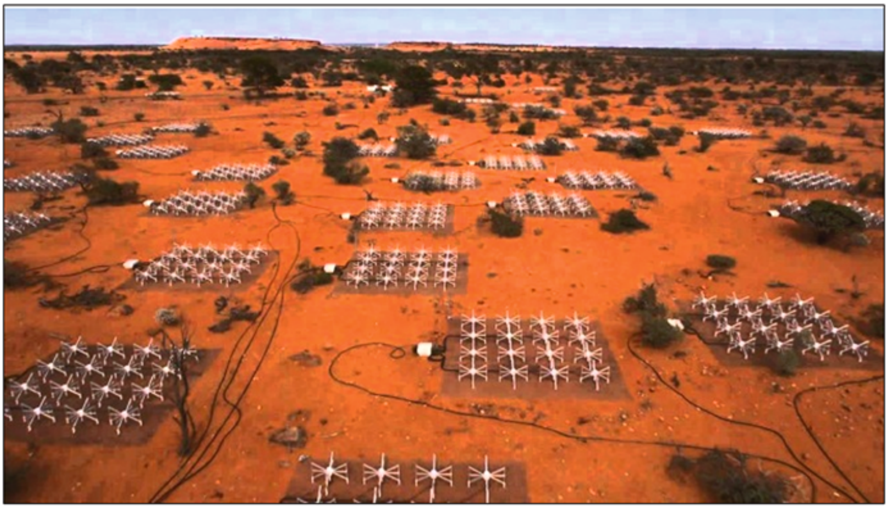

Fig. 65 A view of part of the Murchison Widefield Array. (Courtesy: CSIRO Astronomy and Space Sciences)

3.3.2 China: FAST

As of 2016 China became host to the world's largest single-dish radio telescope, the 500-m diameter FAST (Fig. 66). With an effective collecting area of ~70,000 m^2, this far surpasses the previous record-holder, the 305-m Arecibo Radio Telescope in Puerto Rico, with its effective collecting area of ~31,000 m^2.

Fig. 66 An aerial view of FAST. (Courtesy: www.news.ch)

FAST will probe the radio Universe, hunting for faint pulsars, mapping neutral hydrogen in distant galaxies, and searching for signs of extra-terrestrial communications and intelligence.

This remarkable new radio telescope is located in SE China near the border with Vietnam, where it was possible to take full advantage of the local karst topography.

3.3.3 India

Currently Indian radio astronomers are upgrading both the GMRT and the ORT. With these two refurbished instruments and eventual access to the SKA, Indian scientists with be able to remain at the forefront of international research developments in radio astronomy.

3.3.4 New Zealand

After decades in the wilderness, New Zealand radio astronomy has recently blossomed, thanks largely to the efforts of Professor Sergei Gulyev at the Auckland University of Technology. Since 2015 his group has had access to a 30-m parabola (Fig. 67). New Zealand and Australia have already carried out successful VLBI experiments.

Fig. 67 The 30-m antenna in New Zealand. (Courtesy: Auckland University of Technology)

3.3.5 Thailand

Thailand is the only nation is SE Asia that currently is making major strides in radio astronomy. As well as funding the training of graduate students overseas, the Government has allocated funds for a 40-m parabola (Fig. 68), and construction will begin in 2018. The hope is that eventually there will be three identical dishes in Thailand, in the north, east and south (to maximize baselines), and that these will form a Thai VLBI Network, but also work closely with the existing VLBI networks in East Asia (China, Taiwan, South Korea and Japan) and in Australia-New Zealand.

3.3.6 Other SE Asian Nation

Currently, Vietnam, Malaysia and Indonesia are all actively training graduate students in radio astronomy, both at home and abroad, and all have developed small-scale teaching radio telescopes. However, larger apertures are planned, and hopefully a SE Asian VLBI Network will eventuate.

Fig. 68 This parabola at Yebes, Spain, is similar to the 40-m dish that will be constructed in Thailand in 2018. (Courtesy: National Astronomical Research Institute of Thailand)

4 Concluding Remarks

Radio astronomy has opened a new window on the Universe, especially since World War II.

Over the last 60 years, there has been a succession of remarkable scientific discoveries made by radio astronomers in the USA, in European countries and in three different Asian nations: Australia, India and Japan. The recently completed 500-m diameter FAST radio telescope in China will surely also give rise to many important discoveries in the coming years. These four Asian nations will be joined by New Zealand, South Korea, Taiwan and Thailand, all of which already have, or soon will have, access to cutting edge radio astronomical instrumentation. Hopefully, other Southeast Asian nations will soon join Thailand and develop their own local radio astronomical facilities to an international level.

With these developments, and others, Asian scientists can look forward to a bright future in radio astronomy.

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Part VI
Middle Eastern Astronomy

Astrology and Astronomy in Iran: A Statistical Survey

Seyedamir Sadatmoosavi

Abstract The eleventh and twelfth centuries were a boom time for astronomy in Islamic civilization. This continued with the establishment of the Maragha School in the thirteenth century but there was a decline in the fifteenth and sixteenth centuries. During this period, Europeans faced a revolution in astronomy and there was a paradigm change. Initially, Iranians were unaware of these changes and most serious Persian manuscripts about modern astronomy were written after the eighteenth century.

Therefore it seems that the reaction of the scientific community in Iran toward what had happened in European astronomy was delayed for about two centuries. In this paper the reasons for this delay are investigated. In order to do this we carry out a quantitative investigation of manuscripts in Iranian libraries. Our statistical analysis indicates that there was a correlation between the decline of science in Iran and interest in astrology.

1 Introduction

Aristotle's principles and the Ptolemaic system for the planets were the basic paradigm in scientific societies for a long time. Muslim astronomers translated Greek astronomy in the first Islamic centuries and tried to learn from it. After the eleventh century Muslim astronomers could access a type of astronomy that was adapted to the Islamic environment and was coloured by whatever prerequisites that environment demanded (Saliba, 1996: 59).

An important event that took place after the eleventh century among Muslim astronomers was the emergence of critical approaches towards Greek astronomy and in particular Ptolemy theories. In that century, numerous activities were conducted with special attention to the philosophical foundations of Greek astronomy. As a

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result of this issue, a new school of astronomy book-writers emerged who were seeking to solve the philosophical problems of the Greek astronomical theories. Works of people such as Ibn al-Haytham (AD 965–1039) in al-Shukūk ʿala Batlamyus, Abu ʿUbayd al-Jūzjāni (AD 980–1037) in Tarkīb al-Aflāk and an anonymous Spanish astronomer in al-Istidrāk ʿala Batlamyus, are successful examples of this Intellectual activities (Saliba, 1996: 75–85).

We can follow this tradition in later centuries through Hay'a books. These are astronomical books from the Islamic period that, after expressing mathematical and natural principles, tried to provide a systemic overview of the Earth and the Heavens. Hay'a books adopted a precise and specific structure at the beginning of the twelfth century, and then all hay'a books followed this layout and general structure.

Criticisms that were expressed in hay'a books against Ptolemaic theories, can be seen in the works of al-Tūsī (1201–1274), ʿUrdī (died in 1266), Qutb al-Din al-Shīrazī (1311–1236) and Ibn al-Shāṭir (1375–1304). These astronomers had carried out research at the observatory that had been built in AD 1259 by the Ilkhanid monarch Hulaguin in the city of Maragha, which is located in the north-west of modern Iran (Saliba, 1996: 59–60).

These astronomers criticized Ptolemaic models in their books and tried to provide alternative models for them. Even though these alternative models were not successful, they definitely influenced the future development of Islamic astronomy. For instance, in the 1950s and 1960s E.S. Kennedy showed that Ibn al-Shāṭir's planetary models had many similarities to the Copernican model (e.g., see Kennedy and Ghanim, 1976).

The tradition of writing hay'a books continued after the fourteenth century AD. But there was no novel and serious criticism of Ptolemy. The next books can be regarded as some kind of returning to the past in the history of astronomical theorizing in the Islamic world. After the fifteenth century, the most important and most popular hay'a books in Iran were *Farsi Hay'a* written by Al-Qūshjī and *Tashrīḥ al-aflāk* by Bahāꞌ Al-dīn Al-ʿĀmilī. Nowadays, there are more than 250 manuscripts of each of these two books in Iranian libraries (see Derayati, 2010(2): 1191–1197, 2010(7): 823–840). For a long time in Iran these two books were used as standard astronomical text books in schools and mosques (Saliba, 1995: 46). However, they simply copied Ptolemaic models, and no creativity is found in them.[1]

This era coincided with emergence of scientific creativity in Europe, when the Copernican heliocentric model (1543) and later works by Tycho Brahe (1546–1601), Kepler (1571–1630) and Galileo Galilei (1564–1642) changed the dominant paradigm of the scientific community.

[1]For a more accurate judgment on the content of Hay'a books, see the doctoral theses by Gamini (2013) and Ghalandari (2012).

2 Iranian Awareness of Modern Astronomy

Some of the most important events of modern astronomy in Europe occurred when the Safavid Dynasty was ruling Iran. During this period, many European tourists visited Iran and some of their experiences were published (e.g. Chardin, 1995; Della Valle, 1650; Olearius, 1984; Tavernier, 1678). These (and other books) clearly indicate the existence of a relationship between Western countries and Iran during the Safavid period. Apart from these works, there is no sign that new developments in Western science (and especially astronomy) spread throughout Iran.

Two manuscript letters by Pietro Della Valle and dating to AD 1624 exist in the Vatican Library, and in these Della Valle explains the Tychonic System to an Iranian astronomer. However, there is no evidence that these letters had any impact on Iranian science. Later signs of modern astronomy in Persian literature also are rare, apart from the unreliable treatise by Abū Tālib Safavi that was written between 1770 and 1772 outside the political borders of Iran.

The next important events happened in the nineteenth century, when Iranian scholars translated many astronomical books from French and English into Persian. Dār Al-funūn School was established in Iran in 1851 and eventually became the first modern university in Iran. It began to operate during the Qājār era (which lasted into the 1920s), and Iranian students were taught modern astronomy year after year. It was during this period that Nāsir Al-dīnShāh Qajar approved modern astronomy, and his Minister of Science, ‘I’tizād Al-saltana, called modern astronomy ‘correct astronomy’. This was the first time that a Persian Government accepted modern astronomy (Arjomand, 1997; Sadatmoosavi, 2015: Chapter 1).

Now the question is: Why were Iranian astronomers silence about modern astronomy during the two to three centuries from the time of emersion of the Copernican heliocentric model up to the establishment of Dār Al-funūn School? What engaged Iranian astronomers during this period, and why did they not take modern astronomy seriously?

3 Astrology and Astronomy

The expression ‘ilm al-nujūm was a commonly used term that referred to both astrology and astronomy. Astrology used stars to predict the future so it usually was of popular interest. The manuscripts that were written on this subject mostly are called Ahkām or Tanjīm. On the other hand, astronomy was called hay’a and consisted. of knowledge about the Heavens and the structure of the Universe, and included different planetary models (Saliba, 1995: 66). As mentioned before, the authors of hay’a books in the Maragha School worked on reforming the Ptolemaic model that later was followed in Europe by the Copernican heliocentric model.

Were astronomy (hay’a) and astrology rivals? Is it possible to say that the spread of astrology prevented scholars from becoming engaged in real scientific research? We will examine this idea in the remainder of this paper.

3.1 Tourist Narratives

Some of the European tourists who travelled to Iran in the seventeenth and eighteenth centuries described Iranian society. One of the things that was exotic for these visitors was the particular interest that Iranian people and their Government showed towards astrology.

When the German mathematician and geographer Adam Olearius (1603–1671) came to Iran in 1637, he wrote as follows:

> We know in the past, studying astronomy had witchcraft aspects, and yet it is still valuable for Iranians. Those who are seeking this knowledge are called "astronomer" and are employed by the king or the rich. They have no information about real astronomy which is related to stars' motion, and just know something about astrology. Because they believe that the first (real astronomy) is like a poor mother and the second (astrology) is like a rich girl. And you can achieve to wealth by means of the girl.

> Arabs and Iranians believe that the stars' role is a proven fact on human destiny. They are superstitious people. If an astrologer makes a prediction, they will accept it anyway. Predictors were always in great square of Isfahan and working there. I went few times to watch them and I noticed that women came and asked about situation of their sons who were on a trip. They wanted to know whether their sons will return soon or late. Will their husband come with another wife or not? (Olearius, 1984: 310–313).

The French jeweller and traveller Jean Chardin (1643–1713), who visited Iran several times between 1664 and 1677, described the situation of astrology as follows:

> It is famous that, number of astrologers in Isfahan is equal to the stars of the sky. In the court of the king always some astrologers are serving. The king consults with astrologers in all major or minor affairs. For example, He asks: Is it expedient to go on a trip? Is it good to eat? (Chardin, 1995: 987–989).

Interest in astrology, was not restricted to the Safavid period, and existed in later periods of Iranian history too. The British traveller Jonas Hanway (1712–1786) who travelled to Iran in the middle of the eighteenth century, said:

> The Persians to this day are great lovers of astrology, and show a profound respect for the processors of it, relying much on their predictions. (Hanway, 1753: 25).

3.2 Statistical Analysis

Now we want to examine the intensity of this Iranian interest in astronomy and astrology in different ages. In order to do this, I referred to the catalog of Iranian library manuscripts (Derayati, 2010), and I counted the respective numbers of astronomy and astrology treatises, ordered chronologically.

The first group are the hay'a (astronomy) books and the second group are the books that are about astrology (called Aḥkām, Ikhtiārāt and etc.).

Manuscripts written before the thirteenth century are scarce in repositories. Also, from the beginning of the twentieth century, most of the books were printed and the

Table 1 The publication environment of books

The time of writing		Number of Hay'a books	Number of Astrology books	Total
Islamic calendar	Gregorian calendar			
600–650	1203–1252	2.75	3.75	6.5
650–700	1252–1300	17.75	9.75	27.5
700–750	1300–1349	14	8.25	22.25
750–800	1349–1397	11	5.25	16.25
800–850	1397–1446	27.25	7.5	34.75
850–900	1446–1495	16.25	11.5	27.75
900–950	1495–1543	33	20	53
950–1000	1543–1591	47.5	24	71.5
1000–1050	1591–1640	90.5	53.25	143.75
1050–1100	1640–1688	134.5	89.25	223.75
1100–1150	1688–1737	65	71.25	136.25
1150–1200	1737–1785	31.5	66.75	98.25
1200–1250	1785–1834	114.5	137.75	252.25
1250–1300	1834–1882	153.5	161.75	315.25
1300–1350	1882–1931	32.5	22.5	55

number of manuscripts was just a few. Among manuscripts, non-integers related to those treatises where the time of their writing was not specified. For example, if we know that a manuscript was written between AD 800 and 900 but the exact date was not specified, then a 0.5 manuscript was assigned to the first 50 years and the remaining 0.5 to the second 50 years. Table 1 shows that relatively few manuscripts date to the first six periods (before AD 1495). Therefore, remarks about this period cannot be precise.

Certainly the manuscripts considered here are not all of the manuscripts that were written. We know that some of them did not survive or cannot be dated. So in order to do a better job in analyzing the data, we will use a mathematical model.

This mathematical model supplies random errors. Suppose that inside a bag there are an unknown number of balls of type 1 and type 2, and we extract accidentally n balls from the bag, and find that the percentage of type 1 balls extracted is x. If the error in x is called Δx, we can calculate Δx by using the following equation:

$$\Delta x = \sqrt{\frac{Z^2 x(1-x)}{n}} \tag{1}$$

In this equation, in order to place our confidence interval at 95% we must consider Z = 1.96. Now we can use this mathematical formula for our purpose. In this case, the role of the balls is played by the manuscripts. Table 2 shows the result of our analysis.

Table 2 Periods with important documents

The time of writing (Gregorian calendar)	Number of Astrology books	Percentage of Astrology	Error
1203–1252	2.75	57.7	38.0
1252–1300	17.75	35.5	17.9
1300–1349	14	37.1	20.1
1349–1397	11	32.3	22.7
1397–1446	27.25	21.6	13.7
1446–1495	16.25	41.4	18.3
1495–1543	33	37.7	13.1
1543–1591	47.5	33.6	10.9
1591–1640	90.5	37.0	7.9
1640–1688	134.5	39.9	6.4
1688–1737	65	52.3	8.4
1737–1785	31.5	67.9	9.2
1785–1834	114.5	54.6	6.1
1834–1882	153.5	51.3	5.5
1882–1931	32.5	40.9	13

If we find more manuscripts for a period of time, our mathematical model will be more accurate for that period. So, just as we predicted, the error is too much in the first six periods and it is better to ignore them. The following plot (Fig. 1) is the final result, with the error bars.

This shows the ratio of astrological manuscripts to all of the manuscripts.

The most important events relating to modern astronomy happened in Europe in the sixteenth century and at the beginning of the seventeenth century. This plot shows that when modern astronomy was born in Europe, there was a tendency for astrology to increase in Iran.

The mid-eighteenth century is the time when astrology peaks in Iran, and the percentage of astrology books at this time was 68% (which is twice the mid-sixteenth century level when it was 34%). The seventeenth and eighteenth centuries are known in Iran as times of insecurity, poverty and civil war.

In 1794 (near the end of the eighteenth century), the Qājār Dynasty took the control of Iran and afterwards provided internal regulation and security.

Figure 1 also shows that interest in astrology declined in the nineteenth century. In this century we can see a desire to translate French and English astronomy books into Persian, and consequently the scientific awareness of Iranians increased. In 1851, Dār Al-funūn School (the first modern school in Iran) was established, and in 1861 the Minister of Science for Iran,'I'tizād Al-saltanat, wrote a book titled *Falak al-Sa'āda* that defended modern astronomy and was against astrology. In 1867, one of the first graduates of Dār Al-funūn School, Najm al-Dawla, wrote *Qānūn Nā-ṣirī* in two volumes. This was the most detailed book about modern astronomy that had been written in Iran up to that time (Sadat-moosavi 2015).

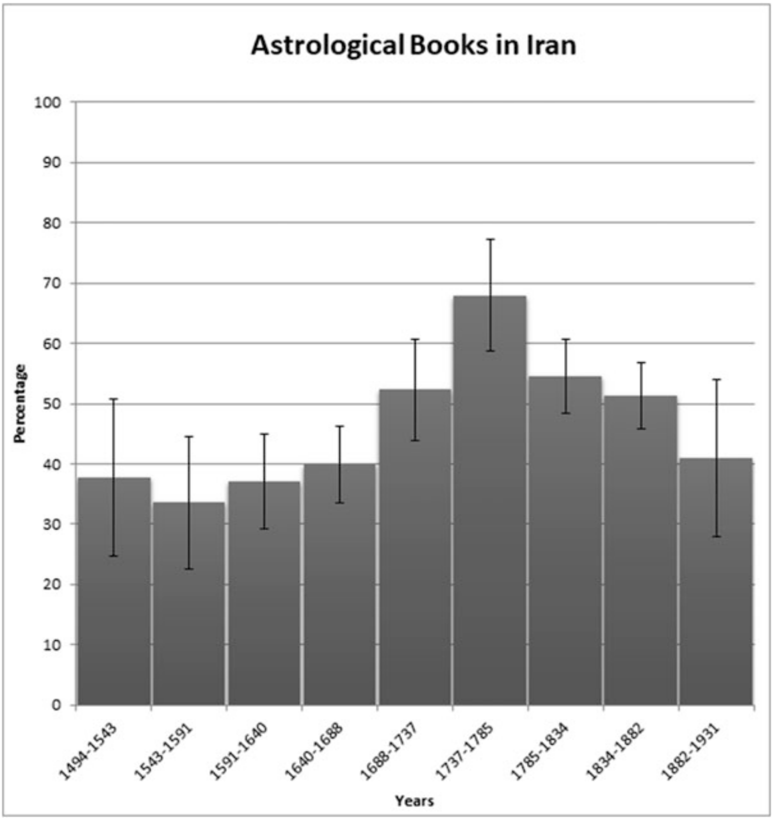

Fig. 1 Publication dates of important astronomical books in Iran

4 Conclusion

The sensitivity and attention of people and scientists in a geographic area to scientific developments that happen in the rest of the world depend on many factors. In this paper we have seen this issue from one perspective and have compared the number of astrology and hay'a (astronomy) books in 50-year periods.

This investigation and data in Fig. 1 show that there was a negative correlation between Iranian interest in astrology and the acceptance of modern astronomy. However, this correlation does not automatically imply causation, and in order to pursue on this issue further we need to consider other factors. Also, it is recommended that colleagues carry out similar research in other countries.

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On the Transfer of Technology and Knowledge in Iran During the Naseri Period (1848–1896)

Carmen Pérez González

Abstract Early in the seventeenth century, the telescope spread quickly to Asia, largely through the V.O.C. (Dutch East Indies Company) officials and Christian missionaries who often carried telescopes as diplomatic gifts for the king of their host countries. However, the story of the influx of telescopes into Iran remains a mystery, although there are a few records that reveal that by the 1660s at least one telescope had arrived to Iran, and that the Capuchin, Raphaël du Mans, may have built one in Isfahan.

However, Modern Astronomy was only introduced into Persia in the mid-nineteenth century, during the rule of Naser al-Din Shah of the Qajar Dynasty (1785–1925). Founded in 1851, the Dar al-Funun was Iran's first secular institution of higher learning, and astronomy was one of the fields of study offered there. After graduating, the best Dar al-Funun students travelled to Europe to complete their education, while many university educated Westerners moved to Iran to become teachers at the Dar al-Funun. But although great efforts were put into introducing Modern Science in Qajar Iran, the adoption of Modern Astronomy was extremely slow. This paper aims to shed light on the reasons for this. The Qajar prince Etezad al-Saltane, Director of the Dar al-Funun and the first Minister of Sciences, played a fundamental role in trying to facilitate the introduction of Modern Astronomy in Persia. Next to him, two others who played an important role in the introduction of Modern Astronomy in Iran were the Court Astronomer Abdull Ghaffar Najm al-Dawleh and Mahmod Kham Qomi who spent 7 years in Paris and Brussels and upon his return to Iran tried unsuccessfully to convince the King to build an astronomical observatory.

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1 Introduction

Iran has a long history of astronomy with renowned astronomers such as al-Ṣūfī (903–986; Kunitzsch, 1965), al-Bīrunī (973–1048; Yano, 2014) and al-Ṭūsī (1202–1274; Ragep, 2014). Three lunar craters are named after these three great figures.[1] Persia also had well-known observatories (Saliba, 1998), such as the Maragha Observatory established in 1259 with al-Ṭūsī as its first Director, and the Samarqand Observatory. In his knowledge of the stars, al-Ṣūfī was one of the leading astronomers of his time (see Hafez et al., 2011). He left a number of works, the most important one being his *ketab sowar al-kawakeb al-tabeta* (*Book of the Fixed Stars*) (Hafez et al., 2015a, 2015b; Kunitzsch, 1986). In this treatise he gives a full description of the classical system of constellations, both according to the 'scientific' Greek classification as laid down in Ptolemy's *Almagest* and to the popular Arabian tradition, adding his own observations and providing corrections to both traditions. Included are drawings of all the constellations and tables of the individual stars in each constellation, with their coordinates. This book became a classic, with many copies being made over the centuries.[2] Al-Sufi's book is arranged by constellation, in the order in which they are presented in the *Almagest*.

Three hundred years after al-Sufi's death, Maragha Observatory was founded in 1259 just south of Tabriz, and represented a new high point in Islamic astronomy (Saliba, 1987). The Observatory boasted a huge library of around four hundred thousand volumes (Sayili, 1981), and possessed many unique instruments, including terrestrial and celestial spheres, a large armillary sphere, and climatic maps of the Earth. The Observatory was also a pioneer in giving instruction in the natural sciences (ibid.).

Samarqand Observatory was built 160 years after Maragha Observatory (Fazlıoğlu, 2008). Several leading astronomers of that time, the most distinguished of them being Ghiyāth al-Din Jamshīd Mas ʿ ūd al-Kāshī (1380–1429; Schmidl, 2014) worked there alongside the Director, Ulugh Beg (1394–1449; van Dalen, 2014). The decline of Samarqand Observatory was followed by a long period of relatively uninteresting astronomical activity until an early (unsuccessful) attempt to introduce Modern Astronomy into Persia took place through the agency of Christian

[1] al-Ṣūfī: *Azophi* (22.1° S; 12.7° E; ϕ: 47.05 km; named in 1935); al-Bīrunī: *Al-Biruni* (17.9° N; 92.5° E; ϕ: 77.05 km; named in 1970 al-Ṭūsī: *Nasireddin* (41° S; 0.2° E; ϕ: 52.05 km; named in 1935). In all, 24 craters on the Moon have names of Arabic and Islamic origin, bearing witness to famous Arabian or Persian scholars. For a detailed list of these craters with full names of the scholars they refer to and their coordinates, see: "Illustrious Names in the Heavens . . ."

[2] In the course of his Ph.D. research on al-Ṣūfī's *Book of the Fixed Stars* Hafez (2010) was able to track down 35 copies located in 20 libraries in the following countries: Denmark, Egypt, England, France, Germany, India, Iran, Italy, Lebanon, Qatar, Russia, Spain, Tunisia, Turkey and the USA (see Hafez et al., 2011: 129). Although ". . . the original manuscript, written by al-Ṣūfī, has not survived . . . we do have the next best thing—a copy made by his son." (Hafez et al., 2011: 130). This is MS5036 in the Bibliotheque Nationale in Paris, which was scribed in 1009, just 23 years after al-Sūfī's death.

missionaries–first Jesuits and later Capuchins–during the Safavid Dynasty (1501–1722).

2 The Introduction of Western Modern Astronomy in Iran

There were three channels which enabled the introduction of Modern (Western) Astronomy into Iran:

1. Technology: the introduction of the telescope (ca. 1650).
2. Translations of books.
3. Education: Dar al-Funun and Iranian students who travelled to Europe to study Modern Sciences.

2.1 The Introduction of the Telescope to Iran

A key event of the early seventeenth century was the invention of the telescope in Holland in 1608, and its prompt diffusion through Dutch and French expeditions and Christian missionaries—especially Jesuits—to Asia. During these expeditions, telescopes were often carried as diplomatic gifts for the kings of host countries. The Vereenigde Ostindische Compaignie (V.O.C., or Dutch East Indies Company) played a fundamental role in the spread of the telescope throughout Asia, to Japan, China, Korea, Siam and India (see Kapoor, 2016; Louwman, and Zuidervaart, 2013; Nakamura, 2008; Rao, 1984; Sluiter, 1997; Zoomers, 2010). The historical reconstruction of the arrival of the telescope in the different Asian countries is of fundamental importance, as in each instance it marked the moment when local astronomers could begin telescopic astronomy.

Records inform us that the telescope arrived in many Asian countries within the first two decades after its invention in Holland. But even if the telescope was soon transmitted to China, Mughal India and the Ottoman Empire, these cultures did not respond in the way Europeans did to this technological innovation. The telescope was a powerful, emblematic symbol of the scientific revolution, and Huff (2011: 18–19) postulates three contexts as necessary to understand its significance:

> First, it is the emblematic instrument of the modern scientific revolution. It is the instrument of empirical observation most associated with the scientific revolution of the seventeenth century.
>
> Second, and most practically, the telescope transformed the practice of astronomy in the seventeenth century: it transformed astronomy from a plodding science into an active, exploratory inquiry, that constantly looks for new discoveries. In that sense, the telescope was a newly invented "discovery machine" ... And, at the same time, the telescope is a "portable laboratory" that could be taken anywhere in the world and used to explore the heavens.

The third context concerns the telescope as a precision instrument.

So, at least technically, Asian astronomers would also have been able to undertake telescopic observations of the Moon and to make telescopic drawings.

While Capuchin missions marked the path through which the telescope reached Iran, the story of its introduction remains a mystery—although there are some clues as to when and how it may have arrived (or been invented) on Iranian soil.

Records point to the fact that, already in the 1660s at least one telescope had arrived in Iran or that one had even been built there. An article published in the Iranian journal *Yadegar* in 1945 (Ashtiyani, 1945) and reprinted years later in *Nojum* (the leading Iranian astronomical journal), informs us that a telescope may have been constructed in Iran by the French Capuchin Raphaël du Mans (1613–1696).

The *Yadegar* article tells how, in his *Riaz-ol-Olama* (1695), Mirza Abdollah Esfahani (known as Afandi) wrote as follows about a renowned engineer known as Tanasobi (full name Thābit ibn Qurra al-Ḥarrānī):

> Mullah Mohammad Saleh Ghazvini in his book titled *Navader-ol-Oloom-val-Adab* (*Experts in Science and Literature*) mentions that, in his time at Isfahan, there was a Western engineer, named Raphaël, expert in technology who had no rival especially in mathematics. He constructed an instrument and learned about that instrument from the western masters; if you look through it at night, you will observe many stars that were not seen before, and especially around some of the planets some stars appear, and the Moon appears in a very strange shape and they claim that there are lands, jungles and towns on the Moon and the Pleiades appears so impossibly huge and myriad of stars at a large distance from each other can be seen through it. Briefly, one can see all sorts of wonders in the sky using this instrument. It looks like an Indian reed which is used for making spears, approximately two cubits long [i.e. 91.4 cm]; it is denser than the reed and is made of cardboard and on its two ends there are two circular glasses similar to eye-glasses. The secret of that industry lies in those two glasses and their circular and concave shape. When you put your eye to one of the glass and look through the reed, this effect influences the two confronting glasses and it is strange (Ashtiyani, 1945: 33–36).

This is the first known description of a telescope in Iranian sources. The writer of *Riaz-ol-Olama* then continues:

> But what Mullah Mohammad Saleh writes about this instrument is nothing new, as right now it is very popular among the people in the west and we have seen it many times in Constantinople and Isfahan and it is, in fact, a type of instrument known as Remote Viewer[3] and we have seen other features in this instrument than the ones he has written about.

Even though the date of his birth and death are not clear, the narrator of the above section, Mullah Mohammad Saleh ibn Bagher Ghazvini (known as Roghani), must have been alive at least until 1669, because his translation of *Al-Sahifa al-Sajjadiyya* appeared in 1662 and another translation from him in 1669, also around that time he must have written *Navader-ol-Oloom-val-Adab*. He was one of the scholars of the Shah Abbas II (1642–1666) and Shah Solei-man (1667–1695) periods, some 50 or

[3]This is a direct translation, but if we want to adopt the terminology used at the time in Europe, then it should be referred to as a 'spyglass'.

60 years after the telescope was used in Europe for the first time to observe celestial bodies (Ashtiyani, 1945).

However, as stated in the *Yadegar* article, the Raphaël mentioned in the writings of Mullah Mohammad Saleh Ghazvini is most probably the French Capuchin Raphaël Du Mans (Richard, 1995, 2004), who led the Capuchin mission to Isfahan from 1646 to 1696 (Richard, 2007) and who in 1660 wrote *L'Estat de la Perse en 1660*, a book he dedicated to his Minister, Jean-Baptiste Colbert (1619–1683; Du Mans, 1890). While in Iran, Du Mans worked as a translator at the Court of Shah Abbas II and Shah Soleiman, being responsible during his sojourn in Isfahan for most of the communication between these monarchs and foreign countries. Since this period corresponds fully with the years Mullah Mohammad Saleh Ghazvini spent in Isfahan, and the French Capuchin was familiar with astronomy and optics, it is highly probable that the Raphaël referred to in Saleh's *Navader-ol-Oloom-val-Adab* was actually Raphaël Du Mans.

Raphaël du Mans may well have known his fellow Capuchin Chérubin d'Orleans (1613–1697), a leading astronomer of the time, whose book on the fundamentals of optics, *La Diop-trique Oculaire*, was published in 1671. In this work, d'Orleans printed extremely detailed drawings of a telescope that he had himself invented and which he used to draw an exquisite map of the Moon. This map became the focus of a major controversy, as another leading astronomer of the time, Johannes Hevelius (1611–1687), accused d'Orleans of plagiarism (Whitaker, 2003, 76–78). On this issue, Blanchard (2013) writes:

> It is interesting that between 1676 and 1681 Chérubin d'Orleans was accused by l'Abbé Claude Comier of plagiarism. Nevertheless, it is yet to be demonstrated that Chérubin plagiarized Hevelius.

Whatever the case, since du Mans and d'Orleans were contemporaries and both were Capuchins, it is likely that they knew each other, or at least that du Mans was familiar with d'Orleans' book.[4]

Neither *Le Estat de Perse* nor the book mentioning du Mans written by Richard (1995) makes any reference to either d'Orleans or to telescopes. However, there are several references in du Mans' work to astrolabes and their functioning, and to the role of the Court astrologers:

> Each year the king spends more than twenty thousand *tomans* to maintain his astrologers, *monagem*, who are always by his side with their astrolabe to suggest the good time for having influence, to dominate, and to say when it is good to sit, to get up, to leave, to eat, to sleep, to wear this or that colour, with the result that he is in their absolute disposal. (Du Mans, 1890*:* 166; English translation by Debora Velleuer).

We can also read several paragraphs devoted to books kept in the Court library, including the following list of the most important books relating to Western astronomy, optics and mathematics:

[4] According to Blanchard (pers. comm., February 2016), it is unlikely that d'Orleans ever travelled to Iran. He argues that if d'Orleans had travelled outside of France at anytime, it could only have been between 1642 and 1665.

> Here they have Almagestum by Ptolemy in Arabic, the *Sphérique* by Ménélaus and Théodose, all kinds of theories about the movement of the planets such as *Coagé Nesseir* by Mirza Ouloukbec; Euclide and all his work, fragments of Arquimedes and Apollonious and other ancient authors, also the perspective of Ebn Heissen, the books of arithmetics, *elme hasabe,* algebra, *elegebre,* the optics, *minaser,* and the movements, *gerre sakril.* (Du Mans, 1890*:* 164–165; English translation by Debora Velleuer).

Here du Mans also compares and comments on the state of development of mathematics and science in general in Persia and in Europe:

> Mathematics grown here is more general but not in sublime degree as in the Occident. Here, all the parts of mathematics are located, *riasi*, but they subordinate all these sciences to the judiciary, *ehkoum*, saying that methods without effect are useless. (Du Mans, 1890*:* 165; English translation by Debora Velleuer).

Séraphin d'Orleans, who lived and worked with Raphaël du Mans in the Capuchin hospice in Isfahan for several years, like Chérubin d'Orleans and Raphaël came from the North African province of Temian. This makes it even more likely that the three would have known each other.

Another book that du Mans may have known was *Occulus enoch & Elliae* that was written by Anton Maria Schyrleus Rheita (1604–1660) in 1645 and provided rich and detailed information on how to make telescopes. As G. Blanchard (pers. comm., February 2016) points out, only a few Capuchins were involved in optics and astronomy during the seventeenth century, so they must all have known each other.[5] Regrettably, the books from the Capuchin Library in Isfahan (near Qa'la-i-tabarruk) were dispersed in the course of the Afghan invasion in the eighteenth century (Richard, 1995: 52, note 120), so it is impossible to know which books on astronomy and optics du Mans would have had access to.

Another important issue mentioned in the *Yadegar* article is that the Persian astronomers from Isfahan had at least seen a telescope in Constantinople. G. Blanchard (pers. comm., February 2016) comments: "I am aware that Chérubin provided lots of telescopes for important people connected to Louis XIV. In the list there is one for the French Ambassador in Constantinople around 1679."

A second possible way for the telescope to have been introduced to Persia was through the Jesuit mission, which was established in Isfahan before the Capuchins arrived. To date, however, no written records have been found to support this hypothesis.

The third possible route for the telescope to reach Persia would have been through the Dutch V.O.C., a topic that I am currently researching.[6]

For the moment, we can only conclude that Raphaël du Mans either constructed his own telescope or was given one by a foreign visitor to Isfahan as early as the 1650s. So the technology needed to make telescopic observations would have been

[5]In the history of optics, another important Capuchin was Father Anian (G. Blanchard, pers. comm., February 2016).

[6]For insightful studies of travellers and missionaries in Safavid Iran see Matthee (2005, 2009, 2012) and Mitchell (2005).

available in Persia a mere four decades after the telescope was invented in Holland. Despite this, no documentary evidence has been found to show that Persian astronomy benefitted from the use of the telescope over the next two centuries.

It is important to note at this stage that there was considerable religious objection to the introduction of Modern Astronomy in Iran, with its central role in establishing the motion of the Earth around the Sun. This was aggravated by the opposition of Modern Astronomers to the astrology that was considered by the *ulama* to be an essential element of Ptolemy's astronomy, as taught in the traditional *madrasas*. Arjomand (1997) has examined the roots and results of this controversy.

2.2 Translations of Books

By 1624 the Italian traveller Pietro della Velle (1586–1652; Gurney, 1986; Della Valle, 1843) had already prepared a Persian translation of the treatise on Tycho Brahe's system written by the Jesuit astronomer Christoforo Borri (d. 1632; Arjomand, 2012; Sayili, 1958).

Simultaneously with this Western incursion, many Iranians—due to the centuries-old political, social and cultural relations between medieval India and Iran—during the Safavid Era moved to India, and particularly to Bombay (Mumbai), Calcutta (Kolkata) and cities in Awadh province. Abu al-Fath Muhammad Sultan, the last Safavid King, fled to Sind and settled in Lucknow in the mid-1790s; Mirza Abu Talib dedicated his tract *Miraj al-Tawhid* to him. As Ansari (1985, 2002, 2006) explains, writings of Indian scholars in Indo-Persian were collected and transported to Iran quite easily. A copy of the tract *Risalah dar Athbat-i hay'at-i jadid* (*Tract on the Proofs of Modern Astronomy*) is extant in the Library of Gharb in Hamadan (Iran), and another tract of Modern Astronomy and Science, *Risalah dar Hikmat-i jadid wa afrinish-i sitaragan* (*A Tract of Modern Natural Philosophy and the Existence of the Stars*), written in 1851, is kept at Tehran University Library (Ansari, 2006).

The first Persian translation of a treatise on Modern Astronomy, Mirza Mas'ud's *Tarjome-ye Hei'at* (*Translation of the Science of Configuration*), was published in Iran in 1818 (Isahaya, 2013). Mas'ud, was a Government official who is best considered a linguist rather than an astronomer,[7] completed the translation as part of his official duties at the Court of Fath 'Ali Shah (1797–1834). James Lyman Merrick, an American Presbyterian missionary in Iran during 1834–1835, also translated a book on Modern Astronomy (T. Heidarzadeh, pers. comm., April 2016).

[7]Isahaya (2013) make an interesting comparative analysis of the first translations of treatises on Modern Astronomy done in Iran and in Japan. He concludes that in both cases the translators should be considered linguists, as they were not astronomers. Rather than advanced astronomical works, the books can be categorized as being for a general readership, and later intellectuals familiar with astronomy declared their dissatisfaction with these first translations. Finally, both translators regarded works on Western Astronomy as lying outside their own astronomical traditions.

In the next section, I will come back to the topic of translations of Western astronomical books and treatises, as during the nineteenth century the number of translated books increased exponentially and became the textbooks for the first generation of astronomy students in Iran.

2.3 Education: Dar al-Funun and the Introduction of Modern Astronomy in Qajar Iran

Mighty is he who has knowledge.
By knowledge the old hearts grow young again.[8]

Modern Astronomy was not introduced in Persia until the mid-nineteenth century, a decade after the introduction of photography, during the rule of Naser al-Din Shah (1848–1896) of the Qajar Dynasty (1785–1925). This period was critically important for the introduction of Modern Science in general in Iran.

Founded by Amir Kabir, Naser al-Din Shah Qajar's first Prime Minister, the Dar al-Funun (Polytechnic University, ca. 1851–1892) was Iran's first secular institution of higher learning (Ehktiar, 1994; 2001; Nabavi, 1990). The fields of study represented there were military and medical sciences, natural sciences, history and geography, foreign languages and translation, technology (printing, photography and telegraphy) and the arts (painting, music and drama). The institute was planned and built under the supervision of the Qajar Prince Bahram Mirza (1806–1882).

The best students at Dar al-Funun travelled to Europe to complete their education after graduating at the polytechnic institute. Shaped by a similar academic, intellectual and professional curriculum, most of them returned home after a number of years abroad, while hundreds of university-educated Westerners moved to Iran to become teachers at Dar al-Funun.

But even if great efforts were put into introducing Modern Science in Qajar, its initial adoption in Iran was extremely slow. Among the many reasons for this was the resistance of the local scientific community to 'Modern' Astronomy, because traditional Persian astronomy focused on calendar-making and divination. The Qajar Prince Ali Quli Mirza Etezad al-Saltane (1822–1880), Director of Dar al-Funun and First Minister of Sciences, played a fundamental role in combating such religious objections. His book, *Falak al-Sa'ada* (*Auspicious Heavens*), published in 1861, was an open attack on the traditional sciences (Arjomand 1997).

Several European travellers refer to Dar al-Funun in their journals, mentioning the Royal Astrologers and the importance of their task at Court and beyond. The Austrian physician, Dr. Jakob Eduard Polak (1818–1891), personal doctor to Naser al-Din Shah and teacher of Medicine at Dar al-Funun, wrote some pages about astrology at Court in his travelogue *Persien. Das land und Ihre Bewohner*:

[8]Ferdowsi, *Shahnameh.* This poem is inscribed on the upper façade of the main entrance of Dar al-Funun.

> The same credits are enjoyed by astrology; the faith is still in full bloom, as in Europe in the Middle Ages. The *munaechim* (astrologer) provides the horoscope (táleh), determines the happy and unhappy hours of a business (Saat), as well as the hour and minute in which the king is to leave or to enter the city ... The astrologers, after mutual agreement, determine different days, one of which, of course, must be the right one. The astronomers use the tables (sitsch) of the famous astronomer from Maragha, and those of the Italian astronomer Cassini to determine the beginning of the year (nauruz), the beginning of the year seasons (fass'l), and eclipses of the Sun and Moon (kaeschuf-e-aftab u mah) . . . (Polak, 1865: 287–288; my English translation).

Another important matter to take into consideration here is that trips to Europe not only by the Shah (Sohrabi, 2012; Pérez González and Sheikh, 2015) but also by Dar al-Funun's brightest students, and also the simultaneous impact of the European scholars who took up teaching posts at Dar-al Funun, Atai (1992: 192) comments on this:

> The students' young age was to their disadvantage in a different way as well. In a culture where a firm tradition of ruling according to the family affiliations of senior statesmen was in place, the young graduates of European schools wouldn't have been welcomed to share power with the older elite. The ruling elite, including the Qajar kings, were more at ease employing foreign advisors and technicians than the European-educated young Iranians. The underutilization of the skills of the returning students may have been due to other factors, which were inevitable in nineteenth century Iranian society. One such obstacle may have been the fact that the mere acquisition of new techniques and sciences would not guarantee their application. For Mirza Mahmud to be able to practice astronomy, for instance, there had to be an observatory available in the country.

The inevitable result of such limitations was that the students were often employed in areas not related to their expertise. Another obstacle in this particular area was cultural. Most young graduates came from the families of notables, dignitaries and the Qajar tribe, who had been engaged for decades in military and administrative professions. While technical professions were considered respectable in Europe, such occupations were, however, seen as unfit for the elite class in Iran. Thus, many students, despite their technical skills, chose civil and military careers over professions related to their training and expertise (Atai, 1992).

With the opening of Dar al-Funun, Modern Science was suddenly introduced to a country whose traditional schools, completely under the sponsorship of the clergy, were acquainted only with traditional science. Without the necessary background for debating such a development, this presented a difficult situation, especially with regard to astronomy (e.g. see Arjomand, 1997; Heidarzadeh, 1998). Traditional Persian astronomy was mainly used for the calculation of the lunar calendar. Hence, with regard to the Moon traditional astronomers were concerned with mapping time rather than space: more precisely, mapping the lunar surface was an alien interest. How this changed, if at all, after the opening of Dar al-Funun must be one of the main research questions of this paper.

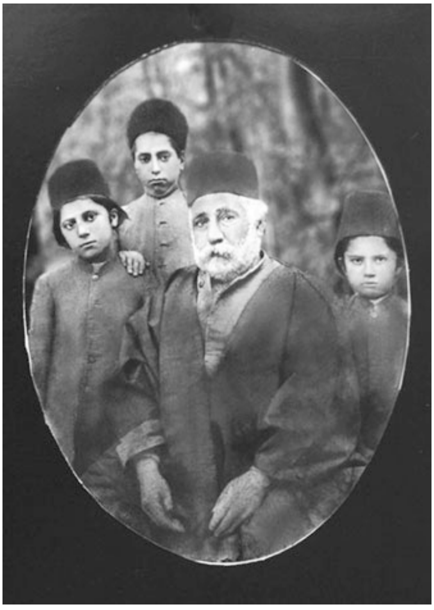
3 Iranian Astronomers During the Naseri Period

3.1 Abdul Ghaffar Najm al Dawleh, Court Astronomer and Dar al-Funun Teacher

Haj Mirza Abdul Ghaffar Najm al Dawleh (1839–1908; Fig. 1) was born in Isfahan (Payerband, 2009a). His father, the clergyman Mullah Ali Mohammad Isfahani, was a famous mathematician. As Payerband (ibid.) explains, in his father's house, the young Najm al Dawleh was brought up in surroundings replete with science and learning, especially in mathematics and astronomy. At the invitation of Etezad al-Saltaneh, who had realized his scientific potential, the *mullah* moved with his family to Tehran, where he received due respect for his scientific knowledge and sound experience in managing Dar al-Funun. Eventually, Najm al Dawleh became a student there, learning English, French and Modern European Science from European teachers. His knowledge of mathematics improved and was complemented by astronomy.

In 1859, at the age of 20, al Dawleh took up a teaching post in Mathematics at Dar al-Funun. He gradually noticed a lack of course books in all the scientific fields taught at Dar al-Funun. Etezad al-Saltaneh insisted that such books should be written in Persian (Atami 2000), and upon his request, al Dawleh began writing textbooks not only on the subjects he himself taught—such as mathematics and spherical astronomy—but also on allied fields, such as geography, topography, mechanics, painting, industrial map designing, population census and technology. By the age of 29 he had written some 20 books (see Ehktiar, 1994: 314–316).

Fig. 1 Portrait of Abdul Ghaffar Najm al-Dawleh, Royal Astronomer to Naser al-Din Shah, ca. 1890. (Courtesy: Palace Golestan Library)



One of al Dawleh's innovations in compiling calendars was to make a logical connection between the date of the Prophet's migration with the months and days of the solar calendar. He assigned the date of the Prophet's migration from Mecca to Medina as the basis of the modern calendar, known at the time as the Jalali Calendar and now as the Solar Hijri Calendar. Writing on the 39th anniversary of Naser al-Din Shah's reign, in the year 808 of the Jalali Calendar (1885–1886), he mentioned the Solar Hijri Calendar in a marginal note: ". . . year 1256 of Solar Hijri Calendar."

Working on calendars was a family occupation in Najm al Dawleh's family, as he noted in the Persian Lunar Calendar of 1874:

> These days, since seventy years ago, in Tehran or Isfahan, whoever has studied mathematics, Iranian and western astronomy and metaphysics, the beginning and the starting point have been in my father's family and they have acquired their knowledge there, either directly or indirectly (Payerband 2009a).

Naser al-Din Shah, who was interested in astronomy, himself became one of al Dawleh's pupils. On his return to Iran from one of his trips to Europe, he bought for him a modern French book on astronomy, which he requested his master translate. Al Dawleh regularly taught the Shah from this book, titled *Aseman* (the Sky). Unfortunately, the translation was never published, and only a few copies of the book were sent to his brother, Fakhr al-Dawleh (1883–1955), and to the Governor of Isfahan, Zel-i al-Sultan (1850–1918).

In addition to working on calendars, and translating and writing books on astronomy, Abdull Ghaffar Najm al Dawleh was active in observational astronomy. He was one of the few Iranians who observed the 1874 transit of Venus, which occurred when General Steib-nitzki's Russian Expedition was in Tehran. About this event he writes in his *Badayet al-Nojum (Novelties in Astronomy)*:

> On 9th December 1874, Venus moved across the Sun once more and people were sent to all corners where this event could be observed. In Tehran, too, some people came from Berlin and on top of the Sepah Salar Garden pavilion, they installed certain instruments. Myself, along with my father and the late Etezad al-Saltaneh, witnessed the transit of Venus across the face of the Sun. Based on this transit they measured the exact distance between the viewpoint and the Sun and thus got the approximate record they had registered before. (Payerband, 2009a).

As Duerbeck (2004) has recounted, the first major Government-funded German scientific enterprise was to send out an expedition to observe the 1874 transit from Zhifu (in China), the Kerguelen Islands (in the Indian Ocean), Auckland Islands (New Zealand), Mauritius (Indian Ocean), Isfahan (Persia) and Luxor (Egypt). The expedition to Isfahan was purely photographic, and included four persons: the photographer Gustav Theodor Fritsch, the astronomer Ernst Becker and two other photographers, the German geographer Franz Stolze and Hugo Buchwald. The party went by train through the Baltic provinces to Tsaritsyn (now Volgograd), took a steamer down the Volga to Astrakhan, across the Caspian Sea to the Persian port of Rasht, and then a caravan of 58 animals to Tehran. After an audience with the Shah, the scientists continued their trip to Isfahan, where a 'Garden palace' outside of the city was used as a lodge, and the instruments were set up in the vicinity (Figs. 2, 3

Fig. 2 The German transit of Venus observing site in Isfahan. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

Fig. 3 The German telescope in place in Isfahan, ready for the transit. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

and 4). In one of the photographs, we can see a small crowd that had gathered to follow the movements of the German Expedition members and the local staff. It mustsurely have been the most interesting event of that whole year. Another photograph shows a portrait of the Chief Astronomer in Isfahan (Fig. 5), whom

Fig. 4 Members of the 1874 German transit of Venus expedition in Isfahan. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

Fig. 5 The Chief astronomer from Isfahan in 1874. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

Payerband (pers. comm., March 2017) believes may have been Abdull Ghaffar Najm al-Dawleh's father.

The Azita and Elmar Seibel Collection holds 12 album prints of this expedition. Apart from photographs of members of the expedition with their instruments and local astronomers, there are four images of what seems to be the cover for a book, maybe on the expedition (e.g. see Figs. 6 and 7). The caption to a photograph of this expedition printed in the *Illustrierte Zei-tung* identifies the four members of expedition mentioned above, and also 'Hoeltzer', specifically Ernst Hoeltzer, a foreign photographer active in Iran, who had settled in Isfahan.

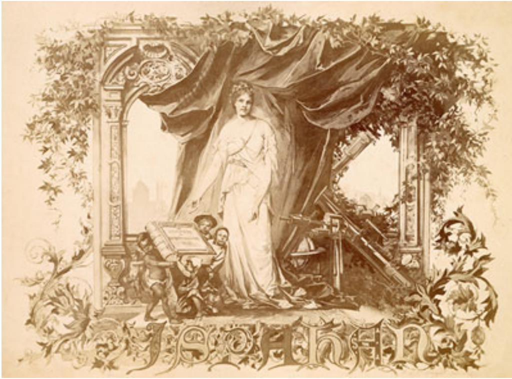


Fig. 6 The German transit of Venus expedition to Isfahan in 1874. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

Fig. 7 The German transit of Venus expedition to Isfahan in 1874. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

Gustav Fritsch's comments on local architecture are not without sarcasm (as noted by Duerbeck (2004: 12):

> Soon a building was raised on the western part of the platform, which excelled through its simplicity, when compared with the nearby castles of Shah Abbas, of a weird architectural style, resembling most closely a shielded battery.

Nevertheless, it must be noted that in the scientific report written by the head of the German Expedition upon their return to Germany, he comments about the generous and effective cooperation of the local authorities with the expedition members and their goals:

> His Majesty the Shah welcomed the expedition, and gave it all his support, including providing an escort, the Persian Colonel Morte-zagoli, who was to accompany the expedition to Ispahan, to arrange a good reception there, and to later return the expedition to Tehran. I am extremely grateful to the Shah and the Colonel for the zeal and the courtesy with which they and the Persian authorities in Isaphan were concerned with the success of the expedition. (Auwers, 1898, 190; my English translation).

Although Auwers' report (1898) makes no reference to any local astronomer, as we have seen, the photographs from the expedition include an image of the Chief Astronomer from Isfahan. It is therefore important to know *how* (if at all) the local astronomers profited from this extraordinary opportunity to observe the most important astronomical phenomenon that occurred during the Naseri period and which could be followed with the help of Western technology. I have found quite a few references to some scientific instruments that stayed in Isfahan, written in the aforementioned report:

> A Heber barometer and two thermometers were given to Mr. Höltzer against the promise of doing regular meteorological observations in Ispahan, and to acknowledge the good services which the expedition had rendered during the journey, and during their entire stay in Ispahan. (Auwers, 1898: 190; my English translation).

Even if the event must have been of extreme interest for both the German and local astronomers, reality is that the results of this first purely photographic expedition were a catastrophe, because on that day and at the precise moment of the transit of Venus the sky was completely covered with clouds. This was quite a disappointment for the whole team, which had prepared all the photographic material needed to record the Transit with the greatest care, as mentioned in the same report. They could only take 24 plates, but none was of the required quality (Auwers, 1898).

Among Abdull Ghaffar Najm al Dawleh's other contributions was adjusting the Hijri Calendar to the Christian Calendar. In his *Comparative Essay* (1903) he included tables with simple instructions for this conversion.

Al Dawleh's most important book (see Fig. 8) was a treatise in Persian on Modern Astronomy titled *Qanun-i Nasiri* (after the name of the Shah), which was written at the insistence of the Minister of Education Ali Quli Mirza. In this book there are interesting illustrations relating to different topics in Modern Astronomy.

Chapter IV of the treatise provides a detailed description of the motion of the Moon, its apparent diameter, crescents, different phases (Fig. 9), orbits, craters, lunar eclipses and solar eclipses, as well as the lunar occultation of the planets. The author was clearly well versed in the work of contemporary English and French astronomers. As Mathur (1985: 156–157) observes, an important conclusion in the treatise is that

> . . . the Eastern mind was not averse to Western learning and that it responded favorably to its acquisition without forgetting its own traditions, as it is clear from the works produced in those days: (1) *Risalah dar Ahwal-I Mulk-I Farang wa Industan* (in Persian) by Muhammed Hussayn ibn Abdul Azim al-Husayni al-Isfahani (d. 1790), (2) *Risalah dar hay at-i Jadid* by Abu Talib al-Hussayni, (3) *Majmu a-i Shamsi* by Abul Khayr ibn Mawlwi Ghiyathuddin, (4) *Miftah al-Aflak* (anonymous).

I have been able to study a copy of this book kept in the Majlis Library (Library of Congress) in Tehran. Chapter VI contains a section on lunar craters and their physical resemblance to terrestrial volcanoes, as well as insights into lunar topography, together with a table introducing the heights and names of twelve lunar craters that presumably were observed by al Dawleh. A further interesting item is a drawing

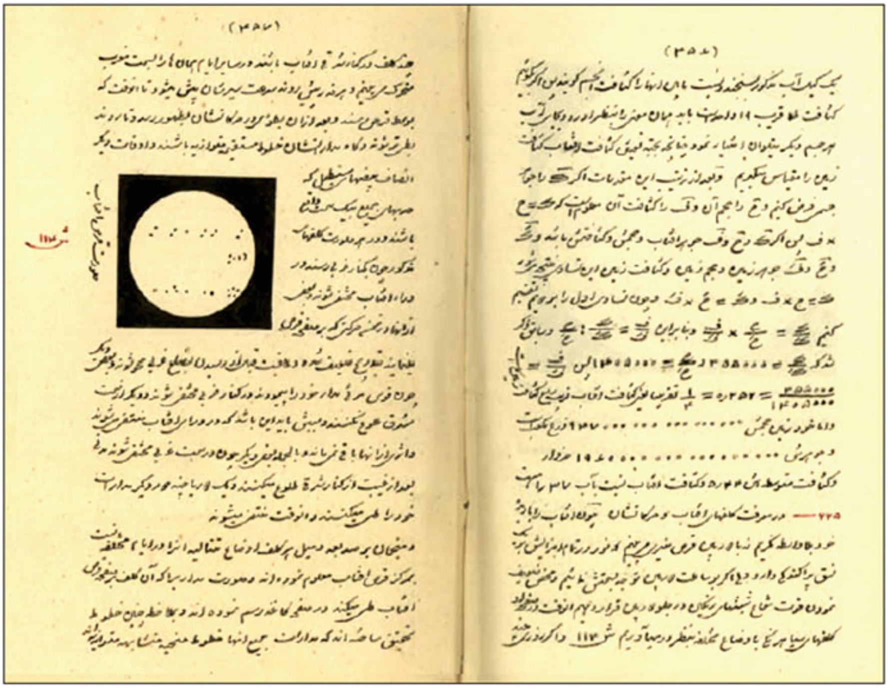


Fig. 8 Two pages from the book *Qanun-i Nasiri* by Abdul Ghaffar Najm al-Dawleh

of a generic lunar crater, with a long explanation of the form of the lunar craters as observed through the telescope.

Najm al Dawleh died in 1908, after 50 years of research, teaching, translating, writing, editing literary texts, discussing technological, astronomical and economic issues, preparing textbooks on mathematics, geometry and spherical astronomy, and developing the natural sciences, but especially astronomy.

3.2 Mahmud Khan Qomi, an Astronomy Student in Paris and Brussels

The second most important figure related to the introduction of Modern Astronomy in Iran is Mirza Mahmud Khan Qomi (1834–1920; Fig. 10), who became a student at Dar al-Funun. After 2 years of study at Dar al-Funun, he completed his *Naser Calendar*, which attracted special attention. In 1858 he was sent to Europe, along with 39 other Iranian students. The group was under the supervision of the Iranian

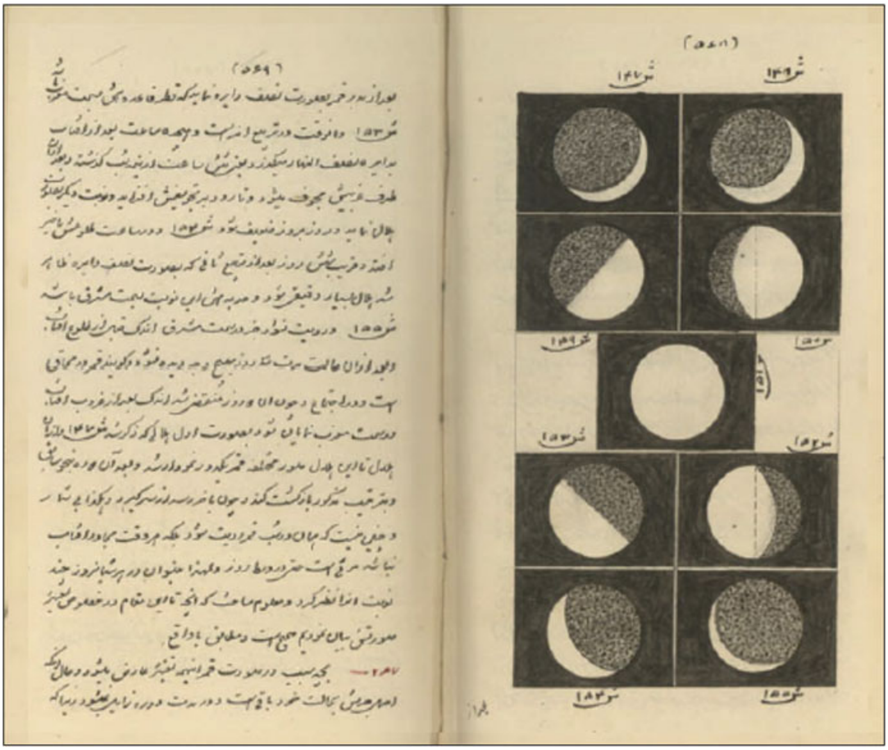


Fig. 9 A further example of two pages from the book *Qanun-i Nasiri* by Abdul Ghaffar Najm al-Dawleh

Ambassador to England and France, Amir Nezam Garusi. Qomi was assigned to study astronomy in Paris, where he attended courses at the École Polytechnique and at the Sorbonne, studying under the guidance of the Director of the Paris Observatory, Urbain Jean Joseph Le Verrier (1811–1877; Lequeaux, 2013). Qomi was the only astronomy student in the Iranian group, and he can be considered one of the first Iranians to be educated in Modern Science. Five years later, after his graduation in Paris, he went to Belgium for further studies.

During the nineteenth century, a popular research area was the quest for new asteroids, and Payerband (2009a) claims that in 1860 a group of astronomers at Paris Observatory, including Qomi, discovered an asteroid that they named 61 Danaë. However, to date no documentation has been found at Paris Observatory about this discovery, and James Lequeux of Paris Observatory (pers. comm., March 2016) points out that "We know of only one student of Le Verrier during all his lifetime: Aimable Gaillot." Meanwhile, Schmadel's *Dictionary of Minor Planet Names* (2007) reveals that this discovery in fact as made from Paris, but by the German-French amateur astronomer Hermann Goldschmidt, who never was employed by

Fig. 10 Portrait of Mahmood Khan Qomi, Royal Astronomer to Naser al-Din Shah, ca. 1870. (Courtesy: Palace Golestan Library)

Paris Observatory.[9] According to Payerband (2009b), feedback on the Iranian students' sojourns in Europe was published in *Dawlat Aliyeh Iran*, and most of the reports were written by the leader of the group, Courvoisier. Several of these reports are devoted to Mahmud Khan Qomi (e.g. see Fig. 11), including the following:

> The astronomer Mirza Mahmood is one of the students dispatched by the state taking lessons in the listed sciences and is attempting to conclude his studies in this field. He is a talented, enthusiastic young man and his educators are content with his efforts, and he has made considerable progress in the science of astronomy. To finish his mission, he is in need of special instruments for observation, which were not provided to him, as expected, in the French Observatory. (Payerband, 2009b: 54).

A significant detail is the advice given to Qomi by Mahmud Khan Naser al-Molk, the Persian Minister in London. He reminded Qomi to cultivate detachment, because he had been in Europe for several years, and if he did not have the proper attitude he would soon die of sorrow because of the state of affairs in Iran (ibid.). Later in this Section it will become evident how wise and premonitory the Persian Minister's words were.

[9]Hermann Mayer Salomon Goldschmidt (1802–1866) was born in Frankfurt, Germany, but moved to Paris in 1836 to continue his training as a painter. However, he soon fell under the spell of Paris Observatory's Le Verrier and decided to devote his life to astronomy. Using a succession of small telescopes he searched successfully for new asteroids, and between 1852 and 1861 made 14 discoveries (61 Danaë was his thirteenth). As a result, in 1861 he was awarded the Royal Astronomical Society's Gold Medal (Anonymous, 1867).

Fig. 11 A newspaper report on Mahmud Khan Qomi's trip to Europe in 1870

It may not be surprising that in spite of his training as an astronomer, like many other leading Iranian students of the period, Qomi became a diplomat, and upon returning to Iran he was granted the title of Khan and the position of *Sarhang*, and made Deputy Director of the Telegraph Bureau (Atai, 1992). He is said to have been dismissed from this post by Naser al-Din Shah, but was later given the title of Mushir al-Wizarah and dispatched by Mirza Husayn Khan Sipahsalar as Chargé d'Affaires and Consul to Baghdad. He also served as Consul.

General in Trabzan (Trebizond) for a while. During the tenure of Sa'd al-Dawlah he served as Minister of Trade, receiving the title of Mush-awir al-Mulk, and he headed the Courts dealing with commercial disputes. After serving in this post, he remained in retirement until his death in 1920 (ibid.).

While still holding the position of Minister of Telegraphs, Qomi tried in vain to convince the Shah to build a Royal Observatory. He would take his observing equipment and telescopes to the top of the Shams al-Emareh Tower in Tehran (Fig. 12), where Naser al-Din Shah would often briefly accompany him. Qomi

Fig. 12 The Shams al-Emarol Tower at the Golestan Palace in Tehran, where Mahmood Khan Qomi made astronomical observations in the 1880s. (Courtesy: Collection of Azita Bina and Elmar W. Seibel)

would tell the Shah about the wonders lying in the night sky, always attempting to convince him to build an observatory. On one of those nights, Qomi told the Shah:

> May his Highness stay in perfect health for long and may his just reign stay forever. His Majesty is well aware that that under the protection of his Royal care and the provisions of Iran supreme state, I spent years of study in the West and in the school of polytechnics. I was educated in astronomy. In the countries of France and Belgium I worked and researched using modern instruments. This day I see it as a responsibility to compensate for this generosity. His Highness is well aware that these days in foreign countries there are constructions and buildings built for research on heavenly spheres and planets and these constructions are the pride of nations and countries and carry with them the name of kings. This humble servant would like to ask for a budget from the Royal Treasury to construct an observatory near the capital city of Tehran and collect the most recent tools and instruments in Iran and to hire and educate a team, and to adorn it with the honorable name of your Highness' kingship. So we can do research and be proud to work in the Royal Nasseri Observatory and your peasants and servants worship the Shah for his Highness' glory and grace and care for modern science . It is not becoming of our power and prestige to possess of the modern tools and instruments any less than other nations in the world (Payerband, 2009a: 55).

Naser al-Din Shah replied:

> Moshaverol-Molk, you are still young and naïve and full of yourself because you have recently returned from foreign lands. At this moment it suffices to tell you that we cannot

Fig. 13 Mozaffer al-Din Mirza with a telescope in Tabriz, ca. 1890. (Courtesy: Palace Golestan Library, Tehran)

> dissipate a fortune in ruling the country young man. We are spending endlessly on lands and court servants and peasants and the embassies of foreign states and every day we have heard nothing but curses. Imagine we spend our wealth on heavens and skies! No! We do not need the Western instruments of entertainments in the heavens. You must understand that money cannot be spent on air and skies. At the moment you'd better prepare to travel to Baghdad again. We will appoint you once again as the chief ambassador. Strive to be successful in this job and not in the business of the air. (ibid.).

Naser al-Din's second travelogue tells of his visit to London and of his interest in the Royal Observatory there—not necessarily, however, for its astronomical use:

> We now descended, and the Heirs-Apparent, with their wives, took leave and departed, as I wished to go to the Observatory. I proceeded to the open ground of the Naval College, in the middle of which there was a large ship of war fully rigged, for the exercises of the naval boys, who were practicing their manual drills there. About five hundred naval pupils, too, were drawn up in line. We stopped a while to see them exercise; and then, mounting a carriage, drove off to the Observatory. The tower of the Observatory is built on a high hill, and is reached by stone steps. Large telescopes are mounted in a species of turrets, which are made to revolve by machinery, so that the telescopes point in desired direction. It has a celebrated Chief Astronomer, who has so often ascended into the air in a balloon. Its view over the city of London and the environs of the river Thames is magnificent. (Shah of Persia, 1879: 174).

Naser al-Din Shah was referring here to the Royal Observatory, Greenwich, and to Sir George Biddel Airy (1801–1892), the Director and Astronomer Royal, who held these titles from 1835 to 1881. Later on, the travelogue relates how the Shah used a telescope several times in both Greece and Russia, not to observe celestial bodies, but as an aid in viewing distant ruins and landscapes.

Naser al-Din's son, Muzaffar al-Din Mirza, when he was still a Prince and living in Tabriz, owned a telescope as well (Fig. 13). In the photograph we can see the Shah looking through the telescope surrounded by Court males.

4 Concluding Remarks

In spite of all his attempts at persuasion, Mahmud Khan Qomi never managed to build a Royal Observatory, and his life was largely spent on tasks far removed from astronomy.

The case of Iran contrasts fully with that of Siam, and illustrates how often the will of just one person, the King, would decide the fate of the introduction of Modern Science and Astronomy in a particular country. King Rama IV, known in the West as King Mongkut (1804–1868), was the 'Father of Thai Science' (Saibejra, 2006) and very interested on observational astronomy. Among other achievements, he accurately predicted the total solar eclipse of 18 August 1868 (Aubin 2010) and used this event to promote Modern Astronomy in Siam and expose the shortcomings of traditional astrological beliefs (see Orchiston and Orchiston, 2018; Orchiston et al., 2018).

Ottoman Turkey's reception of Modern Astronomy also was easier and faster than in Persia, once again thanks to the Ottoman Sultan. In 1868, Sultan Abdulaziz founded the Imperial Observatory, which occupied several locations before reaching its final setting in Kandili in 1911 (Benoist, 2009).

Ironically, then, it seems that the telescope, originally conceived as a *spyglass* and diplomatic toy, failed to develop as a scientific instrument on Iranian soil. The most highly trained of all the Iranian astronomers, Mahmud Khan Qomi, became a diplomat rather than a professional scientist, and spent his life in the service of a monarch who was more interested in the perpetuation of his Royal image on Earth than in celestial issues. The Shah's dismissive attitude, especially to the building of a modern observatory in Tehran, jeopardized the introduction of Modern Astronomy in Iran throughout his long reign (from 1848 to 1896). Fortunately, the attitude of his son, Mozaffer al-Din Shah, seems to have been more open to Modern Astronomy. Possible astronomical activities at the Court in Tabriz need to be researched in-depth, and this is an on-going project by this author at the moment.

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Part VII
Asian Ethnoastronomy and Archaeoastronomy

Astronomy of Some Indian Tribes

Ganesh Halkare, Mayank Vahia, and Wayne Orchiston

Abstract Some Indian tribes are known to have lived isolated lives over many millennia and developed their own perspectives on astronomy. Here we report the study of four Indian tribes from central India, namely the Gonds, Banjaras, Kolams and Korku. We show that the broad philosophy of their approach to astronomy was similar but the details of their perception vary significantly.

1 Introduction

India has a large collection of tribes of different origin but they can be divided into four major groups labelled as Indo Europeans, Tibeto-Burmans, Austro Asians and Dravidians (Tamang and Thangaraj, 2012). Many of these groups live in isolation from the general population and have been isolated from the dissemination of common astronomical ideas found among the overall Indian population. They have therefore developed their own astronomical ideas.

We have studied the astronomical beliefs of four tribes in Central India.[1] The details of these individual studies are presented elsewhere, and they are summarized in Vahia and Halkare (2017). Here we present a comparative study of the astronomy of these four groups.

[1] Since this review paper was written, in 2017, we have studied a further four Indian tribes. We hope to publish papers on these in 2018 and 2019 issues of the *Journal of Astronomical History and Heritage*.

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2 The Tribes Studied

The tribes we have studied were the Gonds (Vahia and Halkare, 2013), the Banjara and Kolam (Vahia et al., 2014), Korku (Vahia et al., 2016) and Cholannaikkans (Vahia et al., 2017). A brief description of these is given below.

In general all these tribes know of the Sun, the Moon and some stars and star patterns (Vahia and Halkare, 2017). The complexity of their astronomical beliefs correlate well with their periods of settlement, suggesting that beyond the basics of the Sun, the Moon and observations of certain stars, astronomy was more a leisure activity. Many Indian tribes do not have an idea of constellations, and do not divide the stars into small groups. However, all know about comets (brooms, or stars with tails) and meteors (stellar excreta), and most recognise the Big Dipper part of the seven stars trailing the trapezium in Ursa Major. Many tribes also see the Milky Way as some sort of a path, for animals, ancestors, etc. While the latter is a common feature, knowledge of meteors suggests lingering long-term memor ies of some spectacular events. Because of the 'delicate nature' of meteors, some tribes are embarrassed to talk about these celestial visitors.

2.1 Gonds

Gonds are one of the oldest but largest of Indian tribes, and claim their roots back to prehistoric times. At their peak they had a large kingdom in Central India. Today they form the largest tribal group on India (see Fig. 1) and are the main keepers of India's wild forests.

They refer to the Morning and Evening stars as Pahat Sukum, and Jevan Tara. They mix up Venus with a generic star that is seen in the evening as the sunlight fades but are more specific about Venus as the morning star. They use lunar haloes to predict the nature of the forthcoming monsoon. The Big Dipper is a precious cot with an old lady in it, pursued by thieves, and this looms large in their belief systems. They believe that the cot is circumpolar and therefore never sets, but since the Big Dipper sometimes sets at the present day, this suggests that this particular belief system is quite old. They also know of Orion, Taurus, Canis Major and the Pleiades, which collectively form a complete and rather detailed farming scene. They also know the region near Leo as Murda, with a dead body and a complete funerary procession.

2.2 Banjaras

They are one of the largest tribes of India (Fig. 2). They were traditionally traders and movers of goods over large stretches of land, and claim kinship to the gypsies of

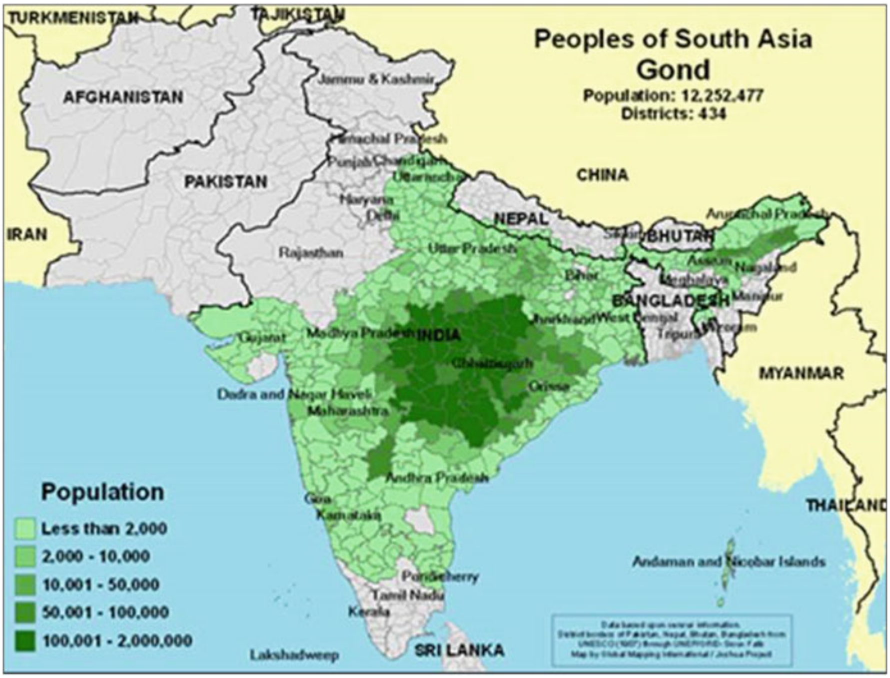

Fig. 1 Geographical distribution of the Gondas (http://www.joshuaproject.net/)

Europe. Some claim their roots to AD 1200 in Rajasthan when internal wars between Rajputs forced them to become wandering traders, while others trace their origins as traders and movers of goods back to the Harappan period (earlier than 2000 BC). They were forced to settle down about a hundred years ago when the spread of the railway throughout India largely made them redundant.

This community, though very proficient in worldly affairs, is not very active in understanding the sky. Even though they were involved in long distance travel, they seem to have done this through ground markers rather than using the stars for navigation or guidance. They know of appan period (earlier than 2000 BC). They were forced to settle down about a hundred years ago when the spread of the railway throughout India largely made them redundant.

This community, though very proficient in worldly affairs, is not very active in understanding the sky. Even though they were involved in long distance travel, they seem to have done this through ground markers rather than using the stars for navigation or guidance. They know of the Morning star and the Evening star as Porya Tara and Subtara (a good star), respectively, while Orion was Harini, a Deer. On the Moon they see an old lady busy weaving cloth under a tree. They refer to the Pleiades as Jhumko tara, a piece of jewellery worn on the forehead. They know Big Dipper as Jamakhat, Yamakhat, a bed of the dead, and they refer to the Milky Way as Mardaar wat, the path of the dead. As with all Indian tribes now involved in

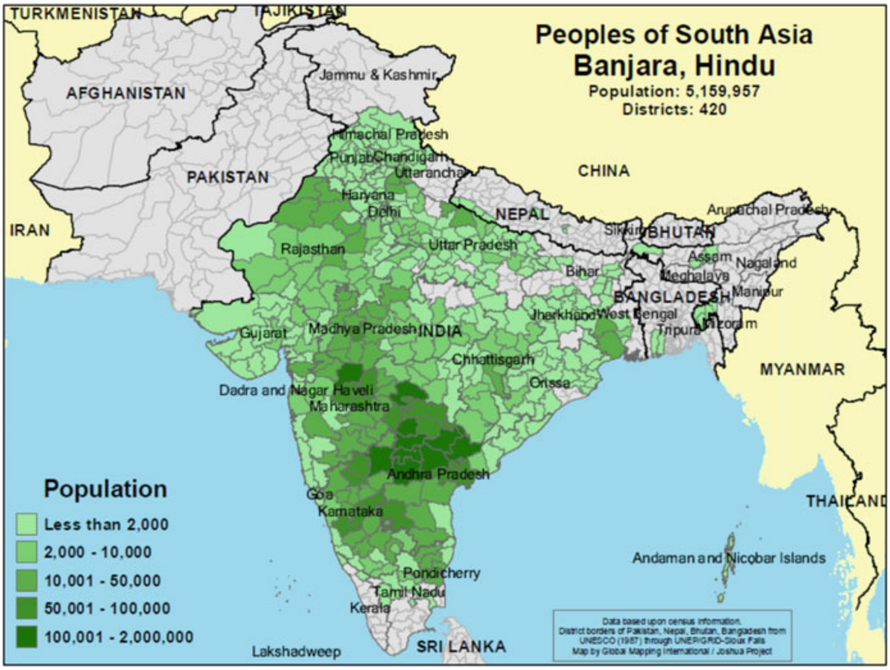

Fig. 2 Geographical distribution of the Banjaras (http://www.joshuaproject.net/)

cultivation, the monsoon is critical for survival, and the Banjaras predict the upcoming monsoon by the intensity and distribution of the glow around the Moon.

2.3 Kolams

Kolams are a small tribe (Fig. 3). Until 50 years ago they were foragers and depended on forest resources for their livelihood, but in the last half century the Government has been trying to settle them. Many elders remember their foraging and wandering lifestyle and regret having to live an unsettling settled life.

They know of the Pleiades as Kovela Kor, one large and several small birds, and they refer to the Big Dipper a cot. The three trailing stars of the main trapezium-following stars are three people, a Kolam, a Gond and Pardhan (chief). They know the belt of Orion as Tivpate (three stars). They refer to the Morning and Evening.

Star (presumably Venus) as Vegud suka and Jevan suka respectively. Interestingly, they remember solar eclipses and state that if the eclipse is total it is good, but if the top half of the Sun is covered this is bad for humans while if only the bottom half of the Sun is covered it is bad for animals. They believe that Pegasus is the sea (Samdur) that provides water for the monsoon and they see five animals around

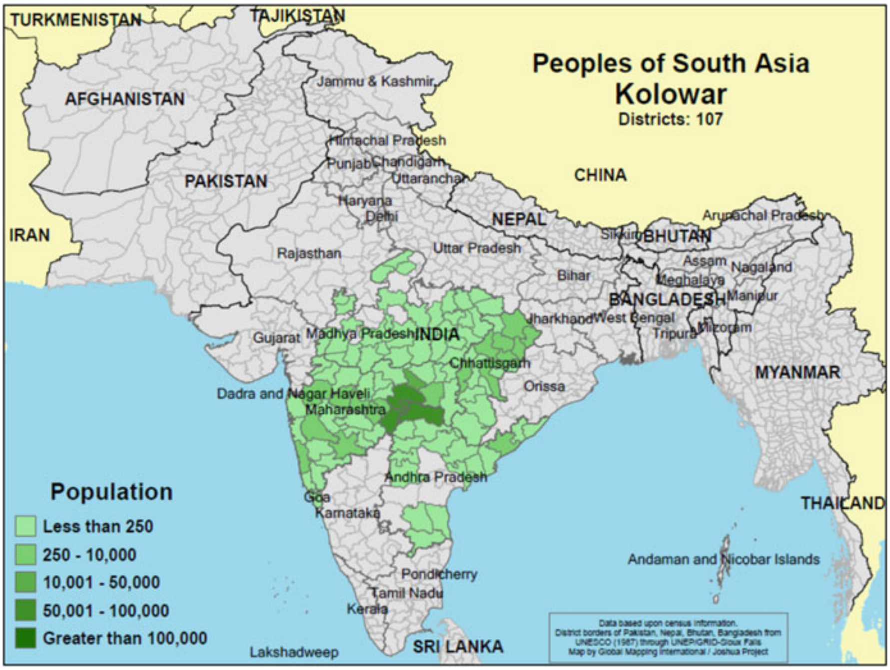

Fig. 3 Geographical distribution of the Kolams (= Kolowars) (http://www.joshuaproject.net/)

Pegasus that predict the intensity of the upcoming rains. They know of Crux as the Mahua tree, while the Milky Way is Margam, a path of the animals.

2.4 Korku

The Korku are an ancient tribe of India that are believed to be of Austro-Asian origin. They trace their origin to the eastern Indian region of Chota Nagpur, but large numbers of these people are.

settled in the forest reserves of central India (Fig. 4). Although living in the same Satpuda Mountain ranges, these groups differ in their astronomical beliefs from other tribes in the region.

They look upon the Milky Way as a path. They have an interesting story about multiple small paths that seem to merge in the Milky Way. They talk of the main path being that of an elder brother and the younger man's wife coming along the path deviates from it out of respect for the elder brothers. They refer to the Big Dipper as a golden cot, while Orion is a plough with bullocks. They are aware that Orion is seen between April and October, during the pre-monsoon and monsoon seasons. They imagine the Pleiades to be the minced-up meat of a cow. They give importance to the glow around the Moon as a monsoon predictor. They also have an interesting

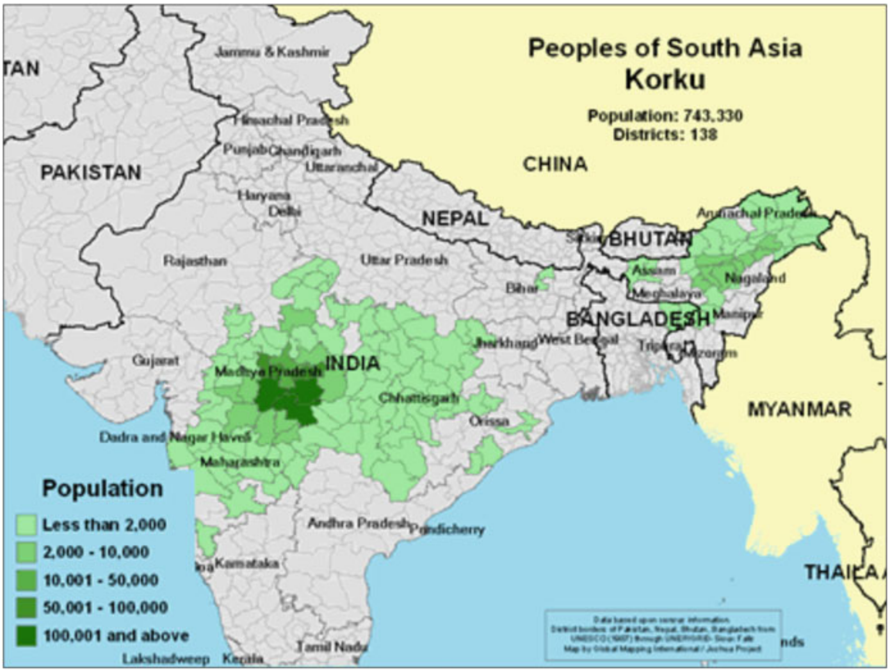

Fig. 4 Geographical distribution of the Korku people (joshuaproject.net/people_groups/17269/IN)

practice relating to solar eclipses: they take a long wooden shaft and put it in a bucket of water during a solar eclipse, and insist that the stick will remain vertical as long as the eclipse occurs and will only fall over when the eclipse ends. They know of Venus as the Morning and Evening Star. They consider the conjunction of Mars and Venus as a suitable time for marriage, and they refer to a comet as a star with a tail.

2.5 *Cholannaikkans*

We also studied the Cholannaikkans (Vahia et al., 2017), an exceptionally small Dravidian group with the entire community consisting of less than 150 individuals. They have largely survived through hunting wild animals and foraging, and are not involved in farming. Their astronomical beliefs do not go beyond the simplest myths relating to the Sun and the Moon.

3 Concluding Remarks

In Table 1 we compare the primary astronomical beliefs of the various tribes mentioned here, while in Fig. 5 we show how the Pleiades are visualised by these communities (and in mainstream Indian and European beliefs). While all of the tribes we studied reside in the same general area of central India, in the general vicinity of the city of Nagpur, long traditions of isolated living and difficult terrain

Table 1 A comparison between the astronomical beliefs of different communities

Object	Banjara	Kolam	Gonds	Korku
Ethnic group	Indo-European	Austro-Asian	Austro-Asian	Austro-Asian
Astronomical Beliefs				
Orion	Harini	Tivpate	Tipan	Plough with bullocks etc.
Big Dipper	Cot of death Jamakhat (Yamakhat)	Mandater (a cot)	An old lady's cot	As an old lady's cot
Morning Star	Porya Tara	Vegud suka	Morning Star	Morning and Evening Star
Evening Star	Subtara (a good omen)	Jevan suka.	Evening Star	
Ursa Minor		Three following stars are three people: a Kolam, a Gond and Pardhan (chief).		
Comet	Star with a tail	Sipursuca (stars with tails)	God's broom	Star with a tail
Pleiades	Jhumko tara (a piece of jewellery)	Kovela Kor (one large and several small birds)	Stones thrown to birds	A lump of minced cow meat, or a tool to remove the husk from the wheat
Milky Way	Path of the dead	Margam (path of the animals)	Path of animals	A path
Meteor	Tara tutgo (broken star)		Stellar excreta	Stellar excreta
Taurus region	When seen in the east brings rain	Bhori (a bird, Aldebaran, with two eggs)	A farming scene	
Crux		A Mahua tree	A Mahua tree	
Scorpion		Snake		Scorpion
Cygnus		Kavadi Kunde (three pots on top of each other)		
Pegasus/ Centaurus		Predicts the monsoon		
Solar Eclipses		Predicts calamities		Use a stick to record its duration

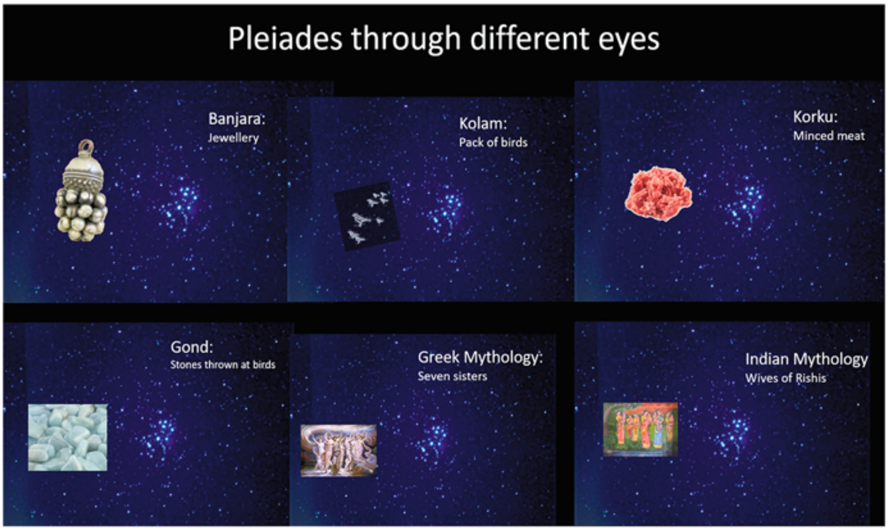

Fig. 5 Constellation of Pleiades as seen by different cultures

imply that they lived isolated from each other. As a result, their astronomical systems differ in various ways, and are only weakly influenced by other cultures.

The astronomical beliefs of these Indian communities can be classified into the following categories:

1. Daily time keeping using the Morning and Evening Stars;
2. Keeping track of seasons and predicting the monsoon, using, for example lunar haloes and Pegasus;
3. Myths and cosmogony using, for example, the Leo region;
4. Memories of ancient observations of comets, eclipses and meteors; and
5. As omen, such as conjunctions of Mars and Venus. etc.

It would appear that the complexity of the different Indian tribal astronomical beliefs are related to their own world views, and the length of their respective periods of settlement and occupations. As might be expected, a tribe's relation to the sky is often reflected in its relation to the land.

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From Megaliths to Temples: Astronomy in the Lithic Record of South India

Srikumar M. Menon

Abstract India has a long history of monuments built in stone—from prehistoric megaliths to later religious monuments like stupas, temples etc. covering a period of nearly four millennia. In this paper we discuss the influence of astronomy on the design and layout of some of these monuments, as well as depiction and incorporation of astronomical objects and phenomena in several of these or their components. In several instances, prehistoric rock art features Sun and Moon motifs, which are also seen in later sculptural art in temples, hero stones, etc.

Megaliths, which are mostly the sepulchral and commemorative monuments of the Iron Age, have a variety of forms, ranging from the simple upright stone to relatively complex constructions like dolmens etc. We demonstrate that at least some megaliths have sightlines to astronomical phenomena on the local horizon deliberately incorporated into their layout. It is quite possible that these early monuments evolved into later monumental structures like stupas and temples.

Temple architecture in southern India followed two main evolutionary trajectories that spanned roughly 800 years. Temples often feature sculptural panels of deities, myths and legends on their outer walls. We examine some of the legends, such as the Tripurantaka legend of Shiva, commonly depicted on temple walls, for astronomical symbolism. Heavenly bodies, such as the Sun, Moon and planets, are deified in traditions of the Indic religions, and we examine some of these deities depicted in temple sculptures. We also discuss the *Dikpalas*—guardians of the directions—often depicted to safeguard temple precincts. The phenomena of Sun Temples, depictions of eclipses, zodiacal stones and *navagraha* worship are also dealt with.

Finally, we examine Sun-facing structures, such as rock-cut temples and structural temples, which are designed to interact with the rising or setting Sun on given days of the year.

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1 Introduction

India has a tradition of building monumental structures that spans nearly four millennia. Although the earliest surviving monuments are probably the ashmounds of the Neolithic in the Deccan, the most widespread early monuments are certainly the megaliths, which are concentrated in, but not restricted to, the southern part of the subcontinent (Brubaker, 2001; Moorti, 1994). The ashmounds of the Deccan Plateau date back to the South Indian Neolithic, approximately 3000–1200 BC (Bauer et al., 2007), and are products of episodic burning of large accumulations of cattle dung over vast periods of time (Boivin, 2004). Opinion is divided among researchers as to whether these are the products of utilitarian activities—such as disposal for the purposes of hygiene, or venues of ritual activity. Boivin (ibid.) and Johansen (2004) favour the latter, making a case for these being "... monumental forms of architecture and the loci of ritual and ceremonial activity." (Johansen, 2004: 309). At least in the case of one ashmound, at Kudatini, Boivin (2004) makes a case for astronomical intent behind the location of the ashmound at that site.

The South Indian Neolithic was followed by the Iron Age, approximately 1200–500 BC, to which period most of the megalithic monuments are ascribed (Menon, 2012a; Moorti, 1994), although megalith production might have its origins in the Neolithic itself. Indian megaliths display a wide variety in form, and studies of their design and layout suggest that some of them at least might incorporate deliberate astronomical alignments.

Rock art in India encompasses a large span of time—from the Palaeolithic to Early Historic times. Sun and Moon symbols are commonly encountered in rock art throughout the subcontinent, and might have influenced later sculptural traditions too.

Stone temples in India start appearing in the archaeological record in the early centuries of the Common Era. At least some streams of temple architecture seem to have been influenced by the megalithic tradition, and there is evidence to suggest that some of the early temples too might have been commemorative in nature, like the megaliths (Menon, 2014). At any rate, the evolution of temple architecture under the patronage of various ruling dynasties spans at least 800 years, and these temples provided a medium for sculptors to portray various myths and symbols, some of which have astronomical themes. Temples also had components such as zodiacal stones and deified icons of heavenly bodies such as the Sun, Moon and the *Navagrahas*. Certain temples also incorporated interactions with astronomical phenomena, such as the penetration of direct sunlight on given days along the axis of the construction to fall upon the deity in the sanctum.

In this paper we discuss the influence of astronomy on the design and layout of some of these monuments, both prehistoric and later structures, and also dwell on the depiction and incorporation of astronomical objects and phenomena in monuments or their components.

2 The Earliest Monuments

As has already been mentioned, the ashmounds of the Deccan Plateau are probably the earliest monumental constructions of the Indian subcontinent that still survive. These structures are mounds built up over large periods of time as cattle dung accumulations were burnt at high temperatures at intervals. Initially, they were thought to be attempts by the Neolithic societies which authored them to keep the surroundings of cattle pens sanitized. The domestication of cattle, goats and sheep, as well as agriculture, were developments of the Neolithic and it is surmised that these early agricultural and pastoral societies did not use dung as fertilizer in agriculture. However, later research shows a more complex picture, and the periodic burning of the dung thought to have ritual and ceremonial importance. Little work has been undertaken about the locational significance of these monuments, although Boivin (2004) makes a case for the deliberate choice of location of an ashmound at Kudatini to facilitate a sightline to the setting Sun behind a local hill for a short period of 3–5 days in April as well as September.

No uncertainty exists about the role of megaliths as monuments, though. Megaliths are the burial and other monuments that were widespread during the Iron Age in southern India. Though the distribution of megaliths is not restricted to southern India, with significant pockets of occurrence in the Vidarbha region of Maharashtra, Jharkhand etc., this monumental practice is encountered widely all over southern India (Brubaker, 2001). This is illustrated in Fig. 1. Indian megaliths exhibit a wide variety in their morphology, ranging from single erect stones called menhirs (Fig. 2), to extensive arrangements of menhirs termed stone alignments (Fig. 3), as well as boulder circles (Fig. 4), dolmens (Fig. 5), cists (Fig. 6), etc. For a full understanding of these various forms, the reader is directed to Menon (2012a, 2012b) and Moorti (1994).

The Early Historic period, following the Iron Age, saw the proliferation of places of worship affiliated to the various Indic religions. These varied from rock-cut sanctuaries to stupas, temples etc. The earliest temples might have been built of perishable materials like timber and thatch, followed by brick structures. It was in the early centuries of the Common Era that the stone temple made an appearance. Various styles of temple architecture evolved in different regions, though a straightforward picture of this is simplistic, with guilds of artisans of various schools migrating and intermingling, so that it is not uncommon to see temples of the architectural style of a particular region in other regions as well (Hardy, 2012). In most regions, temple architecture evolved over periods of several centuries, with the southern region of Karnataka alone having a continuous sequence of evolution spanning some 800 years.

The religious monument as an expression of the beliefs and legends associated with the societies that used them, offers important clues to understanding the various facets of these belief-systems and legends. We will examine some of these associated with astronomy and celestial bodies in later sections.

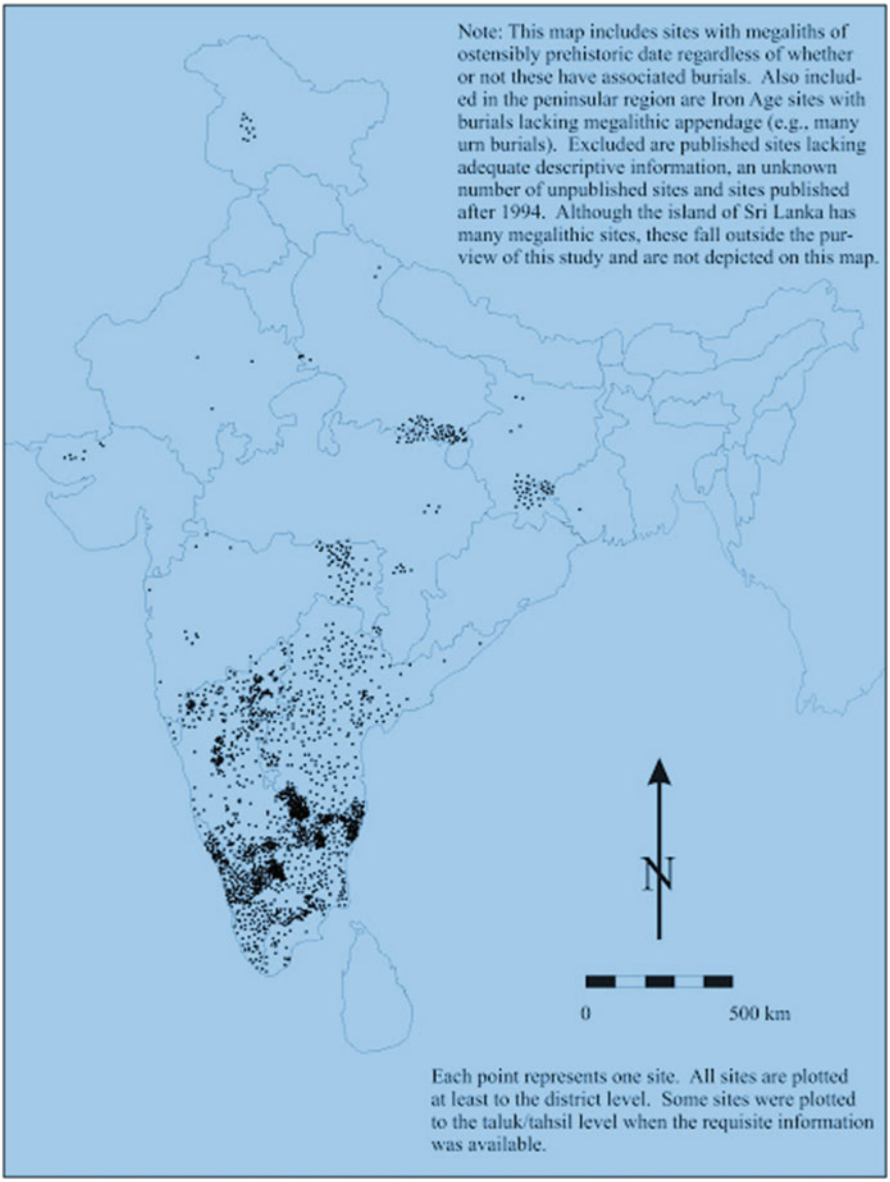

Fig. 1 Showing the distribution of megalithic sites in India. (Courtesy: Professor Robert Brubaker)

Fig. 2 A large quarried slab erected upright at Nilaskal–an example of a menhir. (Photograph: Srikumar Menon)

Fig. 3 More than 2500 boulders are arranged in a diagonal grid at this stone alignment at Hanamsagar. (Photograph: Srikumar Menon)

3 Rock Art and Astronomy

Rock art is ubiquitous in India in space and time.

Depictions in paint on rock surfaces, usually rock shelters, and bruisings and engravings on boulders and rock shelters, abound in all parts of the country. Rock art traditions straddle a wide swathe of time—from the Palaeolithic through the

Fig. 4 A boulder circle at Junapani in the Vidarbha region of Maharashtra. (Photograph: Srikumar Menon)

Fig. 5 Dolmens at Hire Benakal in northern Karnataka. (Photograph: Srikumar Menon)

Fig. 6 A cist burial at Chikel Chetti, near Bandipur in Karnataka. (Photograph: Srikumar Menon)

Neolithic, Iron Age and Early Historic period to even medieval times. Themes depicted in Indian rock art are quite eclectic, and range from contemporary activities like hunting, celebrations and dancing, or conflicts like cattle raids, warfare, to more complex themes possibly depicting the world views of the artists. It is not uncommon to see depictions of heavenly objects like the Sun and Moon in rock art,

Fig. 7 A rock art panel at Onake Kindi, near Hire Benakal. (Photograph: Srikumar Menon)

although it is hypothesized that more complex celestial themes like the appearance of a supernova may have been depicted (e.g., see Joglekar et al., 2011).

One of the most enigmatic rock art panels has been reported from a site called Onake Kindi, south of the well-known megalithic site at Hire Benakal in north Karnataka. On a horizontal rock overhang above a vertical rock art panel showing everyday people and cattle etc. is a depiction of what is unmistakably a megalithic burial (Fig. 7). In the centre is shown an interred human body surrounded by grave goods, separated by a ladder-like motif from a depiction of what looks like water. The stones of the boulder circle surround this central depiction and the whole composition is encircled by a ring of petals and rays, which has been interpreted as Sun and Moon symbols by rock art experts (Menon, 2012b). This could be an early precursor of the medieval tradition of incorporating Sun and Moon symbols in hero stones (Fig. 8), signifying that the memory of the persons being commemorated will last as long as these heavenly bodies do.

4 Megaliths and Astronomy

Several megalithic sites have been associated with astronomical sightlines and it has become rather commonplace to attribute astronomical alignments to megaliths, often without any convincing evidence to do so. As the science of archaeoastronomy has matured, the notion of megalithic structures as ‘astronomical observatories’ as advanced by Hawkins (1965), Thom (1967) and others has given way to the more reasonable hypothesis that astronomical alignments were sometimes built into megalithic structures and their layout for symbolic purposes relating to the religions and cosmologies of the megalith-builders (Ruggles, 1999).

Several Indian sites have been linked with astronomical associations, too. Rao (1993) ascribed astronomical intent behind the layout of the stone circles at Brahmagiri, and he also hypothesized (Rao, 2005) that the stone alignment at Hanamsagar (Fig. 3) functioned as a calendrical device. Kameswara Rao and Thakur (2010) advanced similar claims about the stone alignment at Vibhutihalli, also in

Fig. 8 Hero stones near Manipal in Karnataka, showing sun and moon depictions. (Photograph: Srikumar Menon)

north Karnataka. However, my analyses of these sites do not support these claims, with the exception of Vibhutihalli (Menon, 2012a). The stone alignment at Hanamsagar is the most extensive one reported to date in India, and reports of its size range from 1000 menhirs (Allchin, 1956) to 2500 menhirs (Paddayya, 1995). Until the extent and layout of the menhirs are determined through an accurate survey, it is difficult to conjecture about the astronomical purpose of this monument.

However, some megalithic sites do show intentional sightlines to astronomical events on the local horizon. The stone alignments at Nilaskal (Fig. 9) and Byse (Fig. 10) show that pairs of menhirs separated by several meters frame the rising and setting sun at the solstices (Fig. 11). A given menhir pairs up with different menhirs during the spring and autumnal equinoxes to frame the Sun on the horizon (Menon et al., 2012, 2014), as shown in Fig. 12.

5 Megaliths and Later Monumental Traditions

The Indian subcontinent has a rich architectural tradition, with monumental architecture in the form of evolved stupas and stone temples emerging approximately 2000 years ago. Stupas, of course, date back beyond the period of the monarch Ashoka, but the fully evolved stupa with stone cladding and railings emerged slightly later.

Fig. 9 A view of the megalithic site at Nilaskal, showing a few menhirs of the stone alignment. (Photograph: Srikumar Menon)

Fig. 10 A view of the megalithic site at Byse, showing a few menhirs of the stone alignment. (Photograph: Srikumar Menon)

Temples, too, existed even before 2000 years ago, but the early temples were built of perishable materials and we can only infer their form from depictions on stupa slabs etc. (see Fig. 13). The stone temple, which makes a debut in the early centuries of the Common Era in different parts of the subcontinent, evolved via much cross-pollination of ideas through migrations of artisans and the patronage of various dynasties over nearly 800 years.

It is difficult to imagine such traditions in monumental architecture developing over a short span of time. Conventional narratives of monumental architecture do not examine the prehistoric monument-building traditions for potential seeds of later architectural traditions. Nearly a decade of studying megaliths and other prehistoric monuments as well as later monuments provided me with some insight into possible earlier versions of later structures. One of the sites where these connections are evident is the valley of the River Malaprabha, where the well-known temple architecture sites of Aihole, Badami and Pattadakal are located. This region was

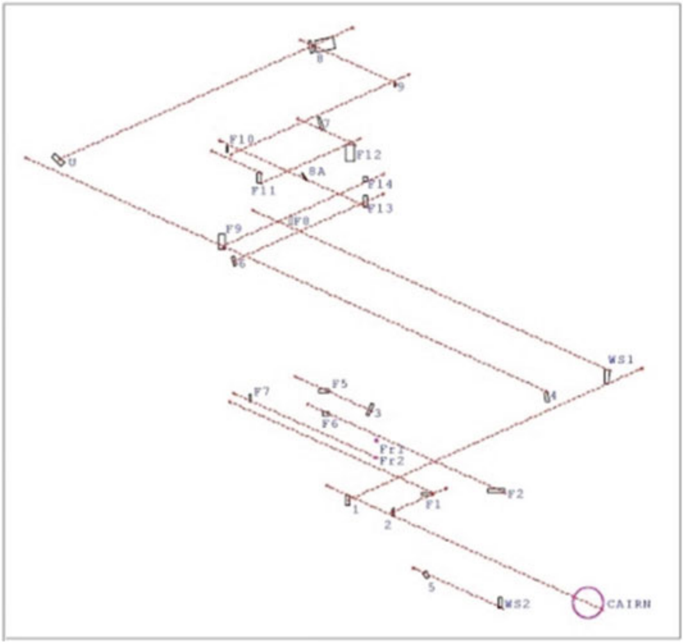

Fig. 11 Plan of the menhirs at Byse showing correlation between pairs of menhirs with the solstice sunrises and sunsets; north is towards the top of the figure. (Plot: Srikumar Menon)

Fig. 12 Two menhirs of the stone alignment at Nilaskal framing the setting sun at winter solstice. (Photograph: Srikumar Menon)

ruled by the Early Chalukya Dynasty for nearly 200 years during the sixth to eighth centuries CE.

However, the region has a history of human occupation that goes much further back in time, with traces from the Palaeolithic, Mesolithic and Neolithic, as well as the succeeding Iron Age and Early Historic periods. This region also has a rich megalithic tradition, generally ascribed to the Iron Age. At several locations, there are temples erected within or very close to megalithic sites. This, as well as evidence for a megalithic structure being modified by temple builders (see Fig. 14), and the existence of memorial temples built over the remains of important persons, points to

Fig. 13 One of the lower drum slabs of the third century Buddhist stupa at Kanaganahalli showing a tree shrine, probably built of perishable materials like timber and thatch. (Photograph: Srikumar Menon)

Fig. 14 One of the temples of the Galaganatha group at Aihole, with a crude megalithic dolmen in the foreground. Analysis of the wedge marks found on the "legs" that prop up the dolmen show that this prehistoric structure was modified by the medieval temple builders. (Photograph: Srikumar Menon)

possible continuity of commemorative traditions from megaliths into later monuments (Menon, 2014).

The similarity in form between cairns and barrows to stupas has been alluded to since early days of research on megaliths in India. It often has been pointed out that

Fig. 15 A panoramic view showing a drum of tightly fitted stone slabs and part of a mound that rose up to the dolmen at the centre of the arrangement, in what is probably an early version of the stupa. (Photograph: Srikumar Menon)

the Buddha himself refers to the practice of building stupas for important personages, thus pushing back the antiquity of the memorial mound to pre-Buddhist times. In fact, the form of the fully evolved stupa can be demonstrated to arise from the structural necessities of containment, as the builders strove to make larger and more conspicuous mounds (Menon, 2016). A unique dolmen at the megalithic site of Mallasandram, near Krishnagiri in Tamil Nadu, which is halfway between a megalith and a stupa (see Fig. 15), lends credence to this hypothesis.

This possible continuity in monument-building traditions from prehistoric times to later periods, potentially hold clues to understanding phenomena such as the entry of shafts of sunlight into the sanctum of some temples, which will be discussed later.

6 Temple Architecture in South India

Some of the oldest temples in southern India are the rock-cut as well as structural temples of the Early Chalukyas in the Malaprabha Valley in present-day Karnataka, and contemporaneous structures of the Pallavas in Tamil Nadu (Srinivasan, 1972). These were executed between the sixth and eighth centuries CE and can be considered the advent of stone architecture in the south. However, remains of brick temples have been found elsewhere and even under the foundations of some of these temples, pointing to the existence of temples in brick and probably timber and thatch prior to the advent of stone temples. In fact, Srinivasan (1972: 33–34) speaks of "... a lingering tradition of a taboo on stone for sacred and secular structures, because of its long association with funerary erections ...", i.e., the megaliths!

Temples in these two geographic regions—the Chalukya- and Pallava-ruled areas—followed different trajectories of evolution over the next eight centuries or so, resulting in a variety of forms, some of which are outlined in medieval texts on the science of temple construction. Hardy (2012) has an excellent introduction to the

Fig. 16 A temple built in the northern 'Nagara' idiom, to the left of frame, in close proximity to another in the southern 'Dravida' idiom to the right. (Photograph: Srikumar Menon)

classification and development of temple forms in India. The development of temple architecture in the Indian region is a complex subject and over the centuries migrations of artisans from different parts of the subcontinent must have shaped this evolution in the various centers of patronage. For instance, the temple form in the northern idiom called the Nagara and the southern idiom of building known as the Dravida are found alongside each other at the Early Chalukyan site of Pattadakal (Fig. 16), and inscriptional evidence from the sites in the Malaprabha Valley seems to suggest that artisans from different parts of the subcontinent worked here and even collaborated on some temple projects.

Both temples and stupas provided a setting for relief carvings depicting deities, narratives from myths and epics and symbols of religious significance, which is elaborated below.

7 Myths on Temple Walls—The Story of Tripurantaka

From the earliest temples, the incorporation of sculptural panels that depicted various religious themes was part of the design—be it on niches in the external and internal walls, on columns, on lintel beams and on ceilings. The richness of this embellishment also went through various degrees of intricacy, depending on the medium and design considerations. For instance, the outer wall surfaces of the Hoysala Temples of Karnataka took the business of embellishment to a whole new

Fig. 17 Part of the exterior wall of the Lakshminarayana Temple at Hosaholalu in Karnataka, built in the Hoysala style, showing how the wall surface is richly embellished with figures of deities, geometrical patterns etc. (Photograph: Srikumar Menon)

level, with dense detail covering entire surfaces (Fig. 17), from plinths and walls to columns, ceilings and towers.

These depictions represented deities, incidents from myths and legends connected with deities, as well as representations of human beings and animals such as elephants, horses etc. One such myth encountered in many temples is that of Siva as Tripurantaka, the destroyer of the triple city of the demons. On most depictions, Siva is shown standing on a chariot, aiming an arrow at three cities which are lined up (Fig. 18). The legend goes that the demons built three great cities—one each of gold, silver and iron, in the sky (Kramrisch, 1981). The great architect Maya completed these cities when the Moon was in conjunction with the asterism called Pusya. It was only when these cities came together in the sky again, when the Moon once more was in conjunction with Pusya that they could be destroyed, by a single arrow. Siva was called upon by the devas to destroy Tripura—the three cities of the asuras, which he did, and the cities fell burning into the western ocean.

Stella Kramrisch (1981: 416) does a detailed analysis of the myth, which has its roots in the Rig Veda, and its transformations over time and comes to the conclusion that originally the myth "... had a cosmo-symbolical dimension." She surmises that the three cities coming together in the sky must have been a triple conjunction of three planets during a Pusya yoga (when the Moon is in conjunction with the asterism Pusya) and that they must have been in one line with the position of Sirius,

Fig. 18 The myth of Shiva as Tripurantaka destroying the three cities of the demons, shown on the exterior wall surface of the Vidyashankara Temple at Sringeri. (Photograph: Srikumar Menon)

which is identified with Rudra-Siva, the archer who brought about the demise of the triple cities. The destroyed cities falling blazing into the western ocean is evocative of the planets in triple conjunction, which must have been brilliant, setting over the ocean.

Kramrisch (ibid.) expands on this:

> Between this primeval initiating deed (of Rudra shooting an arrow at Prajapati, who was desirous of his own daughter Rohini) and the destruction of Tripura extends the ageless myth of Rudra. Though the destruction of Tripura was enacted in mythical time, cosmic phenomena were adduced as witnesses. The change in scenario of the Tripura myth was linked, it appears, with a particular, observed astronomical phenomenon."

Using the Indian ephemeris, M. Raja Rao has advanced 2270 BCE or 503 BCE as possible dates for the phenomenon that inspired this myth.

8 Deifying Heavenly Bodies

Traditionally, heavenly bodies are worshipped as deities in most of the Indic religions. Temples to the Sun god are very common, and shrines to the nine 'planets' are commonly encountered as subsidiary shrines in many temple complexes. There are guardians to the eight directions, too, usually incorporated as imagery on temple walls or ceilings in the appropriate directions. Zodiacal stones depicting the Sun surrounded by the signs of the zodiac are an integral part of some temple traditions.

Apart from this, motifs symbolizing eclipses are seen adorning lintels, ceilings and outer walls in some temple complexes. These will be elaborated upon below.

8.1 The Gods of the Directions

Guardian deities of the world have been known from Vedic times, with early lists having gods for the four cardinal directions, followed by gods for eight directions and later expanded to ten, with the zenith and nadir also included. Wessels-Mevissen (2001) gives a list of these *dikpalas* or guardians of the directions as: Indra for the east, Agni for south-east, Yama for south, Nirrti for south-west, Varuna for west, Vayu for north-west, Kubera or Soma (the Moon) for north and Isana for the north-east, with Brahma for the zenith and Ananta, the serpent vehicle of Vishnu, for the nadir. These gods were believed to afford protection against evil forces according to the religious systems and ritual practices in place during the development of temple architecture between the fifth and eighth centuries CE.

It is understood that a highly developed awareness of space and directions existed in the Indian subcontinent from Vedic times, and some of these concepts were crystallised in the form of representations of these guardians of the directions in sculptural panels when monumental architecture in stone emerged.

The earliest depiction of dikpalas are found in the Buddhist stupa at Bharut, assigned to the second century BCE, where two labelled images have been found. Wessels-Mevissen (2001) notes that the depiction of dikpalas on temple exteriors is restricted mostly to northern India, where the figures usually are part of the ceiling panels. At the south Indian sites of Badami, Aihole and Pattadakal, in the valley of the River Malaprabha in Karnataka, where the northern and southern idioms of temple-building flourished side by side, there are instances of dikpala figures on temple exteriors (Fig. 19) as well as on ceiling panels (Fig. 20).

8.2 Sun Temples

Sun worship is commonly encountered at different places in the world in history, including India (Oldham, 1905). In India, Sun worship has existed from a very early period, although the construction of Sun temples seems to have peaked in the ninth to tenth centuries CE. Apart from the well-known Sun temples at Konark, Modhera (Fig. 21) etc., there are many lesser known Sun temples all over the subcontinent. One such temple is the Malegitti Sivalaya at Badami (Fig. 22). This is very picturesquely located atop a large rock, and is attributed to the sixth or seventh century CE, under the patronage of the Early Chalukyas who ruled the region for a large part of the sixth to the eighth centuries CE. Although the temple currently enshrines a Siva linga, on the basis of iconographic details archaeologists and art historians identify it as dedicated to Surya, the Sun god. The *dwarapalas*, or door-

Fig. 19 Kubera, one of the *dikpalas*, on the exterior wall surface of the Papanatha Temple at Pattadakal. (Photograph: Srikumar Menon)

Fig. 20 *Dikpala* figures on the ceiling of Cave 3 at Badami. (Photograph: Srikumar Menon)

guardians, of the temple have been identified as Danda and Pingala—the attendants of Surya (Fig. 23). Also, a figure on the door jamb of the inner sanctum has been identified as Sanjana, the wife of Surya, who, unable to bear the brilliance of the

Fig. 21 The Sun Temple at Modhera in Gujarat. (Photograph: Srikumar Menon)

Fig. 22 The Malegitti Sivalaya at Badami, which was originally a Sun Temple. (Photograph: Srikumar Menon)

Fig. 23 The *dwarapalas*, or door guardians, on either side of the entry of the Malegitti Sivalaya, are Danda and Pingala –Surya's attendants. (Photograph: Srikumar Menon)

Fig. 24 Surya, the Sun God, depicted on the ceiling of the porch of the Virupaksha Temple at Pattadakal. (Photograph: Srikumar Menon)

Sun's radiation, fled in the disguise of a mare. The story continues that Sanjana's father, the celestial architect Viswakarma, chisels away an eighth of the Sun's brightness, enabling Sanjana to return to him.

Another Chalukya structure—the Virupaksha Temple at Pattadakal, from the eighth century CE —has a ceiling depiction of Surya (Fig. 24) which beautifully illustrates the deification of what is essentially a natural phenomenon. Surya is depicted, as is the convention, standing in his chariot drawn by seven horses, holding two lotus buds in his hands. The chariot is plunging through a cloudy sky and the clouds have been depicted nicely in shallow relief in this carving. On either side of the chariot are two female archers shooting arrows in either direction. They are Usha and Pratyusha—the heralds of dawn and dusk, when it is common to see shafts of sunshine shoot like arrows through gaps in the clouds. This panel, which is one of the finest depictions of the Sun god in the subcontinent, was carved by an artisan named Devaputran according to an inscription in the temple, and is located on the ceiling of the porch of the temple. This panel is also an excellent example of the deification of a celestial body, the iconographic features incorporating what are essentially natural phenomena into aspects of the deity.

8.3 Navagraha *Depictions*

The nine planets featured in the *Navagraha* depictions are Surya (Sun), Chandra (Moon), Mangala (Mars), Budha (Mercury), Guru (Jupiter), Shukra (Venus), Shani (Saturn), Rahu (ascending node of lunar orbit) and Ketu (descending node of lunar orbit). It is interesting to note that the last two—ascending and descending nodes of the lunar orbit—are not physical bodies at all, but are points where the orbit of the Moon intersects the orbital plane of the Earth. It is only when the Moon is at these points that the possibility of eclipses occur. Hence Rahu and Ketu are deified as the upper and lower parts of a demon who was dismembered, so that even when the Moon is devoured (during an eclipse), it comes out of the cut portion of the demon's body.

Each of the planets are given distinct iconographic features. Ketu is often depicted as a snake, a point we will return to in Sect. 8.5 on eclipse depictions. There are temples dedicated to the *Navagrahas* at several places in India, with the largest number being in Tamil Nadu. However, they are most commonly encountered as an integral part of other temples, as subsidiary divinities with the icons of the nine planets usually mounted on a pedestal, either within a shrine or in the open (e.g. see Fig. 25).

8.4 Zodiacal Stones

Zodiacal stones seem to have been part of temples erected in the Deccan Plateau in medieval times. It was common to have a lotus motif, interpreted as a Sun symbol, on the floor at the entry to temples since very early times, as in the Ravulaphadi rock-cut temple at Aihole, excavated in the sixth century CE by Early Chalukyan artisans (Fig. 26). Subsequently, the practice seems to have evolved into depicting the lotus figure as the convex top of an ornate pedestal at the entry to temples (Fig. 27). This

Fig. 25 A platform with the *Navagrahas* at the Chandralamba Temple, Sannati. (Photograph: Srikumar Menon)

Fig. 26 A Sun motif, shaped like a lotus, on the floor at the entry to the Ravulaphadi Cave at Aihole. (Photograph: Srikumar Menon)

pedestal went under the name of *Suryakirana* (literally, Sun's ray), or *Suryakhamba* (Sun pillar) according to Jagadish (2005). Examples from a couple of centuries later show the solar symbol surrounded by signs of the zodiac (Fig. 28).

By far the most elaborate of these is an example from the Amriteshwara Temple at Amritapura, near Shimoga in Karnataka, constructed in CE 1196 and belonging to the Hoysala period. This has an ornately carved solar disk as the convex floor of a dish-like structure, approximately 75 cm in diameter (Fig. 29). The outer edges of the dish, which must have been raised to roughly 15–20 cm high, are now badly broken, but enough survives to show the signs of the zodiac carved at regular intervals on the outside. One of the figures is a depiction of seven horses, symbolizing the Sun, hence it was the Sun surrounded by the signs of the zodiac that was the

Fig. 27 A zodiacal stone or *Suryakirana* at Aihole Museum. (Photo: Srikumar Menon)

Fig. 28 A zodiacal stone, or *Saura Pitha*, at the Chhatrapati Shivaji Museum in Mumbai, from Andhra Pradesh, and dating to about the thirteenth century CE. (Photograph: Srikumar Menon)

sculptural theme. A *pranala* (water spout) suggests that the disk received oblations like the regular *abhisheka* of deities in temples. Cousens (1926) also mentions a similar zodiacal stone found near the Sarveshwara Temple at Naregal in north Karnataka, where the lotus Sun-symbol in the centre is surrounded by the signs of the zodiac on a *pitha* or platform, with pranala. However, this stone, is now lost.

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8.5 *Eclipse Depictions*

In Karnataka, a motif of a disk or crescent being nibbled at by a snake or two snakes (Fig. 30) is commonly encountered in the architecture of the Vijayanagara Dynasty and its successors, from the fourteenth century CE onwards. These motifs are seen on various architectural members, such as ceilings of temples and preceding mantapas, beam soffits, temple walls and compound walls enclosing temples etc.

Fig. 29 An elaborate zodiacal stone at the Amriteshwara Temple, Tarikere. (Photograph: Srikumar Menon)

Fig. 30 A motif depicting two snakes (or a snake and an eel) nibbling at a disk, on the compound wall of the Malyavantha Raghunatha Temple at Hampi. (Photograph: Srikumar Menon)

It is clear that the motif refers to the phenomena of eclipses. It is to be recalled that Ketu is often represented as a snake, or a human with the lower portion of the body in the form of a snake.

Raja Deekshithar (2010a, b) has written two papers about occurrence of these motifs in Tamil Nadu. Although he concludes that these representations refer to specific eclipses that were being commemorated or at least recorded, it is felt, based on the observations at several places in Karnataka, that they were probably carved as good luck charms or auspicious symbols. At Hampi, for instance, they are found alongside other motifs, such as fishes, turtles, etc., carved on the compound walls of the Malyavantha Raghunatha Temple, suggesting that they were motifs intended to ward off evil influences rather than commemorating specific eclipse events.

These depictions, as mentioned earlier, show either a disk or a crescent being nibbled by the snakes, or sometimes, eels. It was initially felt that the disk

Fig. 31 A similar motif at the Shikhareshwara Temple at Kavaledurga, showing a deer inside what can be interpreted as the lunar disk. (Photograph: Srikumar Menon)

represented the Sun while the crescent symbolized the Moon. However, in several instances, there is a deer depicted inside the disk (Fig. 31). This suggests that the disk is also representing the Moon, since the black buck is widely regarded as the vehicle of the Moon.

9 Sun-Facing Structures

We have already seen, in Sect. 4, how some megaliths have been oriented to align with sunrise/ sunset on specific days. The act of aligning the structures to directions dictated by the cosmos is humankind's natural disposition to attune their creations to the cosmos they happen to inhabit.

9.1 Rock-Cut Temples and Sanctuaries

The rock-cut temples of Badami in northern Karnataka, are well-known. During the early phase of development of temple architecture in stone in the subcontinent, several magnificent rock-cut temples in the Hindu and Jain faiths were excavated at Badami and Aihole under the patronage of the Early Chalukyan rulers during the sixth to the eighth centuries CE. In addition, there are several minor excavations of the Chalukyans and their successors found in this region.

In general the location and orientation of rock-cut structures are dictated by the nature and situation of the parent rock mass from which the structure is excavated. However, smaller excavations permit more leeway in deciding the locations and orientations of the structures, due to their diminished sizes.

One of the minor excavations at Badami is a small cave, rectangular in elevation, with two ornamental pilasters at its rear corners, cut into the base of a large rock near the Bhutanatha Temple (Fig. 32). The cave faces cardinal east and is 1.9 m in length and the greatest depth of the excavation varies from 0.9 m on the southern side to 1.3 m on the northern. There is a sandstone ridge approximately 30 m high, situated

Fig. 32 The ‘Sunlight Cave’ at the base of a large rock at Badami. (Photograph: Srikumar Menon)

Fig. 33 The view from within the ‘Sunlight Cave’ showing the sandstone ridge to the east. (Photograph: Srikumar Menon)

nearly 150 m to the east of this rock-cut cave (Fig. 33). The cave contains no icon, but has a Sun symbol painted on the rear wall. The local legend is that the rays of the rising Sun strike it every morning. We have simulated the play of sunlight for different times of the year and have found that the cave is lit up by the Sun as it comes over the ridge throughout the year (Fig. 34). Thus it looks like the intention of the builders was indeed to catch the rays of the morning Sun in the structure. There are two temples, possibly memorials, located atop the rock that contains the cave, and the cave may have served some ritual processes associated with commemoration.

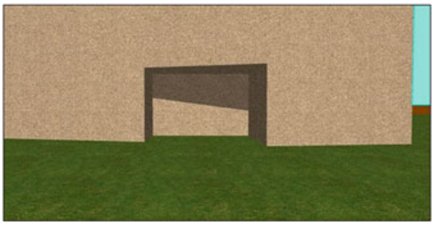

Fig. 34 Our simulation of the cave showing light falling inside it on equinox sunrise. The cave is lit up partially even on both the solstices. (Simulation: Srikumar Menon)

Fig. 35 Photograph showing a shaft of sunlight advancing towards the sanctum with the deity at the Kolhapur Mahalakshmi Temple during *Kiranotsava.* (Photograph: Srikumar Menon)

9.2 Structural Temples and Solar Penetration into Sanctums

Several cases of interaction of structural temples with the solar cycle, with penetration of sunlight into the structure on specific dates, are known (Shylaja, 2007; Vyasanakere et al., 2008).

One such example is the Kiranotsava (literally, festival of the Sunray) at the Mahalakshmi Temple at Kolhapur. The temple faces west (azimuth –256°) and the rays of the setting Sun penetrate to various extents inside the sanctum at two times in a year—between 31 January and 2 February and between 9 November and 11 November (Figs. 35 and 36). The temple is attributed to the seventh century CE, although the present structure might have been constructed as late as the eleventh century. It is not known why these particular dates have been chosen for facilitating the entry of sunlight into the sanctum. Perhaps it has to do with the date of consecration of the deity or some other auspicious date, the nature of which has been lost to us.

Fig. 36 The Sun appearing in the opening of a *mantapa* to the west of the sanctum of the Mahalakshmi Temple during *Kiranotsava.* (Photograph: Srikumar Menon)

It would be useful to study all temples with similar phenomena associated with their structures to determine if there is any rationale behind the choice of dates of entry of sunlight into the sanctum (cf. Kameswara Rao and Thakur, 2011).

10 Conclusions

This paper is intended as a primer to the study of the association of astronomy with stone monuments in the Indian subcontinent, in various contexts. The instinct to orient monuments to cosmic phenomena, such as the extreme risings and settings of the Sun, seems to have prevailed from prehistoric times, exemplified for example by the orientation and layout of the stone alignments at Nilaskal and Byse. This desire to align man-made structures with directions dictated by the cosmos around us is an ancient human instinct that is also manifest in the tendency to orient later monuments, such as temples, so that sunlight penetrates into the dark sanctum on important dates.

Celestial bodies have been worshipped since prehistoric times, and later were incorporated into indigenous religions. Many of the properties of these heavenly bodies were ascribed as aspects of the deities they became in art and literature—as iconographic features and personalities. Astronomy was an integral part of the development of religious thought in the Indian subcontinent, and finds distinct expression in the art of various periods—from prehistoric rock art to the sculptural programmes of temples.

Acknowledgements I am deeply indebted to Professors A. Sundara, Shrinivas Padigar, and Ravi Korisettar and Dr. Corinna Wessels-Mevissen for their continued and generous support over the years on all aspects of archaeology, monumental architecture and art history. I am also grateful to Professor Mayank N. Vahia, Dr. Nisha Yadav and Shri Kishore Menon for insightful discussions as well as their cheerful company on many of the field trips that led to some of the insights outlined in this paper. I wish to acknowledge the kind support of Shri Sukavana Murugan during the site visit to Mallasandram, and his immense knowledge of megaliths, which he generously shared with me. Ms. Adrija Choudhury assisted in the study of the rock-cut minor cave at Badami. Finally, I am thankful to the Homi Bhabha Fellowships Council (Mumbai) for support.

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Astronomical Symbols on Indian Punchmarked Coins?

Terry Hardaker, Mayank Vahia, and Nisha Yadav

Abstract We suggest that some of the signs on ancient punchmarked coins of India may have been derived from astronomical observations.

1 Introduction

Coins have been minted since the early historic period in India, from around 430 BCE. The earliest of them are termed 'punchmarked coins', and were made of silver. They are marked with multiple symbols, the meaning of which is difficult to interpret, but may have included identification of the kingdom, to authenticate their use and to ensure that they were not forged. A typical coin would have between two and five symbols (Gupta and Hardaker, 2014). The issuing authority needed to select various patterns or symbols to incorporate them on the coins. Some of these symbols recur frequently throughout the duration of punchmarked coinage, while others appear only once. Here we discuss some of the symbols found on these coins.

The night sky has made a deep impression on the human mind. The stars provide simple and yet enlightening patterns (joining points in different ways). The movement of the Sun and Moon (with its phases), passing comets, and their association with 'father sky' in early religions would have captivated the imagination. It is therefore natural that when searching for simple symbols to put on coins, the sky would provide an important source of design, apart from animals and plants.

The human relationship with the sky can be dated back at least 15,000 years, the date of the first rock art depicting astronomy in the Lascaux Caves in France (see Rappenglück, 2004). Since then, human fascination has grown significantly with complex dotted patterns that can be found in Indian rock art (Neumayer, 2013) as well as on punchmarked coins (Fig. 1). It is becoming increasingly clear that the

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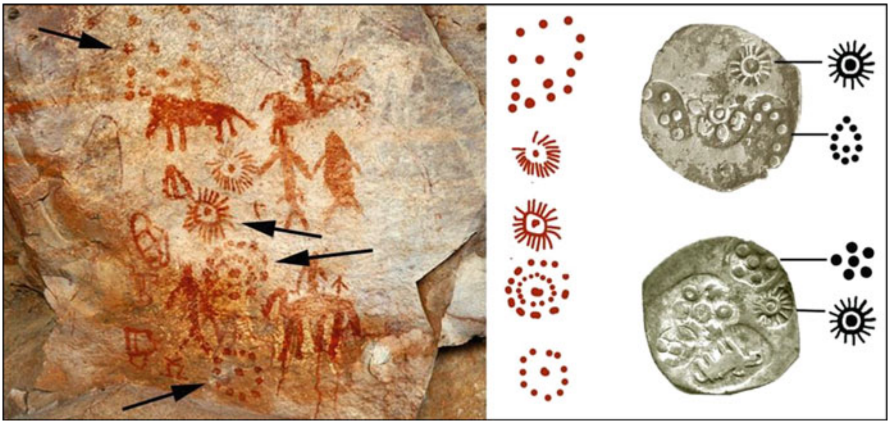

Fig. 1 Rock art from Jihri caves (left), and early punchmarked coins (composition: Terry Hardaker)

small marks commonly seen as adjuncts to the main motifs on rock art as well as on Celtic coins are not just random doodles, but have a coded meaning which often relates to the sky. We therefore propose that signs on coins could be of astronomical symbolism. It is evident that this custom appeared at an early stage in the punchmarked coinage when symbols were mainly geometric, and the coins were being issued by small Janapada states in the Gangetic region (Mitchiner, 2004). We will show that in early Indian coins, one can see several examples of direct representation of stars in the sky. Such a possibility in a European context has been discussed by Marshall (2008).

2 Coins in India

In India the oldest coins are punchmarked coins belonging to early Janapadas and Mahajanapadas (Gupta and Hardaker, 2014). These coins, dated to around the middle of the last millennium BC, are small silver discs or rectangles on which symbols have been impressed using a punch and a hammer. A large number of coins of this period have been published in varying degrees of detail, but we restrict our study to the Magadha/Mauryan series as catalogued by Gupta and Hardaker (ibid.) as representative of a large segment of punchmarked coinage. It should be noted that the coins are typically small, 1–3 cm in size, and the punch marks tend to be no more than 6–9 mm in size, seriously restricting the freedom of expression that an artist could exercise. Whereas rock art offered a broad canvas upon which to place astronomical symbols amongst other motifs, the punch mark presented only a small isolated space to display the subject.

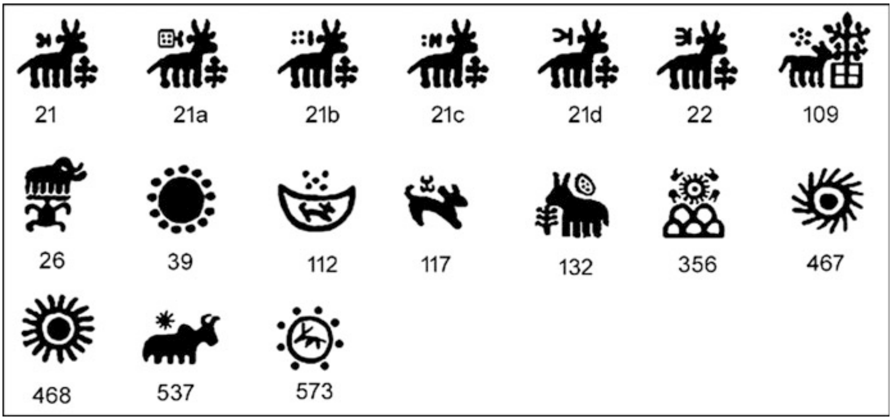

Fig. 2 Some of the symbols seen on punchmarked coins catalogued by Gupta and Hardaker (2014), using their symbol numbers

Fig. 3 The constellation of Pleiades. This image is taken from Stellarium© for 25 December 502 BCE at 5.40 am

3 Astronomical Symbolism on The Coins

In Fig. 2 we present some of the symbols in the coin shown in Gupta and Hardaker's 2014 catalogue.

In the first row of Fig. 2 an animal with some dots or other objects above the animal is seen. The details of these vary. The natural place to put symbols that refer to the sky would be above the main subject, i.e. in the 'sky'. Other examples are seen in symbols 132 and 537. Some of these may represent constellations or asterism, such as the Pleiades, which is a very conspicuous group of seven closely packed stars. In Fig. 3 we reproduce the Stellarium© image of the Pleiades in the neighbourhood of the Moon taken on 25 December 502 BCE at 5:40 am. Note that such events lasting a few tens of minutes would recur once every 18.5 years.

Symbol 112 shows a crescent Moon with a small dog-like animal inside and five dots above the crescent Moon. We suggest that this symbol is an image of the Moon in the Pleiades. This is discussed below. In the second row in Fig. 2 we have symbol 26, with images of an elephant on a tortoise (previously identified as an elephant on a spider). There is a common mythological belief in India that the Earth stands on a tortoise (and similar folklore is found in Europe). Symbols 467 and 468 show a circle with rays emanating from it. This has been a conventional way of depicting the Sun, and symbol 537 clearly shows the radiating circle above the back of a bullock.

4 Possible Depictions of the Pleiades on Indian Punchmarked Coins

Myths about the Pleiades, also known as the ‘Seven Sisters’, are found in many cultures (eg., see Rappenglück, 2008). The Pleiades comprise seven closely placed stars that have held the attention of people for millennia, and because they are located just above the ecliptic they come in conjunction with the Moon every 18.5 years. At this time, the phase of the Moon will depend on the exact Sun – Moon angle. It may thus have attracted special attention as a powerful force in the Janapada period. Some of the Sun, Moon or star arrangements found on early Magadhan coinage are shown in Fig. 4. Note that while the Pleiades is referred to as the ‘Seven Sisters’, in the past the positions and numbers of visible stars varied due to the proper motions of the stars.

In Indian mythology, the Pleiades are the six wives of the sages who form the constellation Ursa Major. Hence a representation of the Pleiades by six or seven stars would be equally valid. The constellation has more than 60 stars, and hence the number of stars seen in the region will vary depending on the observer and the sky conditions.

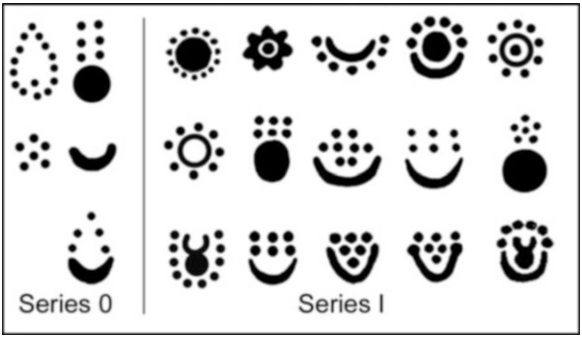

Fig. 4 Possible representations of the Moon and the Pleiades in conjunction on punchmarked coins Series 0 and I are the issues of Magadha janapada dating to the mid-late fifth century BCE (after Gupta and Hardaker, 2014)

5 Conclusions

We consider the possibility that astronomical symbols may be found on ancient coins. We take a clue from early rock art in India to show that dotted patterns in the space above humans and animals suggest the possible representation of stars. Similarly, disks with rays coming out suggesting a representation of the Sun, and a crescent shape suggesting the Moon have also been found in rock art. We then discuss the designs found in punchmarked coins of the early Janapadas of India and show that there are many symbols with dots on the backs of animals suggesting astronomical symbols. We take a specific example of the Pleiades asterism (otherwise known as the Seven Sisters) and show that many designs seem to indicate the marking of the occasion of a Moon-Pleiades conjunction.

The fact that obvious symbols for the Sun or the Moon with arrangements of dots seem to be beyond dispute as astronomical, leads us to suggest that many of the other small arrangements of dots, often shown in conjunction with other motifs such as elephants or deer, also may have astronomical significance.

The challenge now is to try and identify constellation designs and associated symbols.

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Astronomical Aspects of Sukuh Temple, a Fifteenth Century Hindu Temple in Indonesia

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Abstract Sukuh Temple is a Hindu temple located at Karanganyar, Central Java, Indonesia, and was built in the fifteenth century CE during the Majapahit Kingdom, but after the fall of Majapahit when the influence of Hinduism had started to weaken and the Islamic Kingdom of Demak had begun to rise.

This west-facing temple has three gates. In the first gate, there is a relief of a *lingga* and *yoni* (phallus and vagina), as a symbol of fertility. There is also a relief that refers to the year 1359 in the Saka calendar, which corresponds to CE 1437. The second gate has a relief that refers to the year of 1378 Saka/1456 CE. Beyond the third gate was the main building which was shaped like a truncated pyramid.

It is possible that the buildings at Sukuh Temple were aligned with the Sun, as declination measurements of celestial objects above the temple indicate this.

1 Introduction

Astronomy is a science that was first practiced and developed by our ancestors many hundreds of thousands of years ago. Celestial objects such as the Sun, the Moon, the planets and the stars were used for time-keeping in day-to-day activities. These activities included regulating agriculture, scheduling religious worship and determining direction and orientation (including during maritime voyages), and are documented in various ancient sites throughout the world, including some in Indonesia and other Asian countries. Archaeoastronomical research in Indonesia has shown that architecture and astronomy cannot be separated (e.g. see Khairunnisa, 2014).

In this paper we examine the astronomical associations of the Sukuh Temple, a fifteenth century Hindu structure in Indonesia.

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2 Sukuh Temple

2.1 History

Sukuh temple (Fig. 1) is located at latitude 07° 37′ 38″ S, longitude 111° 07′ 52.5″ E, and at an altitude of 1198 m in Karanganyar, Central Java, Indonesia (Sedyawati et al. 2015). The area of the temple is 5500 m^2.

Sukuh Temple is a Hindu temple, and was built with the aim of *pengruwatan*, that is, getting rid of bad powers. The temple faces west and the main gate leads due west to the nearby town of Karanganyar. Sukuh Temple probably was built in the mid-fifteenth century CE when Hinduism and the power of the Majapahit Empire were waning as Islam began to emerge in Java. The appearance of Bhima and Shiva in the reliefs at the temple shows that it was dedicated to ascetics and priests.

2.2 Discovery and Restoration

In 1815 a local resident of Surakarta named Johnson discovered the ruins of Sukuh Temple, but they were first studied in 1842 by Van der Vlis and reported in his book *Proof of a Description of Sukuh and Ceto* (our English translation). In 1864–1867,

Fig. 1 The main building undergoing restoration at Sukuh Temple, in Karanganyar, Central Java, Indonesia. (Photograph: A.K. Rodhiyah)

further studies were conducted by N.W. Hoepermans (1913) and reported in a paper titled "Hindu antiquities of Java" (our English translation). In 1889, R.D.M. Ver-beek (1891) prepared an inventory of Sukuh Temple, and further research was carried out by Knebel and Stutterheim in 1910.

The first restoration of Sukuh Temple was performed by the Department of Antiquities of the Dutch Colonial Government in 1917. After the independence of Indonesia, further restoration was conducted by the Ministry of Education and Culture in 1970. More recently, work was undertaken to remove roots of trees that occupy the site, and this was completed in late October 2016.

2.3 The Architecture of Sukuh Temple

Figure 2 shows a plan of Sukuh Temple, and further details are shown in Figs. 3–13.

The temple contains three different entry-exit gates that access three different terraces, and each of these provides valuable information about the antiquity and functions of the temple.

The first gate (Figs. 3 and 4) features a relief carving of a yoni and a phallus (Fig. 5), symbols that conventionally relate to the beginning of life. Although the

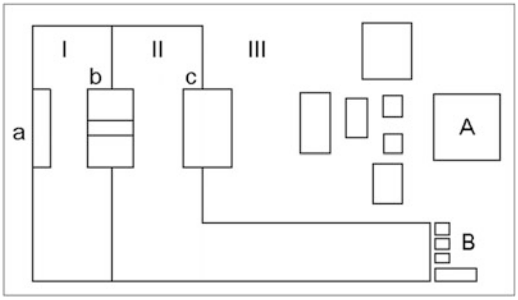

Fig. 2 A sketch plan of the Sukuh Temple. There are three gates (a, b and c) and three terraces (I, II and III). A is the main building (shown above in Fig. 1), and B indicates the presence of elephant carvings (en.wikimedia.org)

Fig. 3 The first gate from the outside. (Photograph: A.K. Rodhiyah)

Fig. 4 The first gate from the rear. (Photograph: A.K. Rodhiyah)

Fig. 5 The carved yoni and phallus inside the first gate. (Photograph: A.K. Rodhiyah)

yoni (vagina) and phallus (penis) are typically seen as Hindu decorative religious elements, staff at Sukuh Temple believe that they originated from Javanese rather than Hindu culture.

On the wall of the south wing of the gate, there is a relief depicting a running man. According to Cruq (1929), this sculpture is a *sengkalan* (a numerical inscription indicating the corresponding year) that reads: "The gate of the giant biting the tail" (Fig. 6).[1] The *sengkalan* is interpreted as 1359 in the Saka Calendar or CE 1437, and it is believed to correspond to the commencement of construction of this temple.

In the north wing of the gate, there is a relief carving of a giant who swallowed humans. The sculpture is also a blind archway *sengkalan* that reads: "The gate of the giant who ate the humans" (Fig. 7). The *sengkalan* is again interpreted as 1359 Saka or CE 1437 (Musses 1923: 269), the same as on the walls of the south wing of the *sengkalan* gate.

The second gate (Figs. 8 and 9) has a relief that reads "The cleric elephant biting the tail", referring to the Saka year 1378, or CE 1456 (Darmosoetopo 1975–1976: 82).

[1]As an aid to understanding them, we have translated this inscription (and all subsequent inscriptions in this paper) from Indonesian into English.

Fig. 6 The south wing of the first gate "The gate of the giant biting the tail", or the gate of the giant snakes that refers to Saka year 1359, or CE 1437. (After Cruq 1929)

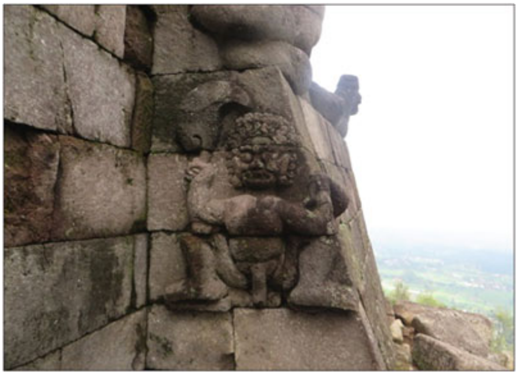

Fig. 7 The north wing of the first gate "The gate of the giant who ate the humans", that refers to Saka year 1359/ CE 1437. (After Musses, 1923)

Fig. 8 The second gate, from the outside. (Photograph: A.K. Rodhiyah)

At the second gate, there are two statues with terrible faces that guard the doors, and embankments that are not complete. In addition, there are some reliefs and one of them is an elephant that reads "an inscription eating the tail", which corresponds to 1378 Saka Calendar, or CE 1456.

On the third terrace (Figs. 10 and 11), there is a relief about the Garudheya story (Fig. 12), Ramayana, *sudamala*, *swargarohanaparwa* and the Bima Sakti story (Sedyawati et al. 2015). They are found on the north terrace. Near the exit, or the

Fig. 9 The second gate, from the rear. (Photograph: A.K. Rodhiyah)

Fig. 10 The third gate, from the outside. (Photograph: A.K. Rodhiyah)

Fig. 11 The third gate, from the rear. (Photograph: A.K. Rodhiyah)

south terrace, there is another relief about the blacksmith story. In front of the main building, further south, there is a carved stone pillar that is full of the Garudheya story. In the upper left corner, there is an inscription in the Kawi language that translates as "Water to clean dirty things", which equates to 1361 in the Saka Calendar (Subroto 1971:234–7). Garudheya is the name of Garuda, the adopted son of Dewi Winata. The goddess had a brother named Dewi Kadru who also became her lover. Dewi Kadru had several adopted children who were in the form

Fig. 12 The relief Garudheya story. (Photograph: A.K. Rodhiyah)

Fig. 13 Stone panels with carved images of elephants and cows. (Photograph: A.K. Rodhiyah)

of snakes. For a bet, Dewi Winata was defeated by Dewi Kadru, so she had to spend her life as a slave to Dewi Kadru and her children. Then Garudheya had to get the water of life as a requirement for the purification or liberation of his mother from the slavery. Note that a carved relief of the Garudheya story is also found at Kidal Temple in East Java, which was built at the request of Anusapati in order to free his mother, Ken Dedes.

On the north side of the courtyard there were three statues of winged human-headed eagles in a standing position with wings outstretched. Only one of these statues is still intact; the other two statues are now headless. Here, there is an inscription on one eagle statue, which dates to 1363 in the Saka Calendar (or CE 1441) (Darmosoetopo 1975–1976: 77) and 1364 in the Saka Calendar (or CE 1442) (Darmosoetopo 1975–1976: 82). On the north side of the third terrace there also are parallel stone panels that were decorated with carved images of elephants and cows (Fig. 13).

The main building on the third terrace has a 15 m^2 trapezoidal base and height up to 6 m (Fig. 1). In the middle of the west side of the building there is a steep narrow stairway leading to the roof. The building that exists today is allegedly only the foundation of the temple, while the temple building itself was probably made of wood. This assumption is based on the existence of several stone pedestals on the roof of the building. In the middle of the roof there is a phallus. Note that a couple of yoni and phallus carvings from this temple currently are stored in the National Museum in Jakarta.

Fig. 14 The carving showing the story of the blacksmith. (Photograph: A.K. Rodhiyah)

The third terrace is located at the upper part of the temple, which is the most sacred place. The third terrace courtyard is divided into two sides, north and south, by a paved way leading to the sacred building in the rear part (see Fig. 2). In the courtyard, there are three parts and—as we have seen—on the northern side there are a lot of statues and stone panel displays.

In the southern part of the courtyard at Sukuh Temple there are three stone panels that were laid in parallel. These panels contain relief carvings depicting a theme taken from a song of the Sudamala story. The story is about Sadhewa, one of the twin knights among the five Pandavas, who managed to do *'meruwat'* (i.e., to remove the curse suffered by Uma, the wife of Batara Guru). The goddess Uma was cursed by her husband because she could not control her anger towards her husband who asked to be served for inappropriate purposes. Due to her strong anger, the goddess was cursed and transformed into a giant, called Bathari Durga. The latter took on the disguise of a warrior in order to be set free. This story is displayed in five relief panels. Moreover, the Sudamala carvings contain underlying religious values and a belief system that is embodied in a ceremony performed by community supporters.

In addition, there are stories of the blacksmith (Fig. 14) that were not only intended to relate to metal-working in fifteenth-century Java, but also were seen as a symbol of immortality after someone had undergone various levels of religious training (Saiwa). In this case, metal was regarded as eternal and unchanging (O'Connor 1985).

In front of the main building, there are three statues of large-sized turtles. Usually, the turtle symbolizes the underworld, which is at the base of Mount Mahameru. In the courtyard of Sukuh. Temple there is a paved way to the south where there is a small temple that contains a small statue. According to local mythology, this small temple was the residence of the ruler of the complex, whose name was Kyai Sukuh.

For some people, Sukuh Temple reflects a philosophy that yields the fullness of life. Each temple building was believed to contain 'Nine Life Energies': flavor, garbha, widya, the word, bhawa, initiative, soul, craft and image. These nine energies were present throughout the temple terrace. Most of these energies were carved into the phallus and yoni, but the craft energy is thought to be contained in the carved elephants.

2.4 Sukuh Temple as a Hindu Temple

Back in the fifteenth century it is likely that the poets in the mandala community associated with the inscriptions at Sukuh Temple lived in isolated localities on the surrounding mountain slopes (Nugraha 2012).

As we have already noted, architecturally the Sukuh complex is divided into three parts, in the form of three terraces entered via ornamented gateways. This architectural arrangement is often referred to as the Tri Mandala: the Nista Mandala in the first part, the Madya Mandala in the middle and the Utama Mandala, which forms the main area. In Hindu philosophy, the three mandalas symbolize the concept of the human journey: birth, life and death, or Satria, King and Brahmana.

3 The Orientation of Sukuh Temple: A Brief Archaeoastronomical Investigation

In archaeoastronomy we can investigate the basic relationship between the movement of certain celestial objects and the design and construction of a building or astronomical site. Thus, we consider a system of celestial coordinates, the correct positions of selected celestial bodies at particular times, and the movement of these celestial bodies with the passage of time (e.g. see Fig. 15).

With the help of Google Earth the orientation of Sukuh Temple could be determined, and it was found to be aligned east-west, while readings taken with a prismatic compass (Fig. 16) showed that the three terrace gates faced due west.

We then used Google Earth to simulate the position of the Sun on 20 March 2016 (at the vernal equinox) and on 22 September 2016 (at the autumnal equinox), as seen by an observer at Sukuh Temple. At sunrise on 20 March obviously the Sun rose due east (Fig. 17) and at sunset on the same day it set due west (Fig. 18). In fact, the precise times of the vernal and autumnal equinoxes vary each year and can occur on 20 or 21 March and on 22 or 23 September, respectively.

The western orientation of Sukuh Temple is interesting given Degroot's (2009) finding that earlier Central Javanese temples were oriented either east or west in the ratio of 5:7, even though Indian architectural traditions demanded that most Hindu temples face to the east.

However, Indian Hindu temples dedicated to Siva were the exception in that they tended to face west (Dagens 1970), and Degroot (2009) also noticed that early Javanese temples that were not associated with local settlements and wet-rice cultivation, but had mainly ritual functions, also tended to be oriented towards the west. Even though it dated much later, we should note that Sukuh Temple also was dedicated to Siva and appeared to serve as a ritual centre for ascetics, so in this regard its western orientation is understandable.

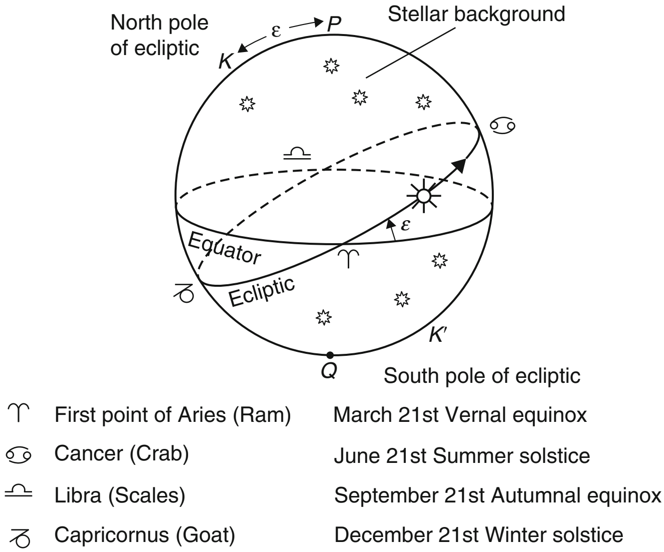

Fig. 15 A diagram showing the motion of the Sun along the ecliptic in the course of a year (after Roy and Clarke 2003: 73)

Fig. 16 Prismatic compass readings showing the western orientation of the Sukuh Temple terraces. (Photograph: A.K Rodhiyah)

4 Concluding Remarks

Sukuh Temple is a distinctive and well-preserved three-terrace Hindu temple located at Karanganyar in Central Java. It has a rich assemblage of inscriptions and carved relief figures that are variously dated to CE 1437, 1441, 1442 and 1456, demonstrating that construction took place during the mid-fifteenth century. It is also clear that the designers of Sukuh Temple were familiar with the four main cardinal directions, and they oriented the temple east-west in order to accommodate rising and setting positions of the Sun during the equinoxes.

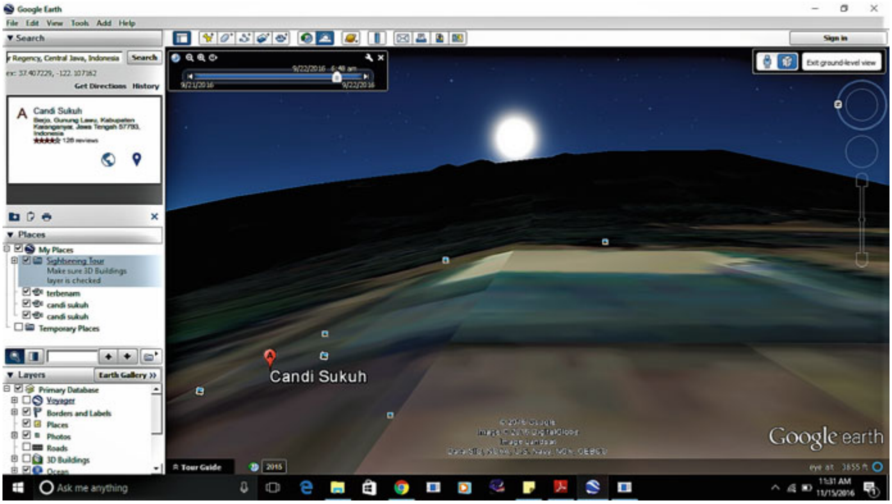

Fig. 17 A simulation using Google Earth of sunrise on 20 March 2016, as seen from Sukuh Temple

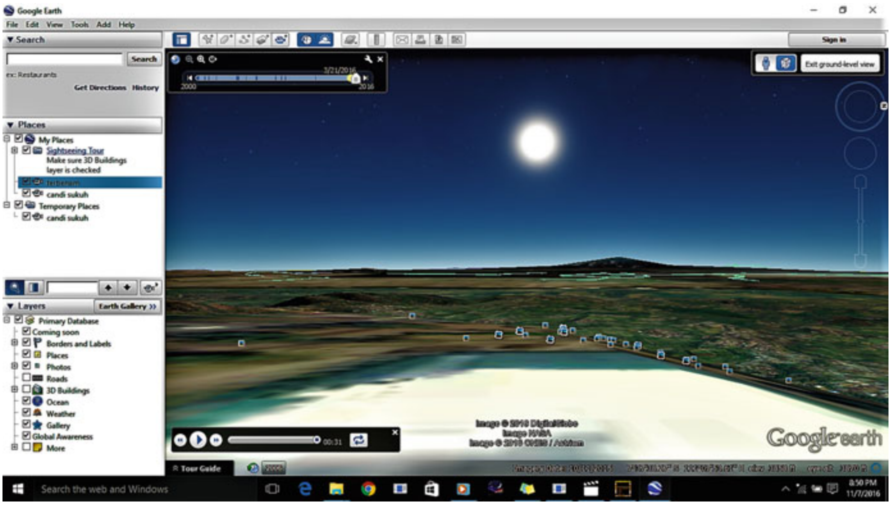

Fig. 18 A simulation using Google Earth of sunset on 20 March 2016, as seen from Sukuh Temple

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The Alignment of the East Outer City Gate at the Ancient Chinese City of Shimao

Lyu Yufei, Sun Zhouyong, and Shao Jing

Abstract Founded around 4200 BP, the ancient city of Shimao is a milestone in research on the origin of Chinese civilization. The East Outer City Gate is the earliest systematically excavated archaeological site in this early city. The structure and orientation of the building, the sacrificial pit arrangements and human sacrifice rites used in the cornerstone-laying ceremony, are all very special and mysterious. This paper shall, preliminarily verify the profound cultural connotations contained in the East Outer City Gate through statistical analyses, scientifically computed data and empirical measurements from the perspectives of archaeology, archaeoastronomy, palaeography and philology etc. Secondly, this paper will try to explore and recreate the astronomy, cosmology and beliefs system of the Shimao people.

1 Introduction

What did early cities, especially capital cities, in East Asia look like during the Late Neolithic and at the end of the Neolithic age (7000–4000 BP)? Evidence in ancient literature and archaeological discoveries are scarce. Up to now, about 60 early cities built during the Longshan period (4500–4000 BP) have been excavated by archaeologists. These cities are mainly distributed throughout Henan, Shandong, Shanxi, Hubei, Hunan, Sichuan, Gansu and Inner Mongolia, etc. (see Fig. 1 for the location of Shimao, the focus of this paper). There were many areas of mountainous masonry located in central and southern Inner Mongolia, ranging from a few thousand to tens of thousands of square meters, and some even exceeding 100,000 square meters. The Tiger Mountain site located at Daihai Lake (Tian, 1982–1983), Ashan located at the southern foot of the Daqing Mountains in Baotou (Institute of Mongolian History . . ., 1984), Heimaban (Cultural Relic Management Institute of Baotou, 1986) and

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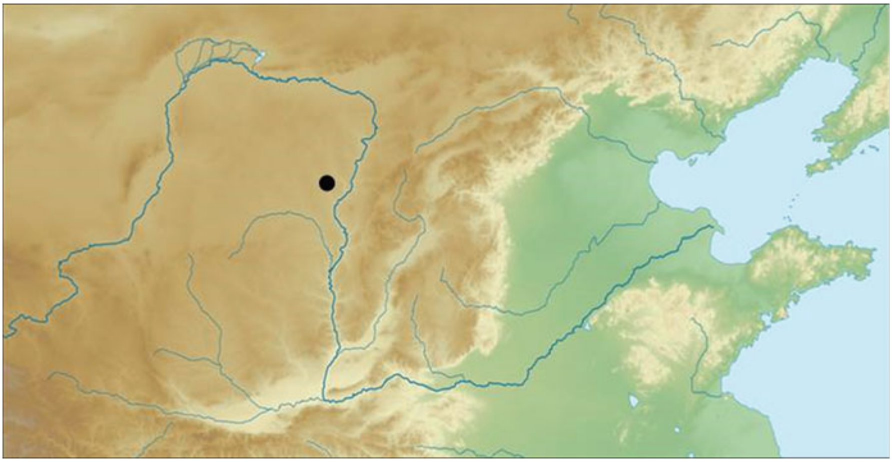

Fig. 1 A map showing the location (the black circle) of the ancient city of Shimao in northern China. (After Wikipedia)

Zhaizita in Jungar Banner (Wei, 1991) probably were the original models that helped develop the structure of the city of Shimao.

Shimao City is located at 110° 18′ 26.66″ E and 38° 33′ 51.24″ N, in Shimao Village, Gaojiabu Town, Shenmu County, Yulin City, Shaanxi Province (Fig. 2). The early city was built on an isolated and desolate hummock composed of gneiss and loess in the southern part of the Mu Us Sandy Land but the northern part of the Loess Plateau. Dongchuan River, which ran from north-east to south-west and spanned the north-western edge of the masonry walls of the Imperial City Terrace of Shimao City, sustained Shimao's culture. This layout is very similar to the Niuheliang sites of the Longshan Culture and the Liangzhu sites of the Liangzhu Civilization (which date between 5400 and 4250 BP).

There was a large time gap between the archaeological discovery of Shimao City and its formal excavation. The preliminary excavations that occurred from 1970 to 1980 aroused considerable speculation in foreign and domestic academic circles (see Dai, 1977). The formal archaeological excavations that started in 2012 in the East Outer City Gate site at Shimao City sparked a wide range of intensive studies by archaeologists and historians on the dating and cultural nature of all aspects of the City (Archaeological Institute of Shaanxi Province, 2013; Hu et al., 2015; Shao et al., 2015; Wang and Sun, 2011).

Fierce debates first arose among historians who tried to match the city ruins with the earliest Chinese city recorded in the historical literature (see Shen, 2013a, b; Wang, 2014; Ye, 2013). However, we believe that before further sites in Shimao City are excavated, large numbers of pots, jades, murals and other artifacts should undergo careful and scientific analysis. We feel that it is too early to cite historical literature, in order to either speculate or try to match the nature of the city with legend, which is still far from being verified and confirmed (Chen, 2013; Sun, 2015).

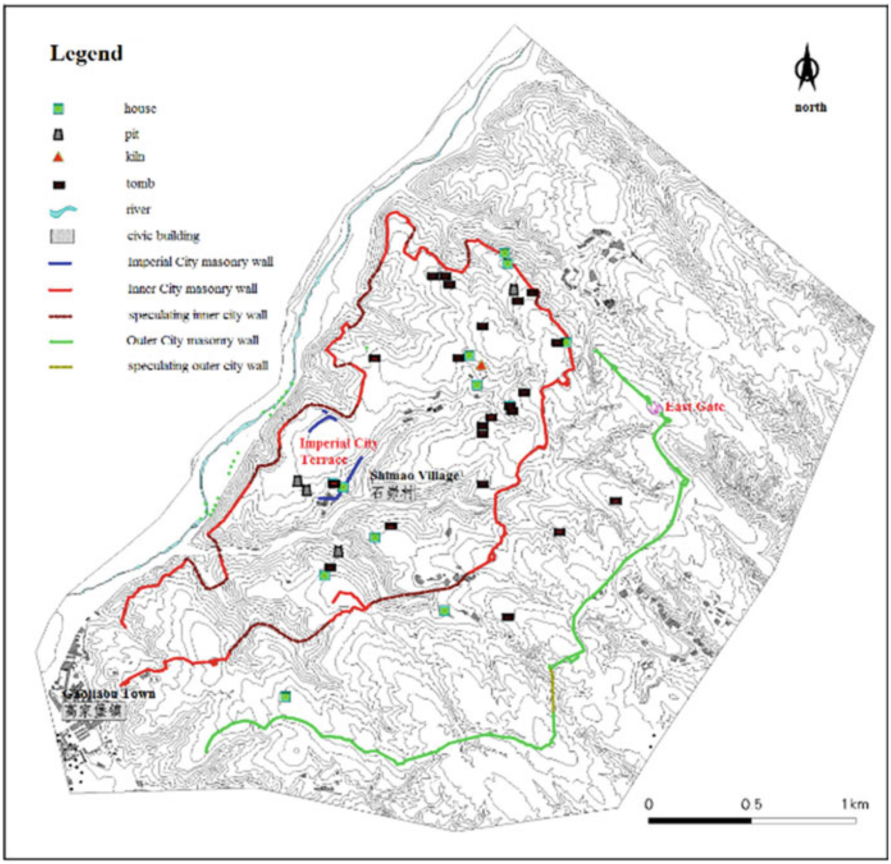

Fig. 2 Shimao City in 4200 BP. (Courtesy: Shaanxi Provincial Archaeological Institute)

Based on three major facts from the current excavation, the East Outer City Gate of Shimao will have profound and far-reaching historical significance and archaeological value.

Firstly, with regards to is position, the East Outer City Gate is located at a strategically high point within the treble city walls that occupy the highest and most prominent position in the city, which overlooked the entire western region of the ancient city. Obviously, back more than 4000 years ago when Shimao people began to build their capital, they paid great attention to this defensive building that was believed to have both high strategic value and cultural significance.

Secondly, the East Gate is very rigorous in design, complex in structure, delicate in architecture, huge in dimension and magnificent in outlook (see Fig. 3). The East Gate would likely rank second only to the Imperial City Terrace, which would have required that Shimao people spend as much manual effort, material resources and even human sacrifices within their power to construct the buildings.

Fig. 3 The shape and structure of the East Outer City Gate at Shimao City. (Courtesy: Shaanxi Provincial Archaeological Institute)

Thirdly, the unearthed cultural relics found at the East Outer City Gate led to several academic puzzles, such as the ritual used in the cornerstone-laying ceremony before construction began, or the alignment, structure and decoration during the construction. We believe that the function of the East Gate is not purely defensive, but what other functions did it have? Why did the Shimao people pay so much attention to it?

2 The East Outer City Gate: Three Puzzles

Not all ancient capitals had large city walls and gates like those archaeologists found for example at Taosi, Erlitou (Xu, 2000), Yinxu, Feng and Hao sites. However, if a site had large city walls and gates it was definitely a capital, as were the Shang Dynasty sites at Yanshi and Zhengzhou, for example. Therefore, the early city at Shimao can be identified as a capital, since it has the largest walls and gates of all late Longshan sites that have been excavated. Furthermore, Shimao City possesses all of the so called "... elements of capital civilization ..." (Xu, 1989: 1117) that proven or suspected capitals of the Xia, Shang and Zhou Dynasties had or did not have.

The East Outer City Gate of Shimao is located at 110° 19′ 31.94″ E and 38° 33′ 56.79″ N, and is 1.6 km due east of the Imperial City Terrace (see Fig. 2). In the archaeological excavations so far, this gate has exhibited exceptionally rich cultural evidence, but it also has provided three major puzzles for researchers regarding its orientation, structure, layout and décor. These are discussed below.

The first puzzle is that the East Outer City Gate does not face due east. Normally the gates of ancient cities around the world are located in the middle of each side surrounding a city, and they face the same direction as the city wall in which they are located. For example, the east gate located in the middle of an eastern city wall will face due east, while a south gate located in the middle of a southern city wall will face due south. However, in the case of the ancient city of Shimao, although the East Outer City Gate is located due east of the Imperial City Terrace, it faced a north-easterly direction. Why was this?

Furthermore, the two gate towers were found to be different in dimensions. Normally, gate towers would be symmetrical in structure and size. However, the gate towers of the East Gate of Shimao City were deliberately arranged to be asymmetrical in structure. The north-western gate tower was square-shaped, while the south-eastern gate tower was almost half the size and had a rectangular appearance. Shimao may be the only archaeological site excavated where the gate towers are asymmetrical. What reason(s) led to this?

Thirdly, the sacrificial pits at the East Gate at Shimao City seem to have been placed randomly, without any plan. Sacrificial pits were discovered within the Gateway itself, in the outer barbican of the East Gate, as well as inside and outside the nearest city walls. Their positioning seems to have been completely random. Archaeologists found human skulls buried in each pit, but the number varied from pit to pit and seemed to be random. However, it was discovered that most of the skulls belonged to young females, and that many of the lower jaws carried burn marks. What was the reason for this?

2.1 The Orientation of the East Outer City Gate

2.1.1 *Yingzao Fashi* (*Standard Forms and Methods of Architecture*) in East Asia

The cognitive pattern of a nation is reflected in the methodologies used by most of its members in understanding nature and themselves, as well as the information-processing practices they used (Tang et al., 2012). Early East Asians and those who came later as ancient Chinese had adopted a totally different cognitive system to that found in the Western world. This cognitive system was initially proposed in the *I Ching* (*The Book of Changes*) in *Xici I* and *Xici II* (*The Great Commentary I & II*), which profoundly impacted Chinese elites for several thousands of years:

> Saints would follow the magical things created by nature, imitate seasonal changes in nature, emulate the astronomical phenomena present in the sky to reveal omens of good or ill luck, and follow *Hetu* [astronomical phenomena of the Azure Dragon] and *Loushu* [astronomical phenomena of the Black Turtle] that emerged from the Milky Way respectively. When the oldest creator, *Baoxi [Fuxi]*, ruled the world, he gazed up to study phenomena in the sky, looked down upon landscapes to learn the law of the Earth, observed features of birds and beasts and all sorts of things that were appropriate for existing on land, collected images both from within his own mind and from outside objects, then he created hexagrams with related ideograms [diagrams] in order to communicate with all gods for their virtues and … to categorize all beings and things by their nature.[1]

From a very early age humans had already recognized that the sky and the Earth held vast amounts of natural information, which was thought to be the ultimate knowledge that humans could learn and imitate. The *I Ching* was just a record of the cognitive styles and practice model for simulating heaven and Earth, which served as the ultimate law among high priests during the East Asian Neolithic age and elites in Chinese dynasties for cognitive behaviour, and set the highest standards for establishing a national system and enacting the decree of the Imperial court. This is why the plaque that reads "Observe Celestial Phenomena and Determine Time" is hung in the Ancient Observatory in Beijing, and the plaque that reads "Establish Directions and Follow the Cosmic Law" is hung in the Palace of Supreme Harmony in the Forbidden City.

Superficially, the practice of observing the sky and celestial phenomena and determining time led to the development of ancient Chinese agricultural time-management systems relating to East Asian crops. Looking down at the ground, investigating the soil and inspecting water quality were necessary for understanding the soil conditions and water resources in a region before selecting the most appropriate places for settlements, so that people could live in harmony with the natural environment. Essentially, this cognitive attitude regarded humans as transient guests between heaven and Earth who had to carefully observe, discover, understand and obey the laws of the Universe in order to live in harmony with nature and sustain an endless source for living between heaven and Earth.

Upholding such tradition, East Asian ancestors were always very careful in selecting sites for their settlements and cities in order to find a geographical landscape that conformed to the ideal of 'oneness of man and nature'. This ideal was derived from prehistoric East Asian cosmological and astronomical belief systems (Cultural Relic Institute of Archaeology of Zhengjiang Province n.d.). Ancient Chinese thoughts about urban (capital) planning sporadically can be seen in some historical books, such as the *Zhou Li* (*Rites of the Zhou Dynasty*), *Shangjun Shu* (*The Book of Lord Shang*), *Guanzi* (*The Book of Sir Guan*) and Mozi (*The Book of Sir Mo*), to name just a few. The *Guanzi* and *Zhou Li* are representative works for the two Schools regarding early urban planning and construction theory, both of which outlined a well-known theory with far-reaching influence.

The *Guanzi*·(*Riding V*) states:

> When establishing a capital, the designer must place it either at the foot of a huge mountain, or on a plain above a high riverbank. When choosing a highland place, it should not be too high to be near a drought place so as to ensure adequate water supply. When choosing a lowland place, it should not be too low to be close to a waterway so as to save the cost of constructing a ditch or embankment. The capital should rely on natural resources and take advantage of a favorable geographical position. Construction of city walls does not necessarily have to follow the rules of geometry and paved roads need not necessarily be confined to a grid system.

Meanwhile, the section titled *Kao Gong Ji* (*Inspection Standards for Architects*) in the *Zhou Li* says this:·

> When a great architect builds a capital, he should plan the city territory in a square shape with each side measuring 9 *Zhou li* [1 *Zhou li* = 415.8 m] and three city gates should be arranged at each side. Within the city, they should place nine vertical main streets and nine horizontal branch streets. The widths of these streets should allow nine carriages to run simultaneously.

> The ancestral temple should be located to the left of the Royal Palace, the imperial divine temple should be located to the right of Royal Palace, and the palace for meetings with state ministers should be located in front, while the marketplace should be located at the back . . . The ridge of the Palace Kadoya was constructed to be five *Zhi* [1 *Zhi* = 10 m long and 3.33 m high]. The four corners of the Palace walls were measured at seven *Zhi*; and the four corners of the city wall measured nine *Zhi* . . . The height of the constructed ridge of the Palace Kadoya is used as the standard height for building the four corners of the city walls of princes; while the heights of the constructed four corners of the Palace walls are the height standard for building the four corners of the city walls . . .

The urban planning and construction theory proposed in the *Riding* emphasizes that nature should be at the center of consideration. This theory advocates conformity of the shape and topography of the city, which should be adapted to the local conditions for convenience and in harmony with nature, without any deliberate attempt at artificial tidiness or symmetry. On the other hand, the *Kao Gong Ji* places people at the center of its planning theory, and advocates breaking away from nature and transforming the environment according to human ideals, while emphasizing complete formulation and standardization and deliberately pursuing artificial tidiness and symmetry.

According to archaeological discoveries, in capitals dating from the Late Neolithic to the pre-Qin Dynasty, the shapes and structures that actually existed in East Asia before the Spring and Autumn Period were more consistent with the planning theory proposed in the *Guanzi*, while the theory proposed in the *Zhou Li* mirrors the shapes and structures of western cities outlined by Hippodamus (from ancient Greece) in 500 BCE, which were characterized by squares with public buildings at the centre of the city, surrounded by a grid pattern of trellis-like and radial roads. Obviously, the city planning philosophy behind the ancient city of Shimao stemmed from the theory outlined in the *Guanzi*.

Some historical records found in the ancient literature concerning urban gates have high reference value. For example, Volume IV in the *Wu Yue Chun Qiu* (*Affairs between the Wu State and Yue State*) titled *He Lyv Nei Zhuan* (*The Inside Story of He Lyv*, *the Most Outstanding King of Wu State*) records that in 514 BCE Wu Zixu, the famous militarist of the Spring and Autumn Period and senior official of the Wu State, "... investigated the soil, inspected the water, [and] abided by the law of heaven and Earth . . .", in order to build the capital of the Wu State for He Lyv, the King of the Wu State. Since Wu Zixu's intent was to build a capital after investigating ('Xiang' in Chinese) soil in the area, 'Xiang City' was another name used for He Lyv City:

> Zixu constructed the capital based on investigations of soil, inspections of water, compliance with the laws of the heaven and the Earth. The capital covered an area of 47 square *lis* [1 *li* = 415.8 m]. It included eight land gates to symbolize winds from eight directions and eight water gates to simulate the eight underworld windows. He also constructed a small city with an area of 10 square *lis* which had three mausoleum gates. Not opening the East Gate reflected a desire to cut off the promise of Yue; establishing the Chang Gate symbolized that the wind of Changhe would flow through heaven's door; thereby setting up the Gate of the Snake to simulate the door down to the underworld. He Lyv intended to go west to conquer Chu State, which was located to the northwest, so Zixu established the Chang Gate to communicate with the air in the northwest. Accordingly, it was also called the Pochu Gate (conquering Chu State); and He Lyv also wanted to expand eastwards and take over Yue State, which was located to the southeast, so he established the Gate of the Snake to restrain the enemy. *Wu* held the pos ition of *Chen* (east-southeast), which was the direction of the

> Azure Dragon, so the tile heads on the South Gate of the small city were shaped like *Nimiao* to symbolize dragon horns. *Yue* held the position of *Si* (southeast-south), which was the location of the snake, so they make a wooden snake inside the South Gate, facing north, symbolizing *Wu's* occupation of *Yue*.

Needham believed that the layout of He Lyv's capital city of the Wu State was a representation of "... a vision of the cosmos ..." in peoples' minds (Wang, 2000). The vision of the cosmos mentioned by Needham refers to Wu Zixu's vision of the center of the cosmos after "... investigating soil, inspecting water, complying with the laws of the heaven and the earth." Regardless of the cause and effect of the implications of the vision of the cosmos, we can prove merely by examining the theories of the arrangement of the city gates that people were very careful to align ancient city gates because they were determined by cosmological considerations. Since enemies of the Wu State included the Chu State and the Yue State, which were located to the north-west and south-east respectively, therefore Wu Zixu's capital included special gates facing north-west and south-east in order to restrain his enemies. Thus, if we do not study this example in depth it appears that Wu Zixu's capital conformed to the planning theory of the Guanzi, which superficially put nature at the center of considerations and advocated conforming to nature, focusing on shape and topography, adapting to local conditions, emphasizing convenience and liveability, and not deliberately pursuing or caring about tidiness or symmetry. But if we look more deeply, the planning of the capital was neither orderly nor symmetrical in nature because it followed perceptions based on East Asian cosmological belief systems. Did Shimao City reflect a similar or identical perception to this?

2.2 *A Study of the Orientation of the East Outer City Gate*

2.2.1 Measuring the East Outer City Gate

The East Outer City Gate of Shimao is located due east of the Imperial City Terrace, but the dimensions of the two gate towers are not the same and the doorway faces north-east, which are abnormal. Why was this? In order to measure the precise orientation of the two gate towers, we took measurements using a geological compass from the four faces of the three tiers inside and outside the masonry of the north-western and south-eastern gate towers.

2.2.1.1 The North-West Gate Tower

The exterior facade on the north-eastern side of the main gate tower faces north by east 58–60°. The exterior facade on the south-eastern side of the main gate tower faces north by east 58–60°. The exterior facade of the central part faces north by east 60°, and the exterior facade in the rear part faces north by east 60–62°. The exterior facade on the north-western side of the main gate tower faces north by east 57–62°. The results of this random sampling are shown in Table 1.

Table 1 Measurements of the orientation of the Northwest Gate Tower

Position of the measurement		North by East (°)
NW side of the central main part of the stone wall		58
		60
Southeastern side	Corner stone	58
		60
	Central stone	60
	Rear stone	60
		62
Northwestern side		57
		58
		60
		62
Mean value		59.5

Table 2 Measurements of the orientation of the Southwest Gate Tower

Position of the measurement		North by East (°)
NE side of the outer protective stone wall		60
NE side of the central main part of the stone wall	SE side	60
		65
SE side of the inner earth rammed terrace		57
		58
		59
		60
Mean value		59.9

2.2.1.2 The Southeast Gate Tower

The exterior facade on north-eastern side of the outer protective stone tier faces north by east 60°. The stone in the west part of the exterior facade on north-western side of the main body of the stone wall faces north by east 68–71°. The exterior facade of the south-eastern side of the main body of the stone wall faces north by east 60–65°. The exterior facade of the south-eastern side of the inner rammed earth wall faces north by east 57°. The results of the random sampling are shown in Table 2.

2.2.1.3 The North-Western Bastion of the East Gate

The cornerstone of the exterior facade on the south-eastern side of the bastion faces north by east 51–52°. The cornerstones of the second tier of the exterior facade on the north-western side faced north by east 58°; and the corner-stone faced north by east 48°.

2.2.1.4 The Inner Barbican

The cornerstone of the exterior facade on the north-western end faces north by west 33°. The stone of the exterior facade on the western part faces north by west 25–30°. The stone on the exterior facade on the central part faces north by west 27°.

These measurements show that the doorway of the East Outer City Gate and the exterior facade of the north-eastern side of the City Gate tower face approximate north by east 59°, and that the first bastion on the north-western side turned slightly to run north along the city wall. The north-west-facing doorway of the Inner Barbican and the doorway of the East Gate formed an angle of 90°. What do the orientation of the doorway and the exterior facade on the north-eastern side of the City Gate tower mean?

2.2.2 An Archaeoastronomical Study of the East Outer City Gate

The orientation of the East Outer City Gate doorway and the exterior facade of the north-eastern side of two gate towers suggests two different possibilities: they were aligned with some geo-graphical landscape feature or with an astronomical phenomenon. Based on the observations of the environment around the ancient city of Shimao, the East Gate does not face any distinctive geographical landscape feature, so it should relate to some kind of astronomical phenomenon or the solar azimuth angle at some point in time. Using computed calculations, we recreated the solar azimuth and astronomical phenomena visible near the celestial equator during the period when Shimao City was planned and constructed.

The solar azimuth angle, A_s, is the intersection angle between the Sun's shadow on a horizontal surface and the local meridian. There are several equations that can be used to calculate A_s at any time, on any day, and for any latitude (e.g. see Duffie and Beckman, 2013), and the one we have chosen is:

$$\cos(A_s) = (\sin(\delta)\cos(\phi) - \sin(\phi)\cos(\delta))\cos(h)/\sin(\theta_s) \quad (1)$$

where δ is the latitude receiving direct solar light at the time of the observation, h is the hour angle and θ_s is the geographic latitude of the observation site. Equations for calculating sunrise azimuth angle at the summer and winter solstice are:

$$(\text{N-E})\ A_s = \arcos(\sin(\delta)/\cos(\phi)), \quad (2)$$

$$(\text{E-N})\ A_{s'} = 90 - 0.5 \arcos[2(\sin(\delta)/\cos(\phi))2 - 1] \quad (3)$$

These equations are based on an assumption that the Earth is a perfect sphere, but the fact that the poles are a little flatter and that there are mountains and depressions everywhere leads to some deviation between calculation and actual measurement.

These equations are related to the nonlinear changing period of the obliquity of the ecliptic (ε), which is about 41,040 years. For a relatively short time period, say the 10,000 years centred on the year 2000 CE, we can use the following equation (which was proposed by Laskar, 1986):

$$\begin{aligned}\varepsilon = 23^{\circ}\ 26'\ 21''.448 - 468093''t - 1.55''t^2 + 1999.25''t^3 - 51.38''t^4 \\ - 249.67''t^5 - 39.05''t^6 + 7.12''t^7 + 27.87''t^8 + 5.79''t^9 + 2.45''t^{10}\end{aligned} \tag{4}$$

where t = T/100 and T is the number of centuries from the year 2000.

Various relative and absolute chronological dating methods indicate that the planning and construction of the ancient city of Shimao occured approximately 4200 years ago.[2] The cumulative deviation in the obliquity of the ecliptic is 47″/century × 42 centuries = 1974″ = 0.5483°, and the obliquity of the ecliptic of Shimao City ε = 23.44° + 0.55° = 24°. The geographical latitude of the East Gate is 38° 34′ 54.5″ (38.58°). At present (21 June 2016), the observed sunrise, half appearance, on the summer solstice of Shimao is at 5:18:58 in the morning, and the solar azimuth angle is 30° 40′; dating back to the summer solstice 4200 years ago (on 13 July 2200 BC), sunrise was at 5:05:50 in the morning, and the solar azimuth angle, A_s(N-E) = arcos (sin24/cos38.58) = 58.65, and $A_{s'}$(E-N) = 90–0.5arcos[2 (sin24/cos38.58)2–1] = 31.35°, about 31° 21′. So the sunrise azimuth angle on the summer solstice was 58° 39′, and the sunset azimuth angle was 301° 21′ (These calculations do not include the solar radius difference, atmospheric refraction or geocentric difference, which do not affect the conclusions).

Based on this calculation of modern astronomy and recreating astronomical phenomena, the East Outer City Gate's doorway and the exterior facade of the north-eastern side of the gate tower faced precisely the sunrise azimuth on the summer solstice 4200 years ago. The result tells us that the designers of this ancient city, the high priests of Shimao, had already observed and calculated the date of the summer solstice and sunrise azimuth angle before they started to build their capital. Thus, we speculate that the Shimao City high priests had already calculated a basic calendar required by Shimao people, and determined the dates of the equinoxes and the solstices, as well as their corresponding mansions in the constellations and the sunrise azimuth angles, before they started planning the East Gate, otherwise the architectural form taken by the East Gate would not have been adopted.

The Shimao City high priests chose to orientate the doorway and the exterior facade of the gate to face the sunrise azimuth angle on the day of summer solstice, thereby allowing the morning sunlight to shine through the doorway and directly illuminate the murals with geometric patterns on the north-eastern wall of the inner barbican. The orientation of the doorway was critical, otherwise the walls on either side of the doorway would cast shadows (see Fig. 4) and reveal that the planning of the Shimao high priests was faulty.

In order to test the validity of the above calculation on 21 June 2016, the day of summer solstice, we carried out observations at the East Gate from dusk on 19 to dawn on 23 June 2016. Taking into account the fact that the doorway and northwest gate towers were the best places for the Shimao high priests to welcome the sunrise on the summer solstice, check points were selected between the wall of the outer

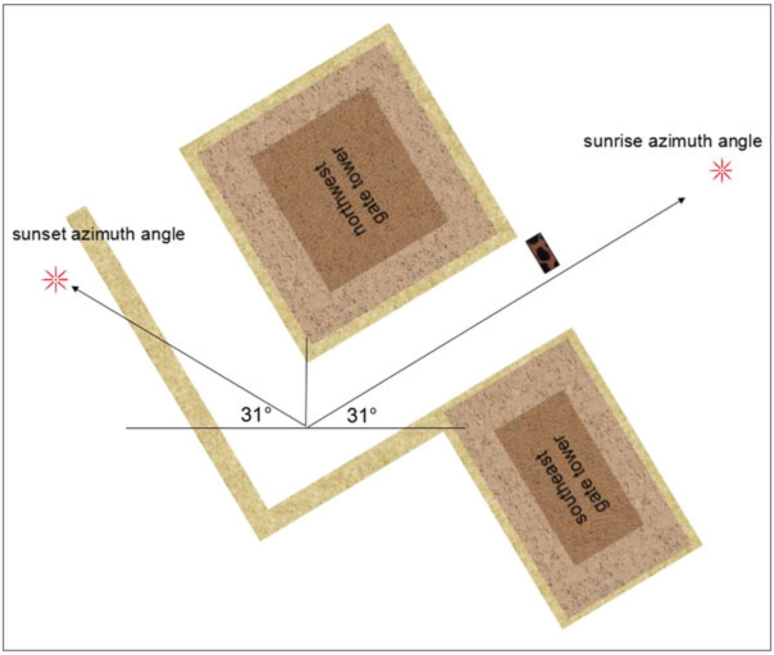

Fig. 4 The orientations of the East Outer City Gate doorway and gate tower. (Diagram: Lyu Yufei)

barbican and the entrance of the doorway, between the rear doorway and the wall of the inner barbican, and on the exterior facade of the north-western gate tower to verify the orientation of the doorway and gate tower (see Fig. 5).

We used three cameras to record the sunrise and sunset. Considering that the ridge of the north-eastern horizon is higher than the East Gate, we selected a time when the upper edge of the Sun just came out from behind the ridge to carry out the measurements, because if the horizon was higher than the real horizon the actual sunrise time would be later than the theoretical sunrise time. After 4 days of actual measurements in the morning, data were obtained regarding the sunrise times and sunrise azimuths on the 20th, 21st and 22nd. On the morning of the 20th, there was mist, the upper edge of the Sun appeared at 5:24, and its azimuth (as recorded by the geological compass) was 29°. On the morning of the 21st, there were clouds above the north-eastern horizon, the upper edge of the Sun appeared at 5:25, and its azimuth again was 29°. On the morning of the 22nd, the north-eastern horizon was completely clear, the upper edge of the Sun appeared at 5:23, and its azimuth was 30°.

Our observations showed that the south-eastern interior wall of the north-western gate tower was totally illuminated, but the north-western wall of the south-eastern gate tower was not. Our results showed that the doorway and gate tower really faced towards the sunrise azimuth angle on the day of summer solstice. Besides, if the sunrise azimuth had moved north by 1° 21′, the inner sides of the two gate towers would have been totally illuminated, which would have been the sight on the day of summer solstice 4200 years ago.

Fig. 5 Data collecting points and alignment of the East Gate. (Courtesy: Shimao Archaeological Team, Shaanxi Provincial Archaeological Institute)

Why did the Shimao people pay so much attention to summer solstice? Why did they plan for the city gate to face towards the rising Sun on the day of the summer solstice? The *Zhou-Bi* (*The Circumference and Gnomon*, the earliest of the Chinese astronomical and mathematical classics, written in 1000 BCE) noted that the

> The winter solstice *[Fa]* and summer solstice *[Lian]* are generated by the change in the Sun's position in its orbit, both of which refer to the two extremes of the daytime and night-time length.

What were the extremes of the daytime and night-time length? The *Kezun Xiandu* (*Comply with the Law of the Sky*), which was written during the Qing Dynasty, records:

> At that day, the Sun arrives at the northern utmost of its orbit, the daytime is the longest and the Sun's shadow is the shortest, so the day is called the summer solstice. Solstice means extreme of the solar orbit.

Since the Shimao high priests had totally mastered the method of gnomon-shadow measurement, they must have known that the shadow of the Sun would become shorter each day (that is *'Lian'*, which means becoming less) after the Sun crossed the equator. When the shortest shadow appeared, it would be marked as the day of the summer solstice, when daytime became the longest, night-time became the shortst, and the sunshine became the strongest. This would be a key period for dry farming in Shimao since the climate before the summer solstice would determine the time to plant the grain.

After the summer solstice, the shadow of the Sun would become longer each day (that is *'Fa'*, which means becoming more), and the sunshine would dwindle until it was the season for people in Shimao to harvest all kinds of grains.

Therefore, the significance of the summer solstice for our ancestors in Shimao was even greater than that of the vernal equinox. It not only closely related to the planting and cultivating seasons of dry farming in the Shimao area, but also closely related to the cosmology and belief systems of our Shimao ancestors of the late Longshan period, when this belief system matured.

3 The Puzzle About the Structure of the East Outer City Gate

3.1 Measurements of the Structure of the Gate Tower

3.1.1 Data and Structure of the Gate Towers

Archaeological excavations show that the two gate towers of the East Gate were divided into three tiers from inside to outside: the inner tier was a rammed earth terrace, while the middle and outer tiers were masonry walls. Although they were not in the shape of a Maya pyramid, their structures were quite similar to the two altar sites of the Yao Mount and Huiguan Mount at the Liangzhu sites.

The outer protective masonry wall of the north-west gate tower is 26.2 meters long, 25.7 meters wide, and the angle formed by the diagonal of both sides $\angle A = \arctan(25.7/26.2) = 44.45°$, closing to the angle of a square; the central body stonewall is 23.4 meters long, 22.8 meters wide, the angle is the same as the outer layer, 44.45°; the rammed earth terrace of the inner layer is 16.5 meters long and 14.5 meters wide, also, the angle $\angle A = \arctan(14.5/16.5) = 41.309°$.

If we divide the north-western gate tower into two equal parts, since the original outer frame width is 25.7 meters, half will be 12.85 meters, and the length is 26.2 meters, with the angle formed by the diagonal and the east and west sides measuring $\angle A = \arctan(12.85/26.2) = 26.126°$; the inner frame is 16.5 meters long, so half will be 8.25 meters, and the width is 14.5 meters, so the angle $\angle A = \arctan(8.25/14.5) = 29.638°$. With such a measurement, even though the Shimao high priests also divided the north-western gate tower into two parts, namely the northern and southern parts, and they stood at the midpoints of the eastern and western sides of the inner and outer frames to observe the sunrise and sunset azimuths on the days of summer and winter solstice, their results would not have been satisfactory.

The outer protective stone wall of the south-eastern gate tower is 26.7 meters long, 17.2 meters wide, $\angle A = \arctan(17.2/26.7) = 32.789°$; the central body stonewall is 25.3 meters long, 15.1 meters wide, $\angle A = 30.83°$; the rammed earth terrace in the inner layer is 16.6 meters long and 8.4 meters wide, $\angle A = 26.841°$.

Although the structure of the two gate towers is similar to the altars at Liangzhu sites, there was no correlation with sky watching or time-determination.

However, not only was the structure of the two gate towers quite standardized, but the alignment of the exterior facades also was quite accurate. According to archaeological discoveries of capital cities from the late Neolithic to the Xia, Shang and Zhou Dynasties, most architecture lacked standardization and precision, such as alter No. 2 at Chengtoushan, Li County in Hunan Province (Cultural Relic Institute of Archaeology of Hunan Province 2003; Institute of Archaeology, CASS, 2003); the No. 2 palace site in Shixianggou Village, Erlitou stage III (Institute of Archaeology, CASS, 1999); the No. 16 rammed-earth building site at the Shang capital in Zhengzhou City (C8G16) (Cultural Relic Institute of Archaeology of Hunan Province, 1983); No.5 and No.6 palace sites of the Shang capital in Yanshi City (Chang, 2010; Henan Task Force …, 1985; 1988); the northeast temple area in Xiaotun Village of the Yin Site in Anyang City (Anyang Task Force …, 2001; Institute of Archaeology, CASS, 1994; 2010); Group A and Group B palace sites at Fengchu Village in Qishan County, Zhouyuan (Chen, 1988; Fu, 1981; Zhouyuan Archaeological Team of Shaanxi, 1979); and Fufeng Zhaochen F3, Yuntang F1 and other sites (Zhouyuan Archaeological Team of Shaanxi, 1981).

Unfortunately, very few Chinese scholars discuss the measurement, alignment, positioning and other technical issues of the architecture, not to mention the cosmological and astronomical belief systems imbedded within them. As for the urban planning of the Mayan civilization in Central America, as long as the structures were religious and ritual in nature, they would be considered and planned carefully in advance by Mayan high priests (Freidel et al., 1993). Such kinds of urban planning would include precise measurement, alignment and positioning. The nature of Shimao City would not be different from that of Mayan city states. Besides, the architectural standard, degree of precision and regularity of the East Outer City Gate of Shimao were all comparable to those that prevailed during the later Xia, Shang and Zhou Dynasties in China.

Before discussing whether or not Shimao people carried out a certain degree of consideration and planning before constructing such a huge urban center, a question first arises just by looking at the two gate towers. How could Shimao stone-masons built a city gate with such precise directions and regular structures without making a series of measurements for their orientation and positioning? When compared with modern engineering designs, we can see that it was basically impossible to finish a building with such a precise and regularized structure without using the above-mentioned procedures and establishing at least one plane coordinate system. Therefore, we believe that the Shimao high priests must have developed the above-mentioned procedures before designing this masonry gate.

The second question revolves around the fact that people living during the Shimao era did not have the compass or an azimuth-measuring instrument. But just like the ancient Egyptians who built the pyramids, the first step for the Shimao high priests in planning the capital would have been to establish directions using a form of sighting instrument and appropriate methodology (see Clarke and Engelbach, 1990). Otherwise, it would not have been possible to build three tiers of long and enclosed masonry walls and the gate with such precision. What were the sighting instrument and methodology used by the Shimao high priests?

Modern scientific studies show that it is impossible to identify directions based on objects on the ground. Even nowadays, if one strays into a deserted wilderness or a forested mountainous area and does not know the stars, the result can be devastating. During ancient times, the only way to identify direction relied on observations of the Sun, the Moon and the stars. There are only two ways to identify alignment by observing the sky: one is to identify the approximate east-west direction by using sunrise and sunset patterns, while the other, more reliable way, is to identify the north-south direction using Polaris (Xi, 2001). Based on literary records and archaeological material, we know that ancient people successively established three levels of calendars that were based on phenology, the stars, and the Sun and the Moon, which they gradually developed until they could accurately identify different directions and measure time. It is safe to assume that the Shimao high priests could not have built such a precise and regularized East Gate if they had not possessed this knowledge.

3.1.2 Measuring Instruments and the Methods of the Shimao High Priest

What is gnomon shadow measurement, and what what are its areas of application? The *Zhou Li·Kao Gong Ji* records clearly:

> When designing a capital, a great designer shall first find a horizontal plane, and then, erect a vertical gnomon with a plumb bob.

This method measures the solar shadow during the day and tracks of the Pole Star at night to determine due east, west, north and south directions. Obviously, gnomon shadow measurements were used to establish the rectangular plane coordinate systems that were employed to construct Chinese capitals in ancient times. As for this method, Li Jie (1103) from the Earlier Song Dynasty (CE 960–1127) gives a clear description in his *Yingzao Fashi* (*Standard Forms and Methods of Architecture*):

> The method of identifying directions: first, set a round board at the center of the site, facing the Sun, with a diameter of 1.36 feet [1 Song feet ≈ 31.2 cm]. Then, set up a gnomon in the center, with a height of 0.4 feet and diameter of 0.01 feet. Draw the end of the gnomon shadow and record the shortest shadow. Then, use a dioptra on it to determine the due four directions by the Sun's shadow. The dioptra is 1.8 feet long, with sides measuring 0.3 feet. Open two round holes at both ends of the dioptra, with diameters of 0.05 feet. At the middle points of the outside, a shaft is installed between the two vertical cheeks measuring 3 feet from the shaft to the ground, with a thickness of 0.2 feet. When using it in the day time, place the dioptra pointing south to let the Sun shines through it to the north. When using it at night, put the dioptra pointing north, look from the south through the two holes to see Polaris. Then, release a plumb bob from each hole and mark the center of the two holes of the dioptra on the ground to denote the directions of north and south, after which the four directions will be aligned correctly.

Ancient literature from the Zhou Dynasty to the Song Dynasty shows that

> The meridian was derived from a gnomon, which is used to measure the length of the sun's shadow and probably the oldest among all astronomical instruments. Observers faced towards due south to measure the sun's shadow during the period of Wu (time from 11 a.m. to 1 p.m.), and faced due north to observe the upper culmination and lower culmination of circumpolar stars passing the meridian during the period of Zi (time from 11 p.m. to 1 a.m.) (Chen, 2003: 140).

In other words, initially identify the directions of east and west by observing the sunrise and sunset during the daytime, and the directions of north and south by observing Polaris during the night.

Why were the Shimao high priests initially unable to identify directions? The reason is that when they began to measure the Sun's shadow during the day time, it was impossible for them to know whether the Sun was in the due east-west direction, namely above the equator (vernal equinox or autumnal equinox). Therefore, they had to take measurements during one complete tropical year (365¼ days) and then make several years of repeated corrections in order to follow the shadow to the two furthest ends of north and south, which were the sunrise and sunset projections when the Sun was at the Tropic of Capricorn and the Tropic of Cancer during summer and winter solstices. Connecting the two projection points at the furthest ends of north and south and taking the middle point, allowed them to identify the due east and west directions.

Similarly, the ancients encountered a complicated problem while measuring the direction of Polaris at night, because during the long period of time from the late Neolithic Age to the Xia, Shang and Zhou Dynasties, there was no bright star at the North Celestial Pole, except for *Zuò-shū* (*Edasich*), meaning the Left Pivot, and *Yòu-shū* (*Thuban*), meaning the Right Pivot, around 6000 years ago. Therefore, when they later measured Polaris, the ancient ancestors had to use the Big Dipper which was ~10° from the North Celestial Pole, and was circumpolar. In the course of a tropical year it circled the Pole and formed the so-called 'North Pole Xuanji' (the dish-like circle that Big Dipper forms during its circulation). By measuring the four extreme points that the North Pole Xuanji encloses during the summer and winter solstices, the ancients were able to adopt the same method for taking the central point to get the due north and south directions. This is the method of gnomon shadow measurement recorded in the *Zhou-Bi* (*Circumference and Gnomon*), the earliest code about East Asian astronomy and related mathematical and geometrical approaches, which was written around 200 BCE.

The regularized structure of the East Gate and the precise alignment of the doorway show that the Shimao high priests had totally mastered the method of gnomon shadow measurement, which was the first scientific measuring milestone in the history of human civilization. Modern people must use modern engineering instruments to establish a rectangular plane coordinate system or a space rectangular coordinate system, but people in ancient times used the gnomon shadow measurement method to establish a similar coordinate system. Using this method not only allowed identification of the five directions for the construction of capitals including the ancestral temple, palaces, walls, gates and other large and important buildings, but also the rectangular plane coordinate system composed of x-axis (horizontal axis), y-axis (vertical axis), and even z-axis (standing axis) for designing buildings. It is safe to say that the Shimao high priests could not have designed and constructed the precisely-aligned gate towers and doorway without having first established a precise coordinate system.

3.2 *Archaeoastronomical Study on the Structure of the Gate Tower*

3.2.1 The Astronomical System of the Shimao High Priests

Why were the dimensions of the two gate towers of the East Outer City Gate so different? Was this caused by the measuring or building skills of the Shimao high priests?

From the precise and regularized standards of the gate tower, it is clear that the Shimao high priests had the ability to design and construct elaborate structures, including ancestral temples, palaces, walls, gates, etc., whose alignments were consistent with their astronomical knowledge and belief systems. Besides, according to common sense, there should have been towers on top of the gate, so from the perspectives of practicality and aesthetics the structures and sizes of the two gate towers on both sides should not have been very different, even allowing for construction errors or even mistakes. Thus, the answer to the afore-mentioned question was certainly 'no'. Like the Liangzhu people, who apparently ignored common sense and chose to erect their holy capital, Pingyao, on low-lying marshland, the Shimao high priests must have had good reason to build two gate towers that were totally dissimilar in size. What was their motivation?

As we have already shown, the doorway of the East Gate and exterior facades of the gate towers were facing the sunrise azimuth angle of the summer solstice 4200 years ago. That is to say, before starting to build the East Gate, the Shimao high priests had already determined the date of the summer solstice and the sunrise azimuth angle and should have believed that the summer solstice was the most important day for people in Shimao. The recreated astronomical sight back to 4200 years ago shows that, when the Shimao people started building their capital, the Sun arrived at the summer solstice point between two mansions, Xingxiu (the star α Hya) and Zhangxiu (the extended net, υ^1 Hya) on 14 July, with Regulus (α Leo) located at right ascension 90° (see Fig. 6).

That is to say, that was the date when the Sun was exactly at the Tropic of Cancer 4200 years ago, and when the sunrise azimuth angle was about (N-E) 58° 25′. Obviously, the Shimao high priests knew this day and this angle.

At the beginning of construction of Shimao City, the Sun arrived at the vernal equinox from the southern hemisphere on 11 April, moved to the celestial equator and circulated in Zhongheng (the Sun's orbit of the equinoxes) raised by the Gai Tian (hemispherical dome) hypothesis in Zhou-Bi, where the Mao Mansion (the Pleiades and η Tau) was located. The Sun then headed north and reached the summer solstice on 14 July, moved to the Tropic of Cancer directly and reached Neiheng (the Sun's position at the summer solstice), where the

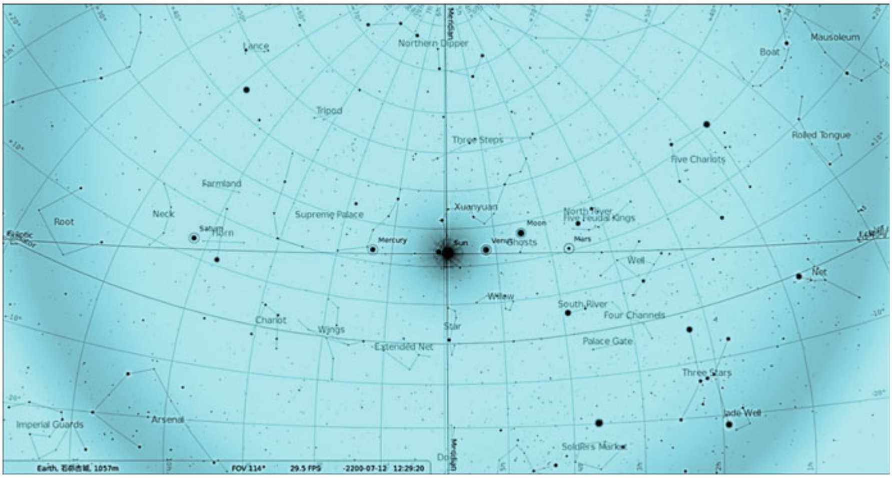

Fig. 6 The symbol stars of the summer solstice as seen by Shimao highest priests on 12 July 2200 BCE. (Source: Stellarium)

Xingxiu Mansion was located. The Sun then returned to the autumnal equinox and moved to the equator and Zhongheng again on 12 October, where the Fang Mansion (Room, δ and π Sco) was located. Finally, the Sun then headed south and reached the winter solstice on 9 January, then moved directly to the Tropic of Capricorn and Waiheng (the Sun's place at the winter solstice), where the Wei Mansion (Rooftop, ε and θ Peg, and α Aqr) was located.

Since the Shimao high priests had accurately obtained the date of summer solstice and the solar azimuth angle, they should have been able to determine the three remaining dates, namely the two equinoxes and the winter solstice, and their related solar azimuth angles, as well as the mansions and equatorial constellations that symbolized these four dates. It goes without saying that the Shimao high priests knew specific stars and asterisms e.g. stars culminating at dusk during the summer solstice, and the Wei Mansion during the winter solstice. East Asians in the Late Neolithic age, including the Liangzhu people who lived on the Pacific Coast, had been practicing their traditional cosmology and they used imperial and ritual buildings to simulate the symbolic constellations in the sky to resemble their ideal Holy City of Heaven here on Earth (see Cultural Relic Institute of Archaeology of Zhengjiang Province, n.d.). That is to say, the Shimao high priests may have used the East Outer City Gate that faced towards the sunrise azimuth angle on the summer solstice to simulate the symbolic constellation of the summer solstice. If the above assumptions are verified, this may explain the puzzle about the special shape and structure of the East Gate at Shimao city.

3.2.2 Cosmology of the Shimao High Priests

Back 4200 years ago, the Shimao high priests noticed that the Xu Mansion (Emptiness, α Equ and β Aqr) and the Wei Mansion were located between modern-day right ascension 263° and 276° and declination −15° and −1°. The two mansions, which were to the east or west of the winter solstice (right ascension 270°), rose above the eastern horizon in the morning at the winter solstice and became the best option to mark the winter solstice. Apart from them, there were two other slightly more distant symbols, the Shi Mansion (Encampment, α and β Peg) and Hégŭèr (the River Drum, Altair, α Aqr).

The Shi Mansion was located between right ascension 292° and 295° and declination −2° and 10°, facing the winter solstice at 25° south-west. Hégŭèr, Alshain (β Aqr) and Tarazed (γ Aqr) was located between right ascension 244° and 246° and declination 6° to 10°, facing the winter solstice at 24° southeast. Hégŭèr was the predecessor of the Niu Mansion (Ox, Dabih, β Cap). Therefore, the Xu and Wei Mansions, as well as the Niu and Shi Mansions were the constellations around the winter solstice on the celestial equator throughout the Longshan period (4500–4000 BP). This was the ancient scientific basis for later Chinese astronomy taking the Niu, Xu, Wei and Shi Mansions as the center of the Beigong (North Palace).

In East Asian cosmology, the constellation at the winter solstice was closely related to the North, death, funerals, etc., which became the prototype of the Xuantang (the Winter Chamber) in the ancient Mingtang (Imperial Palace) architectural system. Therefore, the *Shiji Tianguanshu* (*Records of the Grand Historian: Book of Celestial Offices*) records:

> Xu and Wei, Wei is the rooftop of the house; Xu is for mourning and crying.··Yingshi is the imperial ancestral temple of the heavens which is also called Li Gong [Resting Palace, η–υ Peg etc.] and Ge Dao [Express Way, Ruchbah, δ–υ Cas etc.].

Meanwhile, the *Book of Jin·Astronomical Treatise* has a more detailed record:

> The Xu Mansion's two stars [α Equulii and β Aquarii] are the Minister of burials and the cemetery, in charge of things concerning sacrifices and benediction in temples of towns in the north, as well as crying and mourning at deaths. The Wei Mansion's three stars [ε and θ Pegasii and α Aquarii] take charge of building houses in heavenly mansions and markets; the remaining things are the same as the astrology of the Xu Mansion.··Yingshi's [Shi Mansion, encampment] two stars [α and β Pegasi] are palaces for God's son; one is called the Winter Palace, and the other is called the Imperial Ancestral Temple, taking charge of food supplies for military and civil works. When the star was bright, it meant the country would be prosperous; when the star was small and dull, it meant that the ghosts and gods did not accept the sacrifice.

The contents of the *Book of Jin·Astronomical Treatise* are rather abstruse and hard to understand. The *History of Song·Astronomical Treatise* gives a clearer explanation:

> Yingshi's [Shi Mansion's] two stars were heavenly palaces; one was called the Winter Palace, the other was called the Imperial Ancestral Temple, in charge of food supplies for military and civil works. One of the Shi Mansion stars is the Emperor's palace, the other is the Imperial Ancestral Temple, which is the barn for the King's military, that required the setting up of Imperial Guards to defend them; there are also Li Gong [Resting Palace, η–υ Peg etc.] and Ge Dao [Express Way, Ruchbah, δ–υ Cas etc.], so the six stars of Ligong were around Yingshi.

In short, this meant that the Xu, Wei and Shi Mansions were the core of the North Palace that symbolized the North Chamber of and localities at the Royal Ancestral Temple—the Mingtang. The North Palace took care of death, so it was responsible for sacrifices, benediction, death, funerals and mourning. Why did the people come up with such an understanding? *The Book of Rites·Records of Yin Yang in Mingtang* records that the Emperor used the Yin and Yang of the Mingtang (Imperial Palace) to respond to the seasonal changes of heaven.

This building complex was surrounded in a clock-wise direction by a waterway, symbolizing the rotation of the circumpolar stars, and in the center was the Imperial Palace (which symbolized Zi Gong, i.e. Ziwei Yuan, meaning the Purple Forbidden Enclosure). The Mingtang (the Summer Chamber) was located on the south side, symbolizing Taiwei Yuan, the Supreme Palace enclosure (Virgo, Coma Berenices, Leo and Virgo). The Zongzhang (the Autumn Chamber) was located on the west side, meaning Wuhuang (wǔchē), symbolizing Five Royal Chariots (α Aur, etc.). The Xuantang (the Winter Chamber) was on the north side, symbolizing Yingshi (as above). The Qingyang (the Spring Chamber) was on the east side, meaning Tianshi Yuan, symbolizing the Heavenly Market Enclosure (Hercules, Serpens, Ophiuchus and Aquila). God managed the four seasons in respective palaces. The Emperor followed God's way in governing all things on Earth, and he also listened to the state affairs in respective chambers.

This paragraph explains that the Mingtang was divided into five rooms (the East, South, West, North and Center); the Center Room was known as the Imperial Ancestral Temple, corresponding to Ziwei Yuan (the Purple Forbidden Enclosure), which was the Central Palace of Gouchen (Polaris, α UMi). The eastern chamber was called the Qingyang (the Spring Chamber), corresponding to Tianshi Yuan (the Heavenly Market Enclosure), which was located at the same right ascension as the Fang Mansion (Room, π Sco) and the Xin Mansion (Heart, Antares, α Sco) in the autumn equinox. The southern chamber was called the Mingtang (the Summer Chamber), corresponding to Taiwei Yuan (the Supreme Palace Enclosure), which was located at the same right ascension as the Yi Mansion (Wings, α Crt) and the Zhen Mansion (Chariot, γ Crv) in the summer solstice. The western chamber was called Zongzhang (the Autumn Chamber), corresponding to Wuche (α Aur), which was located at the same right ascension as the Bi Mansion (α Tau) at the vernal equinox. Finally, the northern chamber was called Xuantang (the Winter Chamber), corresponding to the Shi Mansion (the Encampment, α Peg) in the winter solstice.

Such relationships show that the Mingtang was the etiquette building that corresponded to the symbolic constellations of the North Celestial Pole, the equinoxes and the solstices. As a result, the Emperor could imitate God by establishing laws and regulations, by preserving an attitude of neutrality, by observing celestial phenomena in order to determine time, and by listening to the civil affairs happening throughout the country during the four seasons. These records provide a literature basis for the nature, structure and function of the East Outer City Gate. The winter solstice was located in the middle of the Xu Mansion and the Wei Mansion at the beginning of the construction of Shimao. Then, when was the winter solstice located at Yingshi? Refer to Fig. 7.

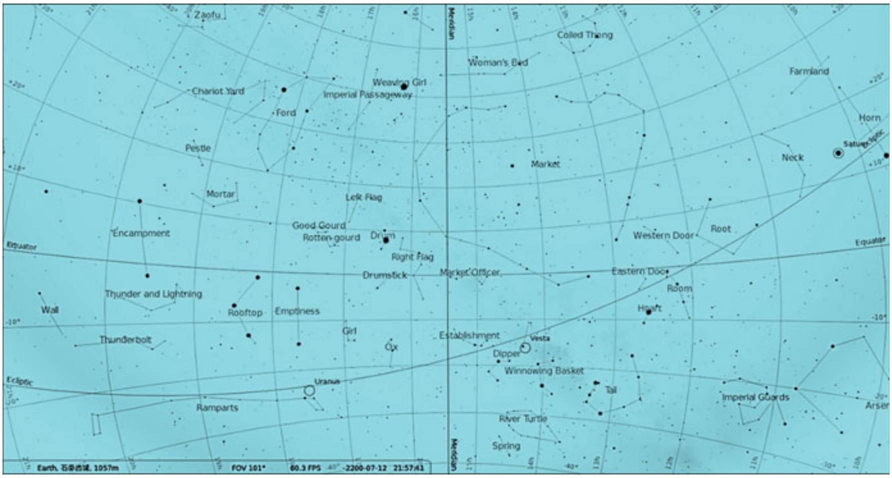

Fig. 7 The Xu (Emptiness) Mansion, Wei (Rooftop) Mansion and Shi (Encampment) Mansion as viewed from 9 p.m. to 11 p.m. at the Summer Solstice during the Shimao era. (Source: Stellarium)

Yingshi is composed of Shi Mansion I (Encampment, α Peg) and II (β Peg). Shi Mansion I is on the south side and II is on the north side of the celestial equator, symbolizing an entrance building on the celestial equator. Therefore, they are called Tianque (heavenly gate tower) or Tian-men (heavenly entrance), which are the sixth mansion of the North Palace (Black Tortoise). Shi Mansion I and II reached the winter solstice in 6368–5974 BCE (right ascension 270°), 1200 years earlier when the Xu and Wei Mansions reached the winter solstice. The *Book of Rites Yue Ling* (*Monthly Government Decree*) has no record of the Shi Mansion, but does mention the Bi Mansion:

> In the midwinter, the sun is located at Dou Mansion [South Dipper, α Sgr]; the culminating star at dusk is Bi Mansion; in the morning, the culminating star at dawn is Zhen Mansion [Chariot, γ Crv].

The Bi Mansion was located at 15° south-east of the Shi Mansion. The time that it arrived at the winter solstice was far earlier than that of the Yingshi. *Zhou Li·Kao Gong Ji·Zhouren* records, "Turtle-and-snake soaring in four directions symbolizes Yingshi." The *Zheng Xuan* said: "Yingshi, also called Xuanwu Xiu (Black Tortoise), form four stars with Bi Mansion." Yang-jiong from the Tang Dynasty said on the Shao-shi Mountain Shaoyi Temple Monument, "Taiwei (Supreme Palace Enclosure) Yingshi (Encampment, α Peg) is Mingtang (Imperial Palace) for delivering governmental decrees." That is to say, the ancients also regarded Yingshi as the northern chamber of the Mingtang-Xuantang (the Winter Chamber). It shows that even in the period from the Warring States to the Han Dynasty when the Shi Mansion had moved far away from the winter solstice, the ancients still maintained a distant memory of the cosmological tradition that Yingshi was the symbol of the winter solstice from a very long time ago.

3.2.2.1 The Wei Mansion

The Wei Mansion (Rooftop) is composed of Wei Mansion I (α Aqr), II (θ Peg) and III (ε Peg), which are called the “Wei Mansion (Rooftop) Three Stars”, and is the fifth mansion of the Northern Palace. The Wei Mansion, the easternmost point of Wei Mansion II (θ Peg) and the western-most point of Wei Mansion III (ε Peg) had pas-sed the winter solstice between 4755 and 4430 BCE, which is 1200–1500 years later than in the case of the Shi Mansion.

The *Yue Ling* (*Monthly Government Decree*) records:

> In the midsummer, the sun is located at the East Jing Mansion [Well, μ Gem], the culminating star at dusk is Kang Mansion [Neck, α Vir), the culminating star at dawn is Wei Mansion [Rooftop, α Aqr].··in the first month of winter, the sun is located at Wei Mansion, the culminating star at dusk is Wei Mansion, the culminating star at dawn is Xing Mansion [Star, α Hya].

Obviously, people of the Warring States period regarded it as the symbol of the summer solstice and early winter. The shape of the three stars of the Wei Mansion was just like a rooftop, so it referred to the beam frame of the upper layer of a house. Therefore, Shiji Suoyin quoted from *The Book of Rites*: “The mansion in the center is covered by high rooftop (Wei Mansion), so as-cend to the roof to avoid war hazards.” The *Shiji·Book of Celestial Offices* records: “Wei Mansion (α Aqr) is related to building of houses.” while *the Book of Jin·Astronomical Treatise* says that the Wei Mansion “. . . is in charge of con-structing houses in heavenly mansions and mar-kets . . .” Thus, it can be seen that the Wei Mansion actually refers to the beam frame and roof of the Xuantang (Winter Chamber).

3.2.2.2 The Xu Mansion

The Xu Mansion (Emptiness) is composed of Xu Mansion I (β Aqr) and Xu Mansion II (αEqu), which are called “. . . Xu Mansion (Emptiness) two stars . . .” and is the fourth star and center of the North Palace (Black Tortoise). The Xu Mansion two stars are basically on the same right ascension. The two stars reached the winter solstice 3823 and 3802 years ago respectively, which was 600–900 years later than the Wei Mansion. The *Book of History·Yao Dian* (*Yao's Code*) records, “When nighttime equals daytime, the culminating star at dusk is Xu Mansion. That proves the arrival of mid-autumn.” It means that at dusk during the autumn equinox, the Xu Mansion was close to upper culmination. Furthermore, the *Yue Ling* (*Monthly Government Decree*) records:

> In the last month of autumn, the Sun is located around the Fang Mansion [Room, π Sco], the culminating star at dusk is Xu Mansion while the culminating star at dawn is Liu Mansion [Willow, δ Hya].

This means that in the last month of autumn (about the period from the Cold Dew to Frost's Descent), the Xu Mansion was at upper culmin-ation at dusk. Both mid-autumn and the last month of autumn took the Xu Mansion as the symbol of the culminating star at dusk, the interval between them being 1 month. From the recreated astronomical chart, if the descript-tion of the *Yue Ling* (*Monthly Govern-ment De-cree*) was based on the astronomical sight on the day of Frost's Descent (13 October) around 400 BCE (the early period of Warring States), then the description of Yao Dian (Yao's Code) should belong to the time from late the Long-shan period (2300 BCE) to early Xia Dynasty (2000 BCE) (see Biot, 1862; Chu, 1926; de Saussure, 1907; Liu, 1930), which was about the time when Shimao City was constructed. No matter what period it belonged to, people in the Warring States period regarded the Xu Mansion as the symbol of autumn, containing within it the meaning of dying and chilly senses. Therefore, the *Er Ya·Shi Tian* (*Handbook of Celestial Ob-jects*) records:

> The symbol constellation of Xuanxiao (Empti-ness) is the Xu Mansion ... [and this] Mansion is in the due north and the color of the north is black; Xiao means consuming, consuming also means emptiness.

Therefore, Xuanxiao is referred to as the dark ruin in the far north, namely Xuantang. As a result, the *Book of Jin·Astronomical Treatise* names it the Minister of state, taking charge of things concerning capital residences, sacrifices and benediction in the palace that relate to Ming-tang (Summer or Bright Palace).

3.2.3 Which Mansion Did the East Gate Simulate?

Among East Asian ancestors, the Shi Mansion (Encampment, α Peg), Wei Mansion (Rooftop, α Aqr) and Xu Mansion (Emptiness, β Aqr) were the symbolic constella-tions of the winter solstice during the Late Neolithic age. Among them, the Shi Mansion was the symbol of the winter solstice in the early stages of the Yangshao Culture era (7000–5000 BP); the Wei Mansion was the symbol of the winter solstice in the middle stages of the Majiayao Culture era (5000–4000 BP); and the Xu Mansion was the symbol of the winter solstice in the middle stages of the Xia Dynasty (c. 3,800 BP). However, the constellations between the Wei and Xu Mansions were the symbols of the winter solstice in the early construction stages of Shimao City.

From the perspective of traditional East Asian astronomy, high priests tended to observe the constellations appearing on the eastern horizon, at culmination and on the west horizon at dusk at the times of the equinoxes and the solstices, as the symbols for them. During the summer solstice 4200 years ago, if the high priests sought the constellations with the naked eye at dusk, they had to wait until 20:40 p.m. when the Sun was 8° below the horizon. At this moment, the Wei Mansion (α Aqr) and Xu Mansion (β Aqr) were located between the eastern horizon and culmination, which complied with observational tradition. And at that time, only the Shi Mansion (α Peg) was located on the eastern horizon. Therefore, from the perspective of the Shimao high priests, although the Wei and Xu Mansions were the symbolic constellations of the winter solstice, the Shi Mansion complied most with the requirements according to the standards of appearing at dusk.

The structure of the East Outer City Gate of Shimao is complex. From the perspective of architect, first there was an outer barbican to the north-eastern part of the two gate towers which formed an angle of 90° with the doorway and turned to the south-east, with sacrificial pits placed inside and outside. In addition, there was an inner barbican that also formed an angle of 90° with the doorway but turned to the north-west, and contained murals with geometric patterns painted on the inner wall. This shows that both the outer and inner barbicans had high-grade etiquette functions. Secondly, the gate tower on the northwest side was a square with each side around 26 meters long, but the size of the gate tower on the south-eastern side was reduced by nearly a half. The scale of the north-western gate tower was more magnificent, but the size of the south-eastern gate tower complied more with the observational standards at the time when the ancient city of Shimao was constructed. This shows that the Shimao high priests might have thought that the south-eastern gate tower complied more with the observational requirements, but was too small to hold ceremonies, so they built the north-western gate tower nearly double the size of the south-eastern gate tower.

From the perspective of astronomy, the special structure formed by the two gate towers of the East Gate and the outer and inner barbicans looked just like the house with its roof composed of the Wei Mansion three stars and the Xu Mansion two stars, facing towards the north-east (see Fig. 8). Furthermore, the Wei Mansion I star (α Aqr) had an apparent magnitude of 2.95, which was second only to the Xu Mansion I star (β Aqr). Meanwhile, the orange-hued Wei Mansion III star (ε Peg) had an apparent magnitude of 2.4. Obviously, Wei Mansion III looked brighter than I, and in addition was orange-red in color. If Shimao high priests used the north-western

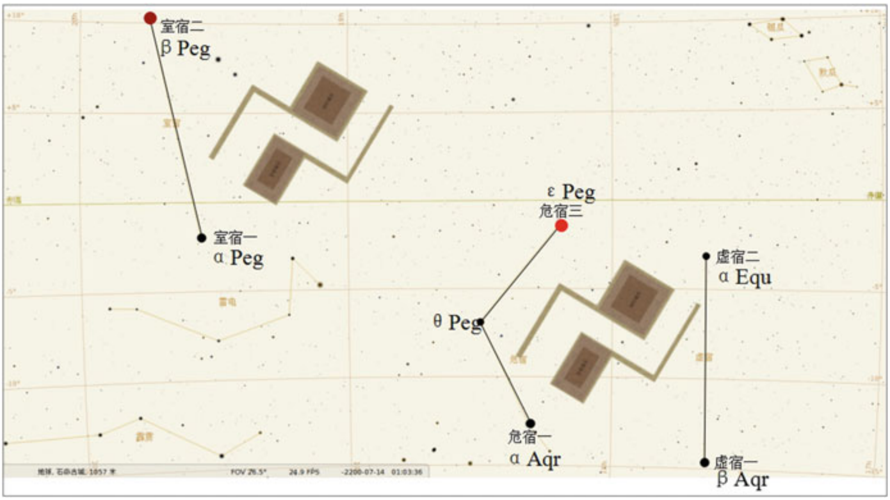

Fig. 8 Comparison of the astronomical sights formed by the Shi, Xu and Wei Mansion from the Outer City East Gate. (Diagram: Lyu Yufei)

gate tower to simulate Wei Mansion III (ε Peg) and the south-eastern gate tower for Wei Mansion I (α Aqr), then the structure of the East Gate is understandable.

If we only focus on the two gate towers, their structure also had something in common with the Shi Mansion. The Shi Mansion II star (β Peg) was a red giant. Its volume is 95 times greater than that of the Sun, its brightness is 1500 times that of the Sun and its apparent magnitude is 2.40 (although, of course the ancient Chinese knew none of this). Meanwhile, the Shi Mansion I star (α Peg) was a Main Sequence star with an apparent magnitude of 2.45. We know that bright red stars received special attention from prehistoric East Asian astronomers. There was at one time a first-class giant red star located exactly at the autumnal equinox during the Liangzhu Civilization (5300–4300 BP). This marked the arrival of the vernal equinox, drew much attention from the Liangzhu high priests and became the core of the Liangzhu calendar. That was the Xin Mansion II star Antares (α Sco), commonly known in ancient East Asia as ‘Big Fire’. Xin Mansion II always had the same supreme status as the Big Dipper in East Asian astronomical systems. It was called ‘大辰 (Da Chen: The Greatest Star)’, and regarded as one of the Three-Chen. Since the ancients thought that it was the ‘Lord of Time’ and the ‘Lord of Season’, like the Big Dipper, it became one of the dual-cores in East Asian astronomical systems as well as the core of the ‘Fire Calendar’—an ancient constellation calendar based on the Great Fire (Xin Mansion II, α Sco) (see Cultural Relic Institute of Archaeology of Zhengjiang Province n.d.).

The ancients also believed that Xin Mansion II marked the ‘Vision of Daytime’ from spring to summer, and symbolized the arrival of brightness. It became the astronomical and cosmological origin of the Mingtang (the Summer Chamber or Bright Chamber)—the core of the Chinese royal ritual system and the imperial palace and temple architecture based on East Asian astronomy and cosmology from prehistoric times through to the Xia, Shang and Zhou Dynasties.

The ancients often used red and pyromancy to signify the Big Fire. Did Shimao high priests use the East Gate to simulate the Shi Mansion and to symbolize Xuantang—the Northern Chamber of the Mingtang, or adopt a similar color description and carry out ritualistic activities for the ‘Small Fire’—Shi Mansion II (β Peg)? The remaining red-based murals in the inner barbican and the pyromancy sites around the East Gate are worthy of further research.

4 The Puzzling Sacrificial Pits of the East Outer City Gate

4.1 An Archaeological Study of Human Sacrifice and Decapitation Sacrifice

From the perspective of East Asia, large-scale human sacrifice rituals were concentrated from mid-west to northwest, namely in the circle of archaeological cultures of the upper and middle reaches of the Yellow River. From a chronological perspective, human sacrifice rituals appeared in the early part of the Yangshao Culture (7000–5000 BP) during the Late Neolithic era, became popular in the last stage of the Qijia Culture, and lasted until the Shang Dynasty.

Human sacrifice involved the most solemn sacrificial ceremonies in some nations and reflected that there were seriously hostile nations and a lot of large-scale ethnic conflicts and wars during this era throughout the region. This led to looting and the capture of large numbers of slaves from alien races and foreign nations, which was accompanied by widespread killing and human sacrifice. Although behaviour like this was brutal, it was the highest ritual expressed to the souls of ancestors, as well as the highest sacrifice to the nation and the nation's supreme God. Its purpose was to pray for the well-being of peoples and nations, eliminate disasters, consolidate the monarchy, and unify the world. According to the *Shuo Wen Jie Zi* (*Dictionary*, written in AD 100), "Ritual, daily personal practice, people sacrifice to God with ritual and ask for well-being."

Starting from the late Yangshao Culture, the ethnic conflict in the upper reaches of the Yellow River gradually intensified, and this was reflected in human sacrifices. The No. 1 house at Xi'an Banpo Ruin was located in the center of the settlement, and with the largest area and a central hearth it must have been the ceremonial center for members of the settlement. There,

> On the lime layer under the south wall, a human skull was discovered, and a broken coarse pot was discovered near the skull. (Institute of Archaeology, CASS, 1963: 18).

This appears to be evidence of the early human decapitation sacrifice left over from the ritual cornerstone-laying ceremony at this settlement.

During the Longshan period, the Yellow River valley became a killing field between indigenous tribes and immigrants, and between nations from the east and west of East Asia. Human and decapitation sacrifices became more common and occurred on a larger scale. There were pits with human skulls at the Longshan Culture house sites at Shuang'an Village, Qishan County, Shaanxi Province, which were the result of human and decapitation sacrifices during corner-stone-laying ceremonies. The use of adult and child sacrifices in house foundations, wall bases and on the insides and outsides of walls was a phenomenon that reflected not only the ritual customs practiced at this time during house construction, but also the ongoing social conflicts in this region (Li, 1981).

In the Qijia Culture cemetery at Qinghai, headless burials and amputated limb burials were more prominent. In those tombs of the Qijia Culture in Liuwan cemetery, Ledu County, Oinghai Province, a considerable number of tombs had incomplete skeletons (Archaeological Team . . ., 1984). The Shimao site dated to the same era as the Qijia Culture, and the sacrifice pit at the East Gate by and large reflected the environment of the time.

The main sources of large-scale human sacrifices in the upper and middle reaches of the Yellow River were young men and women from alien races or nations. Tortoise plastron and ox scapulae from the Shang Dynasty contain more than 1350 pieces relating to human sacrifice, among which over 1990 pieces were associated with human sacrifice divination. The total number of recorded human sacrifices was 14,197, which included 7426 from the

Qiang race (Hu, 1974). The variant ideographs of 'Qiang' described this race as "… the upper half of the character was a goat, and the lower half was a woman …" (Zhao, 2009:164), namely 'Jiang' in Chinese, which means "… the shape of a woman with ram's horns on her head, referring to the women prisoners from the Qiang race who were captured." (Zhao, 2009: 185). Thus it is clear that 'Qiang' on plastron refers to men and 'Jiang' refers to women. Using people of the Qiang race for sacrifices was referred to as 'Qiang sacrifice' in the oracle. Such sacrifice was divided into two sub-categories: one was 'human sacrifice', which used Qiang or Jiang for the sacrifice, and the other was 'body sacrifice', which used specific body parts of Qiang or Jiang for the sacrifice (such as the skull, torso, limbs, etc.) Those who were going to be sacrificed were killed by decapitation, burying or chopping; decapitation was the most common method (Wangen, 1983). Jiang often were used as sacrifices to ancestors and river gods (Wang, 2007). The sources and killing methods of the human sacrifices found at the Shimao Site were similar to those described above.

Human sacrifices of people from alien races or nations in the middle and upper reaches of the Yellow River were widely used in the ritualistic activities of cities, ancestral temples, palaces, princely tombs and gods of mountains and rivers. For example, during the laying of the cornerstone, setting of the bases, installation of doors and completion of buildings in the north of Xiaotun Village, Yin Site in Anyang City, human sacrifice ceremonies were held and some carriages, horses, humans and animals were buried in parts of the architecture. Most of the human sacrifices used in this group of Royal Palaces from foundation to completion were young men, mainly in single burials, three- or five-person burials, kneeing burials, backwards burials, decapitation burials, etc. Some of the skeletons lacked their upper limbs; some only had limb bones; some skeletons had their hands tied behind their backs while others had their hands tied to their chests; but many sacrificial burials contained only the skulls—there were no skeletons) (Anyang Task Force …, 1987). After physical examination, it was determined that the human sacrifices of Yin Site included men and women, and occasionally children. The men and women were young, mostly between the ages of 20–35 years. The sacrificed men were all decapitated, and cut at the waist, and dismembered, with their hands and feet amputated. Usually, the bodies of women and children were undamaged and were buried directly in pits.

Compared to the human sacrifices at the Yin Site, the human sacrifices near the East Gate Site at Shimao showed four distinct differences:

1. Most of the sacrifices were associated with the cornerstone laying ceremony, and very few or even zero human sacrifice were used in other building stages (e.g. only one sacrificed child was found in the completion of the northwest gate tower);
2. Mainly adolescent women, and a few men, aged between 12 and 20 were sacrificed;[3]
3. The heads were buried neatly in the sacrificial pits (e.g. see Fig. 9), while the bodies were buried separately elsewhere, or were missing (which was typical of decapitation sacrifices); and

Fig. 9 A decapitation sacrificial pit near the East Outer City Gate. (Source: Shimao Archaeological Team, Shaanxi Provincial Archaeological Institute)

4. Some of the lower jaws of these skulls were burned black, and had obviously been incinerated. That is to say, they were buried after their skin had been burned off, which was typical of burning and burying sacrifices.

How did the Shimao high priests arrange these burial pits? Why did they use mostly young women rather than young men for the sacrifices? Why were decapitation, burning and burying sacrifices held simultaneously?

4.2 A Study of the Sacrificial Pits Near the Outer City East Gate

4.2.1 An Archaeoastronomical Study of the Layout of the Sacrificial Pits

Archaeological excavations showed that K1 sacrificial pit was located to the north-eastern part of the outer barbican; K2 at the entrance of the doorway; K4 and K5 to the north-west of the first bastion, inside and along the base of the city wall; while K6 and the jade tablet were between the north-western gate tower and the first bastion. If we walk along the city wall, looking at the positions of the sacrificial pits relative to it, they spread outside and inside the city gate, outside and inside the city wall, and

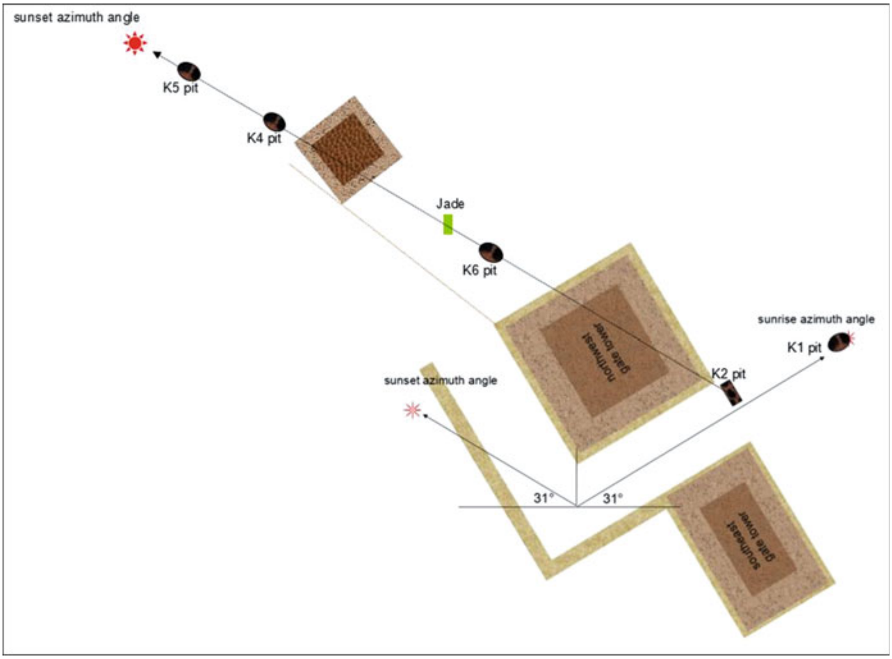

Fig. 10 Decapitating Sacrificial Pits of the East Outer City Gate Site of Shimao. (This diagram is based on data provided by the Shimao archaeological team, Shaanxi Provincial Archaeological Institute)

seem to bear no relationship to one another. However, if we take away the city walls and focus on the situation before any construction took place, the arrangement of these sacrificial pits becomes obvious (see Fig. 10). It turns out that the five sacrificial pits show a very clear alignment: K1 and K2 sacrificial pits pointed east by north 30°, and K2, K6, K4 and K5 sacrificial pits pointed west by north 31°. That is to say, the first two sacrificial pits pointed at the sunrise azimuth angle on the summer solstice (14 July) 4200 years ago just as the doorway and the exterior façade of the gate tower do; while the later four sacrifice pits pointed at the sunset azimuth angle on the same day. The city wall was built afterwards, above the sacrificial pits, winding and twisting its way along the north-western ridge.

To test the above calculations, we observed the alignment of the sacrificial pits while investigating the orientation of the doorway and gate towers of the East Outer City Gate. Although the Shimao high priests arranged for the sacrificial pits to face towards the sunrise or sunset azimuth angles on the summer solstice, the K2 and K6 sacrificial pits could not be used for observations because the K2 pit was located between the two gate towers and the K6 pit between the north-western gate tower and the bastion. Therefore, we could only use K4 and K5 as our main measuring points, and the top of the north-western gate tower as the auxiliary observation point. At the same time, we used two cameras to record the whole process of measuring the sunset.

Taking into account the fact that the north-west real horizon of the East Gate was below the hummock ridge, we chose the moment before the Sun disappeared totally below the ridge to carry out our measurements. After 4 days of actual measurements at dusk, we obtained the sunset time and sunset azimuth on 19 and 20 June 2016. On the 21st and 22nd, there were clouds in the western sky, so we could not carry out any observations. The actual process of observation was as follows: we planted a test pole in the center of the K4 pit and another one outside the K5 pit, so that the two test poles pointed at the Sun 10 min before sunset. Five minutes before sunset the test pole at the K5 pit needed to be moved to the edge of the pit so that the two poles would point at the Sun. Finally, when the Sun fell behind the north-western ridge, the test pole at the K5 pit needed to be moved to the center so that the two poles would point at the Sun.

At dusk on the 19th, after some rain, the sunset time was 20:00 and the degree shown on the geological compass was north by west 61°. At dusk on the 21st, the sky was cloudless. The sunset time was 20:00 and the degree showed on the geological compass was north by west 60°. The actual measurement showed that the K4 and K5 pits faced towards the sunset azimuth angle at the summer solstice. Since the K2, K6, K4 and K5 pits were in the same straight line, we confirmed that the four sacrificial pits planned by the Shimao high priests faced sunset on the summer solstice.

From the arrangement of the sacrificial pits, the stratigraphy revealed during the archaeological excavations, and the positions of the East Gate and city wall, we can rule out the possibility that the sacrificial pits were excavated after the city wall was built. Obviously the Shimao high priests held a grand cornerstone-laying ceremony before building the East Outer City Gate, but they did not hold any ceremony when setting the base, installing the doors or completing the building. The cornerstone-laying ceremony included the decapitation, burning and burying of human sacrifices.

Based on the above study, we can draw the following additional conclusions. The Shimao high priests had already completed at least two aspects of the systematic measurements before building the East Gate. Firstly, they had measured the date of the summer solstice and the sunrise and sunset azimuths angles in the Shimao area using gnomon shadow measurements in order to determine the equinoxes and the solstices. Secondly, they established a rectangular plane coordinate system that they used when building the East Gate. Only after the completion of a large number of measurements could the Shimao high priests excavate two rows of sacrificial pits that precisely faced towards the sunrise and sunset azimuth angles before the cornerstone laying ceremony. Then they buried the incinerated skulls, with different numbers in different pits, and completed the decapitations, burning and burying, which were the highest levels of the sacrificial ritual. This phenomenon shows that the Shimao high priests not only paid much attention to the cornerstone-laying ceremony, but they also expressed high esteem for and infinite hope in the gods of heaven and the spirits of the Earth. Only after a rectangular plane coordinate system was established was it possible for the high priests to command a large labor force and arrange the construction of the city gate, the barbicans and the bastions with such precise alignment and regularized structure.

This series of sacrificial pits proved yet again that the East Outer City Gate was indeed built to face towards the sunrise azimuth angle at the summer solstice and express the high esteem that the priests had for the gods and spirits that were in charge of the heavens, the Sun and the summer solstice.

4.2.2 Study on the Sacrificial Ritual of the East Gate

4.2.2.1 Paleographical Study of the Sacrificial Ritual

The incinerated skulls that were buried in the sacrificial pits near the Shimao East Outer City Gate illustrate an important fact: that burning was the core of the ritual ceremony that also integrated previous decapitations and later burying procedures. The connotations of the ritual were abundant.

The 'Fa' Character

The 'Fa' character is an ideogram that can be used as a verb or as a noun. It has quite a few versions in plastromancy, but the basic character form is  (stage I Former7.2.1). It is composed of 'Ren' (human) and 'Ge' (dagger). When used as a verb it means using a dagger to behead a kneeling man (Yao, 1979: 371), but when used as a noun it means the head and body of a captive awaiting a decapitation sacrifice (Huang, 2005: 28).

Another form is  (stage I Human 3053), which is composed of 'Qiang' and 'Ge' and means decapitating a man of the Qiang race. Another form is  (Later 37.7), which is composed of 'Jiang' and 'Ge' and means decapitating a woman of the Qiang race.

The *Shuo Wen* (*Dictionary*, written in AD 100) says: "Fa, means assaulting, a man carrying a dagger." while the *Guang Ya* (*Thesaurus*, written in AD 200) records: "Fa, means killing." All of them refer to an executioner.

Archaeological excavations reveal that decapitation sacrifices were a popular practice in the middle and upper reaches of the Yellow River region from the late Neolithic era to Shang Dynasty (Huang, 2004). In a decapitation sacrifice, the head, human body and human blood were sacrificed separately Gao, 1992: 14). Divination on plastrons shows that decapitating women of the Qiang race often occurred simultaneously with sacrificial rituals involving prayers for rain (Xu, 2006).

The 'Liao' Character

The 'Liao' character is an ideogram that means sacrificial burning (i.e. pyromancy), and can be used as a verb or a noun. It mainly has three versions: ,  (B8683),  (Later I 24.7). Its form and meaning in inscriptions on bronze ritual vessels eventually became ambiguous. Its form and meaning on seal characters completely broke away from its original versions recorded on plastrons and scapula.

Shuo Wen records: "燎 (Liao), means setting fire." but this is neither the original character nor the original meaning associated with tortoise plastrons or ox scapulae divination. The character which comes nearest to its original meaning of is '柴 (Chai)'. The original character from oracles of Chai is , which has a homologous relation with . *Shuo Wen·Shi Bu* (*Dictionary Divination*) explains: "Chai means setting sacrificial fire by firewood for the God of Heaven." The *Shiji·Jijie* (*Collective Interpretation of the "Records of The Grand Historian"*) quotes Sr. Zheng Xuan as saying, "Chai means a burning sacrificial fire." 'Chai', setting a sacrificial fire with firewood for the God of Heaven completely complies with the original meaning of the plastromancy, and should be the character that evolved from oracle bones. Most researchers believe it means piling up pieces of firewood and burning them (Li, 1995). It only refers specifically to sacrificial burning on altars in rituals, because not all firewood burning can be called Liao. Therefore, the *Er Ya·Shi Tian* (*Thesaurus·The Heaven*, written around 200 BCE) explains: "The sacrificial ritual for heaven is called Fan Chai (burning sacrificial firewood)." Liao refers to sacrificial fire for the God of Heaven by burning firewood and generating capnomancy (smoke). *The Book of Rites·Sacrificial Methods* says, "Burning sacrificial firewood on an altar means sacrifice for the heaven." Meanwhile, a commentary from Sr. Kong Yingda says:

> Burning sacrificial firewood on Tai (heavenly) altar means storing up firewood on an altar, while putting jade and livestock on the fire-wood for burning so that the capnomancy and smell can reach heaven.

Since Tai means heaven, the Tai alter refers to the Tian alter (the Temple of Heaven), and

> Heaven is too high, so burn sacrificial firewood on an altar . . . [because] the god is in heaven, and nobody can reach it without burning fire-wood.

It can be seen that burning a sacrificial fire does not refer to normal burning of firewood, but specifically refers to the ritual of burning sacrificial firewood for the God of Heaven.

The 'Yi' Character

The character 'Yi' should be a phonetic loan and the palaeographers have not yet identified its origin. The original text should be ,  and  whose shapes looks like burying a bull (head), a goat (head), a human or other offerings in pits, meaning 'burying' (Xu, 2006).

The *Shuo Wen* says, "Yi means deep and remote burying . . ." while the *Er Ya·Shi Tian* says, "Sacrificing to the earth means Yimai (deep burying)." The *Zhou Li·Chun Guan·Da Zong Bo* (*Zhuo Li·Spring Official·Minister of Sacrificial Rites*) says, ". . . sacrifice for the mountains, forests, streams and marshes through burying and sinking." Sr. Zheng Xuan explains: ". . . sacrifice for mountains and forests is called burying, for streams and marshes is called sinking." The *Lu Shi Chun Qiu* (*Master Lü's Commentaries of History*) says, "You Nian Yi Tu, Wu Nian Yi Tu." and *Gao You* explains,

> Sacrifice for the earth (Tu) means Yi (burying). Nian means grain. Sacrifice for the Earth with grain is to reward its merits; sacrificing to the earth without grain is to pray for the gods to avert disaster.

'Earth' here means the God of Earth. *The Book of Rites·Rules of Months* says, "Center is the reign of the Yellow Emperor, whose god is the God of Earth." The *Huainanzi·Tianwenxun* (Writings of the Masters of Huainan·Guide to Astronomy) says, "In central Earth, the emperor is the Yellow Emperor, whose assistant is the God of Earth, sticks to the laws to rule the world." The God of Earth is the 'Central Earth', which later refers to the God of Grain. The ancients sacrificed to the God of Earth to pray for the harvest of grain. *The Book of Rites·Sacrificial Methods* says, "Yimai Yu Taishe, Ji Di. Yong Xing Tu." Sr. Kong Yingda explains,

> Burying the sacrifices in Taishe is sacrifice for the God of Earth, by burying silk fabrics and sacrifices in the suburbs is sacrifice for the God of Earth.

Therefore, burying is the ritual for sacrificing to the God of Earth. The *Han Shu·Jiao Si Zhi II* (*Treatise of Rites in Suburbs*) says, "Sacrifice for the God of Heaven and the God of Earth uses one animal, burning and burying one animal." This shows that burning and burying were usually integrated into the sacrificial ritual, and burying the sacrifice after burning it. The *Shan Hai Jing·Nan Ci Er Jing* (*Code of Mountains and Waters·The Second Range of Mountain in the South*) says:

> The head of the second range of mountain in the south·its sacrifice: fur, burying the Bi (a round flat disk of jade with a hole in its center).

Yikan refers to the sacrificial pits used for burying sacrifices, jade objects and silk fabrics.

Interpretation of the Three Characters

Interpretations of these three characters show that the cornerstone-laying ceremony in the East Gate of Shimao City was a complex ritual that integrated three different ritual forms. This was the same system that was found in the Xia and Shang Dynasties. Sacrificial burning (pyromancy) was the core of a complex process. The *Zhou Li·Chun Guan·Da Zong Bo* (*Rites of Zhou·Official of Spring·Minister of Sacrifice*) says,

> Yin Si (sacrificial smoke, i.e. capnomancy) is for the Hao Tian (Center of Heaven, meaning North Celestial Pole) God. Shi Chai (sacrificial firewood) is for the Sun, the Moon and the stars. The You Liao (burning sacrifices, i.e. causinomancy) is for the gods of life, death, wind and rain.

Sr. Zheng Xuan explains:

> 'Yin' means smoke. People of the Zhou Dynasty valued smells and the smell of smoke, 'You' means piling up firewood.··All three kinds of sacrificial rituals require piling up firewood and sacrifices. Some may burn the jade objects and silk fabrics to generate smoke to reach the heavens.

The *Da Zong Bo* listed the three kinds of pyromancy:

1. Yinsi (capnomancy) is the method of generating sacrificial smoke for the God of the North Celestial Pole (Center of Heaven), commonly known as the Hao Tian God;
2. Shichai is the method of piling up sacrificial firewood for the Sun, the Moon and stars; and
3. Youliao (causinomancy) is the method of burning sacrificial objects on the firewood to pray for wind and rain.

In the *Zhou Li·Clarification*, Mr. Sun Yirang says:

> I privately study the meaning of them and think that Yinsi (capnomancy) is the way of generating sacrificial smoke; Shichai is the way of piling up sacrificial objects on firewood; and Youliao (causinomancy) is the way of burning the sacrifices on firewood. Although the rituals are different, the grand ceremony uses the method of burning firewood.

This theory is much the same as the theory of Zhou Li which also involved capnomancy, piling up firewood and causinomancy. The *Wen Xuan·Zhang Heng* (*Zhaoming Anthology·of Zhangheng*) says, "Blow up the blazing flame of You Liao (Causinomancy), create high smoke to reach Tai Yi (God of North Celestial Pole)." The *Xue Zong* explains: "Collect firewood to set fire and spread the flame to reach the celestial pole." Under ancient East Asian cosmological and belief traditions, our ancestors hoped to convey their awe and veneration to the God of North Celestial Pole with the help of smoke, gas and smells rising into the clouds from burning firewood and sacrificial objects on firewood, and they prayed for good weather for the crops, a golden harvest, and for the prosperity for humans and livestock.

The objects used in pyromancy can be divided into three categories:

1. Plants that were easy to burn, such as fire-wood, grass, grain, etc. that remained in the wood-ash sacrificial pits (i.e. botanomancy);
2. Pottery and stone artifacts; and
3. Animals, human sacrifices and other items that needed to be burned with fire-wood (i.e. causinomancy, plastromancy or scapulimancy).

In the mid-Neolithic era, plants, pottery and stone artifacts were the main choices for pyromancy. In late Neolithic, preferred items for pyromancy included pottery, stone artifacts, plants and animals, while at the end of the Neolithic era, the burning of aliens and foreign prisoners began to emerge.

Burning human sacrifices became the highest form of ritualized pyromancy, which had developed from the primary pyromancy ritual of botanomancy. This made the sacrifice ritual more tragic and devout, and the purposes of the prayers clearer. This kind of ritual existed in ancient civilizations in contemporary Western and Southern Asia, and it also emerged later to some extent in Mesoamerica and in Incan culture.

While studying ethnographic data collected world-wide, the British anthropologist Edward Tylor (1992), pointed out that

> The sacrifices which usually had a certain status in the history of religion were composed of delicious things, which were offered to the gods with the help of fire.

As we have seen, ‘Liao Ji’ (pyromancy) was an important sacrificial ritual system implemented by East Asian tribes and nations in prehistoric and ancient times. It was also a very ancient prayer activity controlled by high priests.

According to material obtained from archaeological excavations, the primary pyromancy ceremonies had already appeared 6000 years ago. Large tracts of burnt-red earth derived from pyromancy were discovered at the sacrificial altar No.1 in Daxi Culture stage I at the Chengtoushan Site in Lixian, Hunan Province (Cultural Relic . . ., 2007: 266); at sacrificial locations of the late Songze Culture at Fuquanshan Site, Qingpu District, Shanghai; and on the altars of the Liangzhu Culture (Huang, 1993; Shanghai Municipal Cultural Relics . . ., 2000: 18, 64). From 6000 to 5000 BCE, the scale of the altar increased and there were more remains from pyromancy. Dongshanzui site in Kazuo and Niuheliang sites in Jianping, Liaoning Province of the late Hongshan Culture had large scales pyromancy sites. Large tracts of gray-black or braised soil with a thickness of several tens of centimeters, burnt animal bones and other remains after causinomancy were found on the altars in these two places (Cultural Relic Institute . . ., 2012: 482; Guo and Zhang, 1984).

From 5000 to 4000 BCE, pyromancy became even more popular. There were large numbers of remains of burnt rice from causinomancy at the eastern and western parts of the large rammed earth raised platform of Mojiao Mount in Liangzhu sites (Cultural Relic Insititute . . ., 2005). The red clay rectangular top central layers of the Yao Mount and Huiguan Mount altars and the hollow square ash ditch around showed that there was a strong tradition of pyromancy in this region (Cultural Relic Institute . . ., 2003). From 4000 to 2000 BCE, pyromancy had spread to a vast region of East Asia that extended to the north and south as well as from the coastal inland. The East Gate’s sacrifice pits at the Shimao site showed that by this time pyromancy had developed to include human sacrifices. After the Xia and Shang Dynasties, the tradition of pyromancy became even more severe, as seen at the Erlitou site, the Shang city site in Yanshi City, in Xiaoshuangqiao, the site in Zhengzhou, Henan Province, and the Sanxingdui site in Guanghan City, Sichuan Province, etc.

During the Shang Dynasty, the Holocene megathermal maximum receded; the climate deteriorated; agricultural production problems increased; wars with alien races and foreign nations intensified; and human sacrifices developed to include captives of alien races and foreign nations, such as people of the Qiang race (who became the largest source for human sacrifices). Although the major purpose was still to worship the (Hao) Tian God, the God of (the Center of) Heaven, i.e., the God of the North Celestial Pole, more of the sacrifice ceremonies involved prayers for rain and snow, as well as good weather. The purpose of the sacrifice ceremonies became more urgent, and their form became more tragic.

The *Huainanzi* records,

> When Tang was the emperor of Shang Dynasty, a great drought lasted seven years and the diviner suggested pyromancy with human sacrifices to the God of Heaven. Therefore, Tang commanded his people to pile up fire-wood, then he cleaned his hair, nails and body, sat on the firewood and waited to burn himself. When the firewood was going to be burned, it rained.

This record reflects climatic change during the Shang Dynasty, and documents the relevance of pyromancy.

Plastron and scapulae divination have left many records of pyromancy. 'Liao Yu Yue' and 'Liao Yu He' refer to setting up rammed earth platforms for pyromancy on mountains or along riversides to make sacrifices to the God of Heaven and pray for wind and rain, which were all closely related to agricultural activities. The character 烄 (Jiao), in the *Shuo Wen*, "... is composed of 交 (Jiao) and 火 (Huo)." with a shape that looks like a human sacrifice with his legs crossed siting on fire. "Jiao is related to rain ..." which shows that the purpose of Jiao is burning humans to pray for rain, which has the same meaning as 'Liao' and 'Chai'. However, the *Yupian* (*Jade Dictionary*) says, "Jiao means burning the crossed firewood to sacrifice for the god of heaven ..." which is not accurate.

4.2.2.2 An Archaeoastronomical Study on the Sacrificial Site

Sites of pyromancy discovered in archaeological excavations all presented two important features relating to the geographical environment and their astronomical alignment: they were sited on high open ground that faced the Sun. High and open ground was ideal places for making sacrifices to the God of Heaven.

First of all, from the perspective of the geographical environment, the site for pyromancy was usually selected on natural hills, or at least on a large-scale artificial rammed-earth raised platform. The names Dongshanzui and Niuheliang indicate that such sites were on hills or ridges, and were geographically isolated and aloof from the plains, while Chengtou Mount, Fan Mount, Fuquan Mount, Huiguan Mount and Yao Mount were not on hills or hillocks but were actually sited on large-scale artificial rammed-earth raised platforms, which were about ten meters higher than the surrounding swamps and marshes.

The geographical environments of the Dongshanzui, Niuheliang and Shimao East Gate sites all were similar, and were suitable for high priests who wished to watch the movements of of the Sun, the Moon and the stars, and calculate celestial trajectories and seasonal changes (Discussion ..., 1984). Just as recorded in *The Book of Rites·Sacrificial Vessels*, "When former emperors held sacrificial rituals, they would count on hills for choosing high terraces for sacrifices to the God of Polaris." Stand higher, stand closer to heaven and the smoke, gas and smells can reach the God of Heaven (the North Celestial Pole) more quickly! Therefore, people would certainly select high hills for ancient rituals and sacrifices, and to present their 'treasures' to the God of Heaven. That was why Mount Tai became the Emperor's choice for holding Fengshan Ceremonies (for sacrifice to Heaven and the Earth) after the Qin and Han Dynasties. Mr. Fu Qian explained in the *History of the Han Dynasty·Sacrifice I*: "Feng means increasing the height to get closer to the heaven, which should give credit to the heaven." Mr. Zhang Yan also explained: "The heaven is too high to reach, so we carry out the Fengshan Ceremony on Mount Tai for sacrifice, looking forward to get closer to the God."

Secondly, from the perspective of their astronomical alignments, the sites for pyromancy were usually located at places that were clearly exposed to the Sun, and the associated buildings also had certain alignment relationships. This was not only for the purposes of gnomon shadow measurements for calculation of the dates of the equinoxes and the solstices but also for cosmological reasons: to face the Sun, locate the Yang (sunny) position and receive Yángqì (energy of sunshine). There were two preferred Yángqì alignments: to the east and to the south. The *Book of History·Yao Dian* (*Yao's Codes*) records:

> Therefore, (Emperor) Yao gave orders to the Xi (family) and the He (family) to worship the Hao Tian (north celestial pole), to watch the circulating rules of the sun, moon and stars, and to develop a calendar for calculating time.

Separately, (Sr.) Xizhong (Xi the senior) was appointed to live in Yu Yi (the east), named a sunny valley, to greet the sunrise with respect and to arrange the agricultural activities in the spring season. When the length the daytime and night-time were the same, the star culminating at dusk was Niao (Bird, the Zhang Mansion (Crop, Extended Net, υ^1 Hya) in the Vermilion Bird), that day was determined to be the vernal equinox. At that time, people were scattered in fields transplanting rice, and birds and animals began to reproduce.

Repeatedly, (Sr.) Xishu (Xi the junior) was required to live in Nanjiao (the south), named the summer capital, to greet the day of the summer solstice with respect and arrange agricultural activities in the summer growing season. When the daytime became longest, the star culminating at dusk Huo (Big Fire, the Xin Mansion (Heart, α Sco) in the Azure Dragon), and that day was determined to be the summer solstice. At that time, people moved to high ground, and feathers of birds and fur of animals became sparse.

Xi and He were the first generation of high priests who were in charge of observing astronomical phenomena and determining times in the ancient legends of East Asia. The general observing of astronomical phenomena and determination of times led to the development of the sidereal calendar. In the late Neolithic era, to make calendars more accurate the most advanced scientific methods of measuring time (using the shadow of the gnomon) were introduced. The purpose of setting up a pole (a gnomon) was to measure shadows, and the objects to measure were the Sun and the Big Dipper. The purpose was to determine the center and the four poles of the Earth (the East, West, South and North Poles), so as to establish astronomical and geographical coordinates. It was thus clear that Xi and He were the first generation of astronomers who were masters of gnomon shadow measurement. Since Xi and He were in charge of observing and measuring the Sun's shadow, they became the Sun gods, and even the goddess who gave birth to the Sun in the legend (Cultural Relic Institute of Archaeology of Zhengjiang Province n.d.; Dong and Fan, 2000).

The tradition of observing astronomical phenomena and determining time was closely related to the millet and rice agricultural economies in small watersheds (He, 1969). East Asia was the birthplace of the earliest rice and millet agriculture (see Fuller et al., 2007; Jiang and Liu, 2006; Li et al., 2007; Nasu et al., 2007; You Zhang and Hung, 2010). These two kinds of agriculture, especially that of rice, required ancestors to care greatly about the farming season. It was an important factor that led to the high development of East Asian astronomy (taking the Big Dipper and Antares as the core) and associated ritual systems (taking the heaven sacrifice rituals in the spring and summer seasons as the core) in ancient times.

In East Asia ancient cosmology, the East and the South were the places with plenty of sunshine and Yángqì (warm or bright energies). Thus they were called 'Yanggu', which means the Sunshine or Bright Valley) and 'Mingdu', which meant the Summer or Bright Capital, declaring the growth and reproduction of all living things on the Earth. Therefore, Yao ordered Xizhong and Xishu to set up sacrificial locations for the God of Heaven in the east and the south respectively, to greet the Sun in spring and summer and attract more solar energy.

As the *Book of Rites·Jiao Te Sheng* (*Suburb's Important Sacrifices*) says,

> ... sacrifice to the heaven in the south suburb to greet the arrival of the summer solstice. Take the sun as the Lord of gods. Mr. Cui says, 'There are four times in a year to greet Qi, sacrifice to the sun in the east and the moon in the west.'

At the Chengtou Mount city site (6000–4800 BCE) in Lixian County, the square altar No.1 belonged to the first stage of the Daxi Culture (6400 BCE), with a service time as long as several hundred years. It was located on the inner bank of the round ditch due east of the ancient city in the period of the Tangjiagang Culture (6000 BCE). Altar No. 2 belonged to the same time period and was located slightly west of altar No.1. During the second stage of the Daxi Culture the round altar 2 was relocated to an inner bank of the ditch due south of the ancient city. In other words, during the first stage of the Daxi Culture, there were only altars No.1 and No.2 and these were both sited due east. One hundred to several hundred years later, altar No.2 was moved so as to face due south. The tombs on altar No.1 have M774 as the core. The connecting line of the four tombs including M770, M774, M773 and M767 clearly pointed east by north 28–29°, namely the sunrise azimuth angle at the summer solstice during the first stage of the Daxi Culture in the Lixian area (Cultural Relic ..., 2007: 166). They had almost the same astronomical, cosmological and belief connotations as the East Gate of Shimao City and its five sacrificial pits, including that the altar should be located at 'Yanggu', face towards 'Mingdu', and have the functions of

> ... greeting the sunrise respectfully and arranging the agricultural activities in the spring season ... [and] identifying and greeting the day of the summer solstice respectfully and arranging the agricultural activities for the crop-growing season.

4.2.2.3 An Archaeoastronomical Study on the Sacrificial Items

Upon comparing archaeological and literary data, we believed that the alignment of the East Gate at Shimao City has the same meaning as that of the east altar at Chengtoushan in Lixian. Its geographical environment is similar to the altars of Dongshanzui in Kazuo and Niuheliang in Jianping, and their sacrificial functions, symbolic meanings and cultural connotations are basically the same. Their main sacrificial objects include: the God of Heaven (the North Celestial Pole), the gods of wind and rain, the summer solstice and the spirits of the Earth. As already mentioned, the major objects worshipped with decapitation sacrifices were the God of Heaven and wind and rain.

In other words, decapitation sacrifice was for the God of Heaven and to pray for good weather. Liaoji (pyromancy) was divided into Yinsi (capnomancy), Shichai (sacrificial firewood) and Youliao (causinomancy). The major target of Yinsi was the God of Heaven; of Shicai, the Sun, Moon and stars; and of Youliao, the wind and rain. Similar to decapitation sacrifices, Liaoji also sacrificed to the God of Heaven and extended to the Sun, the Moon and the stars, praying for good weather. Someone once said that the major targets of burying sacrifices were the spirits and the God of Earth, but in fact it is more the necessary follow-up steps of decapitation sacrifices and pyromancy, because all the burning residue, including plant and animal ash and unburned animal and human sacrifices had to be buried.

In addition, in the ancient cosmology, the summer solstice was closely related to Yīnqì (cold or dark energies), so sacrifices at the summer solstice were closely related to the spirits and the Gods of the Earth. What then caused the God of Heaven, the wind and rain, the summer solstice, and the spirits of the Earth, etc. to have a relationship with decapitation sacrifices, pyromancy and burying sacrifices? It is necessary to understand the archaeoastronomical connotations of the God of Heaven (the God of the North Celestial Pole), as well as the concept of the summer solstice in ancient East Asian cosmology.

Firstly, the Hao Tian God refers to the God of the North Celestial Pole, which was also called Taiyi and Tianyi. According to astronomical records, in 4000 BCE the North Celestial Pole star, ‘Taiyi’, was the First Great One (κ Dra). Needham (1990: 203) thought it was Draco 42 or 184, and Feng Shi thought it was 3599 Boss. But in 4500 BCE, ‘Tianyi’ was ι Dra. This means that the construction of Shiaomao Ancient City spanned the era when the North Celestial Pole star gradually changed from Tianyi to Taiyi. Obviously, the legend that Tianyi and Taiyi became the loftiest God of Heaven (the North Celestial Pole) originated in this era.

The *Shiji·Tianguanshu* (*Book of Celestial Offices*) records that “Among the celestial pole stars in the Central Palace, the brightest one is Taiyi, who is the permanent residence there.” It meant that the celestial pole was the palace of God Taiyi, the God of the North Celestial Pole. The *Huangdi Jinkui Yuhengjing* (*Yellow Emperor·Critical Code on the Big Dipper*) says:

> Tianyi, the lord of gods, lives in the Xuanji (the heavenly dish-like circle formed by the Big Dipper) of the Central Palace, guards Yuheng, controls the four seasons, masters Yin and Yang and holds the rules and regulations, located at the center of Kui (the bowl of the Big Dipper) and Gang (the handle of the Big Dipper).

This clearly points out that Xuanji, which was formed by the circumpolar rotation of the Big Dipper around the North Celestial Pole, was the sacred residence of Tianyi, the God of the North Celestial Pole and the Lord of Gods. The *Zhou Bi* said, “Zheng Bei Ji Shu, Xuan Ji Zhi Zhong·Ci Yang Jue Yin Zhang, Gu Bu Sheng Wan Wu.” This means that there is no Yángqì (warm or bright energies) at all in Xuanji, which is formed by circumpolar rotation of the Big Dipper, and nothing can grow there. It is the residence of the God of the North Celestial Pole—the creator of the material world. The *Taishang Xuanling Beidou Benming Changsheng Miaojing* (*Ingenious Code for Chinese Zodiac Longevity from the God of the Big Dipper in North Celestial Pole*) states that

> The Big Dipper takes charge of life and death, and is the resource that nourishes all living things and aids humans. All people with emotions receive energies from the heavens and the Earth and the order of Yin and Yang to be a man or a woman, to live a long or a short life, all of which abide by the law of the Big Dipper.

This means that the Big Dipper was also both the source and destiny of life. Sima Zhen said in the *Shiji·SuoYin* (*Exploration*), "... the celestial north pole is Tianyi and Taiyi." Both Tianyi and Taiyi were once the North Celestial Pole star. The *I Ching* (*The Book of Changes*) says: "Tianyi generates water." while the *Bamboo Slips of Guodian* records:

> Taiyi generated water and water assisted Taiyi in return. In this way, heaven was created. Heaven assisted Taiyi in return, and the Earth was thus created.

Water is the resource of life (Jingmen Museum, 1988). How could it symbolize the resource of all things and life? The ancients usually showed creation of life with a female's body or with statues of pregnant women. The objects worshiped in the temple at No.1 site (N1 J1) in Niuheliang, the round altar at No.2 site (N2Z3) and Dongshanzui G6 in Kazuo should be the God of the North Celestial Pole of the same type that symbolized the Universe and the origin of life on the Earth (Lyu, 2015). It was also the subject for decapitation sacrifice and pyromancy at the East Gate of Shimao City. The corresponding positions were the North Celestial Pole and the Arctic Xuanji (circumpolar rotation circle of the Big Dipper) where there was no Yángqì but was filled with Yīnqì. Its most reasonable image would be nothing better than a young woman's body with pure Yīnqì. What people in Shimao City had inherited was obviously this cosmological tradition that has been recorded in the historical literature. Thus, it is now clear how young women were related to the God of the North Celestial Pole in cosmology. The reason that the Shimao high priests used a large number of young women from alien races or foreign nations in their decapitation sacrifices, pyromancy and burying sacrifices becomes all too clear.

Secondly, what were the relationships between the summer solstice, the wind and rain, and the spirits of the Earth? The *Zhou Li· Chun Guan·Da Si Yue* (*Rites of Zhou·Official of Spring·First Minister of Imperial Music*) records:

> People sacrifice to the gods of heaven at the winter solstice, and sacrifice to the spirits of the Earth at the summer solstice.

> On the day of the winter solstice, people should perform music on the round altar. When the music finishes six variations, the gods of heaven will descend and people shall give sacrifices to them. ·On the day of the summer solstice, people should perform music on the square altar. When the music finishes eight variations, the spirits of earth will ascend and people shall give sacrifices to them.

According to the *Zhou Li*, people of the Zhou Dynasty held sacrificial rites on the round altar on the day of the winter solstice to give sacrifices to the God of Heaven and the souls of the ancestors. They held the sacrificial events at the square altar on the day of the summer solstice to give sacrifices to the spirits of the Earth and the souls of mountains and rivers. The ritual systems of the Zhou Dynasty recorded in the historical literature during the Qin and Han Dynasties do not match the actual altar combinations from the Neolithic Age with those of the Xia and Shang Dynasties discovered during archaeological excavations. However, according to Chinese traditional beliefs, sacrificing to the spirits of the Earth at the summer solstice had certain reasons.

Zhang Heng said in the *Xijing Fu* (*Poetic Essay for the West Capital*), "Ri Bei Zhi Er Han Dong." "Ri Bei Zhi", quoted from the *Zhou-Bi*, means the summer solstice. According to the ancient cosmological and belief systems of East Asia, He believed that Yángqì (warm or bright energies) reached its maximum at the summer solstice and began to change from flourishing to decadence while Yīnqì (cold or dark energies) began to change from decadence to flourishing, so it was called 'Handong', which means getting colder every day. Jia Sixie from the Northern Wei Dynasty recorded in the *Qimin Yaoshu* (*Important Know-how of the Qi People*, the earliest and the most comprehensive agricultural encyclopedia written by Jia Sixie in AD 540), that "After the season of Grain in Ear in May, Yángqì began to lose and hidden Yīnqì began to germinate." That is to say, at the summer solstice, Yángqì reached its maximum and started to recede while Yīnqì germinated and grew stronger every day.

Heaven symbolized Qian and Yáng and the Earth symbolized Kun and Yīn, so the summer solstice was related to the spirits of the Earth, the gods of the Earth and the souls of mountains and rivers. According to the farming season in East Asia, if Yīnqì grew too much or too little, it would result in disorder of the solar terms. Therefore, the *Lyu Shi Chun Qiu·Yue Ling* (*Lü's Commentaries of History·Monthly Government Decree*) and *The Book of Rites·Yue Ling* (*Monthly Government Decree*) both record:

> In the second month of summer, the day of the summer solstice arrives, Yīnqì and Yángqì begin to fight with each other for flourishment and decadence. If government decrees in winter are implemented in the second month of summer, hail will freeze and damage the grain, block roads, and lead to the arrival of a filibuster. If government decrees in spring are implemented in the second month of summer, the grain will mature later, hundreds of snakes will appear frequently and people in the country will suffer famine. If government decrees in autumn are implemented in the second month of summer, the grass and trees will wither and fall, fruits will mature earlier and people will suffer plagues.

The summer solstice was the time when all flora grew at their utmost. If Yīnqì was too strong or too weak, it would affect the appropriate growth rate and harvesting season of crops, especially the staple food, grain. Therefore, *The History of the Later Han Dynasty·Book of Etiquette V* says:

> In the second month of summer, all things grow up to their most healthy and strong stage. On the day of the summer solstice, Yīnqì germinates and people are afraid that the crops will not flourish.··Therefore on May 5th, people will use red rope and five-colored print to decorate their doors, in order to deter Yīnqì (dark energies).

The ancients believed that Yinqì germinated from the time of the Dragon Boat Festival to the summer solstice. No matter whether it grew too fast or too slow, it would affect the maturity of the crops as scheduled, so it should be regulated by strengthening or weakening Yángqì.

Therefore, the ancients believed that they could use young women with pure Yīn bodies to carry out decapitation sacrifices, pyromancy and burials sacrifice to achieve the effect of sacrificing to the God of the North Celestial Pole in order to regulate Yīn and Yáng, namely to inhibit the growth rate of dark energy and thereby ensure good weather and a better harvest. To achieve this goal, the ancient ruling class organized large-scale ritual activities around the country before or after summer solstice. Thus, the *Yue Ling* (*Monthly Government Decree*) says:

> In the second month of summer, the ruling class orders musicians to repair Taopi drums, fine-tune a variety of musical instruments such as qins, chimes, pipes and Xiao, hold shields and weapons, regulate Yusheng, and renovate Zhong, Qing, Zhu and Yu. The ruling class orders the officials to arrange sacrificial ceremonies for its people to the sources of mountains and rivers, the God of Yu (Rain) with grand music. The Emperor also ordered hundreds of counties to hold sacrificial ceremonies for rain and hundreds of officials to do good things for the people and pray for the harvest of grain.

The Chinese character '亏 (Kui)' is an abbreviation of '圬 (Wu)'. 'Wu' means "... filling the ground pits." With the Chinese character '雨Yu (rain)' at the top and '亏 Kui' below, it becomes the character '雩' that means rain filling up dry lakes. Sr. Zheng Xuan says:

> When Yángqì grows too much, there will be long and severe drought. The sources of mountains and rivers can form clouds and rain. Water comes from these sources, so humans should sacrifice to these sources first. 雩 (Yu) is the sacrificial ritual of praying for rains. Yudi means setting up the altar near the south suburb to sacrifice to the Five Essence God and former emperors.

The *Zhou Li·Si Wu* (*Ministering High Priest*) said, "If a country suffered a drought, the ruling class could order the high priests to dance in the Yu ceremony." Sr. Zheng Xuan said:

> Yu referred to the sacrificial ritual during a drought. The Emperor would sacrifice to the Hao Tian God. Officials below dukes or princes would sacrifice to the Gods of Shanggong.

Meanwhile, the Zhou Li·Priestess says that

> Priestesses take charge of the sacrifices for preventing seasonal hazards. When there is drought, they bath with aroma and dance in the Yu ceremony.

Finally, Sr. Zheng Xuan says: "... order the priestesses to dance and offer sacrifices for drought by worshipping the Yīn." Meanwhile, Zheng Zhong says: "Order the priestess to pray for rain."

What was the Yu ceremony? The *Analects of Confucius·Xianjin* says, "Take a bath in Yi River, feel the winds on the Wuyu platform, sing the songs and return home." The Wuyu platform is an altar in the Lu State that was used for praying for rain. Wind and rain came successively, so the dance to pray for rain imitated the wind from all directions.

After the above analysis, the relationship between young women and the summer solstice; the spirits of the Earth, the mountains and rivers; and the wind and rain in the cosmology of the Shimao people becomes clear, and the motives and purpose of sacrificial rites by the Shimao high priests are also apparent.

The Lament of Asclepius, an ancient Greek prophecy, says, "Do you not know, Asclepius, that Egypt is an image of heaven." Western scholars long ago recognized that ancient Egyptian architecture embodied a large number of observations of the stars and an understanding of the Universe. Meanwhile, the well-known American historian, sociologist and expert on cities and urbanisation, Lewis Mumford (1961), states in his *The City in History*, "We can say that the first seed of the city was sown by people as the ritual gathering place constructed for pilgrimage." Göbekli Tepe in Anatolia, Turkey, stands as proof of this comment. This site was excavated by the University of Istanbul and the University of Chicago in 1963, and contains what is arguably the world's oldest temple (which has a date of 9559 ± 53 BP).

How could the Liangzhu and Shimao high priests of the late Neolithic period in East Asia, who had already mastered astronomical and cosmological traditions, construct a capital without any relation to their belief systems? From the presence of jade in the ruin, Shimao City contains a rich East Asian Neolithic ritual system. Meanwhile, the exquisite architecture of East Outer City Gate, shows that Shimao City also contained a rich prehistoric astronomical and cosmological belief system.

Notes

1. Unless otherwise stated, in this paper all Chinese to English translations were made by the authors.
2. To date, Peking University has tested more than twenty datasets on the age of Shimao Ancient City, and the earliest of these gave a date of about 2200 BC. However, on the basis of the archaeological evidence we believe that the initial construction occurred around 2300 BC. Later, The Imperial City Terrace, Inner City and Outer City may have undergone gradual repairs.
3. Further research is required to determine whether the sacrificed individuals were from alien races or nations.

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