Govind Swarup*

Tribute to a Legend

Dhruba J. Saikia

Govind Swarup put radio astronomy in India on the world stage with the indigenous construction of state-of-the-art radio telescopes at low radio frequencies, incorporating many innovative features. A passionate scientist and an educator with unbounded enthusiasm and energy, he has been a source of inspiration for the academic and scientific community. This article traces his life and contributions, with some reminiscences that are likely to touch, motivate and inspire the young readers of *Resonance*, just as it has many of us who have had the privilege of working with him.

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Keywords
Govind Swarup, Kalyan Radio Telescope, Ooty Radio Telescope, Giant Metrewave Radio Telescope.

1. Introduction

Govind Swarup was always full of innovative ideas as he worked at the frontiers of radio astronomy, building state-of-the-art radio telescopes. He had no hesitation in discussing or bouncing his thoughts and ideas off his colleagues and students, often in the corridors or canteen or any other place where he might meet them. Some may even say that his ideas evolved quite rapidly and sometimes were difficult to keep up with. But the sparkle and curiosity in his eyes on a wide variety of topics, discussing what is most exciting in a field with intense energy and enthusiasm, was not only a delight to see but very inspiring too, especially to young students. My initial taste of this was during the summer school of 1976, and immediately after, I joined his group in August 1977. Both these occasions were after the results from the Ooty Radio Telescope (ORT) in 1975 provided further evidence in support of the big bang model of the Universe. On the very first day of my

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joining, for well over two hours on the morning of 16th August 1977, he spoke of the work that had been done by the group, the new problems that needed to be addressed, possible instruments that could be built to address these, and his vision for the growth of the group. He advised me to concentrate more on interpretation and theory, and with his very liberal outlook, let me work for several months with C. V. Vishveshwara at the Raman Research Institute (RRI). Besides his enthusiasm, vision, and energy, what touched me from those early days was the humility and simplicity of the man, operating in a very egalitarian ambience from a modest office at Ooty, thinking of building the next big telescope to answer another big question of the day. For well over forty years, there has perhaps not been a single correspondence that he has not responded to, the last one being a WhatsApp message about a month and a half before he passed away.

He never availed of any special privileges for himself. Although Govind, as we all affectionately called him, and my colleagues at the National Centre for Radio Astrophysics (NCRA) of the Tata Institute of Fundamental Research (TIFR) spent more than a decade building the Giant Metrewave Radio Telescope (GMRT), they put in place a system where anybody across the world could propose for observing time on an equal footing, including themselves. Time was allocated based on scientific merit alone by a committee chaired by a person outside NCRA-TIFR. This far-sighted and altruistic step brought out the best that the telescope could offer and helped foster collaborations of Indian astronomers with the global community. Although such a system was in place in large radio telescopes such as the Very Large Array (VLA) located in New Mexico, USA, this was novel at the time it was introduced in India. This has now become the norm for different telescopes in the country.

Though researchers at NCRA-TIFR spent more than a decade building the Giant Metrewave Radio Telescope, they put in place a system where anybody across the world could propose for observing time on an equal footing, including themselves. Time was allocated based on scientific merit alone by a committee chaired by a person outside NCRA-TIFR. This far-sighted and altruistic step brought out the best that the telescope could offer and helped foster collaborations of Indian astronomers with the global community.

The summer school of 1976 on astronomy and astrophysics, where I first met Govind, was one which he had initiated. G. Srinivasan then at the Raman Research Institute (RRI) mentions about receiving an invitation from Govind for a meeting at RRI to discuss the school; the meeting was also attended by Rajaram Nityananda and V. Radhakrishnan, then Director of RRI [1]. These initial interactions led to a long and fruitful association between the two institutions. Govind offered the use of the ORT to Radhakrishnan and his group at RRI which led to a vibrant collaboration between the two institutes in both astronomy and instrumentation, exchange of ideas and movement of persons between the two institutions. Some of the pioneering work on low-frequency radio recombination lines by the RRI group was done using the ORT. As stressed by Rajaram Nityananda [2], all this happened without any formal agreement but was made possible by the passion for science and vision of two remarkable individuals, Govind and Radhakrishnan. Decades later, the λ21-cm feeds for the GMRT, which has yielded many exciting results, were to be built at RRI. This effort was led by N. V. G. Sarma, who was earlier with the Radio Astronomy Group at Ooty. Another significant example of collaboration between RRI and NCRA-TIFR was the GMRT array combiner and the pulsar receiver (polarimeter) for GMRT, which were designed and built by another team at RRI. In this case, two inspired grand-students of Radhakrishnan, T. Prabu and P. S. Ramkumar played leading roles in the realisation of the respective systems employing the then latest digital technology [3, 4]. Both these systems were widely used at GMRT before the fully software-based systems came in place. Many years later, Rajaram Nityananda became the Centre Director of NCRA-TIFR, while G. Srinivasan chaired the GMRT Time Allocation Committee during its formative years, setting high standards of fair and objective reviewing of proposals. In an era when institutions rush to showcase the MoUs they have signed, this was an example of a beautiful and fruitful collaboration between two institutions driven by a common passion for science without any formal documents.

To make images of the sky, a correlator estimates coherence in the signals from different pairs of telescopes. Its output data streams, known as visibilities (analogous to the fringe visibility in the Young's double slit experiment that we study in optics), from all pairs put together are related via a Fourier transform relation with the sky brightness distribution. An array combiner, on the other hand, sums the signal intensities or voltages from all antennas to produce output spectral information with high time resolution in the so-called incoherent and coherent (or phased) array modes, respectively. These array combination modes facilitate sensitive searches and studies of pulsars, which are rapidly rotating neutron stars with periods as short as about a millisecond.

Going back to the summer school of 1976, this led several of us including Chanda Jog, Shrinivas Kulkarni, Ashok Pati, M. Vivekanand, to take up astronomy and astrophysics as a career. This was the forerunner for similar schools to be held regularly at both Bengaluru and later at Pune. Govind was also instrumental in getting the Joint Astronomy Programme started, which has been hosted by the Department of Physics of the Indian Institute of Science, Bengaluru since 1982. Govind also shifted part of the radio astronomy group to the TIFR Centre at Bangalore which was headed by Vijay Kapahi to promote greater interactions with the astronomical and engineering community there. These initiatives reflect Govind's broader vision of developing the persons for the future in both science and engineering.

Let's have a brief look at his life and contributions. The early days at Ooty, where the entire group worked as one large family with excellent camaraderie, and results from the ORT have been described by S. Ananthakrishnan and V. Balasubramanian [5], GMRT results on atomic hydrogen in distant galaxies by Nissim Kanekar et al [6]. More detailed accounts of his life can be found for example from his interviews with Indira Chowdhury [7], articles by G. Srinivasan [1], W. M. Goss [8], Wayne Orchiston and Sudhir Phakatkar [9], Divya Oberoi and Poonam Chandra [10], and Govind's autobiographical account in the *Annual Reviews of Astronomy and Astrophysics* [11]. His innovativeness throughout his career has been highlighted by Ron Ekers in the inaugural Govind Swarup Memorial Lecture held on 23 March 2021 [12].

2. Early Years

Govind Swarup was born on 23 March 1929 in the small town of Thakurdwara in district of Moradabad in Uttar Pradesh. Govind's life and work have been interwoven with the growth of the field of radio astronomy. His birth was about a couple of years or so before Karl Jansky's serendipitous discovery of radio emission from the centre of our Galaxy, which opened up the field of radio astronomy [13]. Jansky reported his results in a paper titled "Electrical disturbances apparently of extraterrestrial origin", in April 1933 at a meeting of the International Union of Radio Science. Govind had his early schooling at the Sanathan Dharam School in Thakurdwara, besides being taught by his grandfather, before his family shifted to Moradabad and he completed his schooling from Hindu High School in 1944. Noticing Govind's early interest in science, his father sent him to Ewing Christian College, Allahabad where he studied physics, chemistry and mathematics for two years before moving on to Allahabad University in 1946. Ewing Christian College, supported by the American Presbyterian Church, was one of the best colleges in the country, while Allahabad University had some of the outstanding academics of the time. These included K. S. Krishnan (who co-authored the paper on the discovery of the Raman Effect with C. V. Raman), B. N. Srivastava, G. B. Deodhar, Gorakh Prasad, Rajendra Singh, N. R. Dhar in the sciences, and Harivansh Rai Bachchan, Tara Chand, Firaq Gorakhpuri, Ishwari Prasad in the arts and humanities, among many others. K. S. Krishnan taught Govind electricity and magnetism during his BSc at Allahabad University. He completed his MSc in 1950 before joining the National Physical Laboratory, whose foundation stone was laid in 1947 by Jawaharlal Nehru and which had K. S. Krishnan as its first Director.

Besides Govind's passion for science, he was also strongly influenced by the nationalistic fervor of the time. He took part in the Quit India movement of 1942, and was influenced by Gandhi. He subscribed to Gandhi's weekly magazine *Harijan*, read Gandhi's autobiography which he received as a prize in school, listened to Nehru's inspiring speech on the midnight of India's independence as it was relayed from Anand Bhawan, and given the prevailing political groups at Allahabad University, he was not attracted by the right-wing ideology. He recalled the Bengal famine of the early 1940s while he was in the hostel. Men and women, apparently from well-to-do families, came begging, and Govind and his friends gave whatever they could [7, 11].

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An enriching educational experience across the boundaries of disciplines is the hallmark of any great University. This was also true of Allahabad University of that time. This along with a strong nationalistic zeal from those early years were perhaps strong contributing factors to bring Govind back to India, and to build some of the best radio telescopes completely indigenously. His visits to Australia and the United States, where he did is PhD at Stanford

University are described later in the article.

3. National Physical Laboratory (NPL)

On joining NPL, its Director K. S. Krishnan who was Govind's former teacher at Allahabad, gave him a few papers to read by Bebris Bleany and asked him to set up an apparatus operating at a wavelength of 3-cm (10 GHz) for detecting paramagnetic resonance. Electron paramagnetic resonance was first seen at Kazan University by the Soviet physicist Yevgeny Zavoisky in 1944, and was developed independently by Bebris Bleany at the University of Oxford. This was a hot topic of the time, and a challenging job for someone just after his MSc. By cannibalizing parts of surplus radar equipment procured by NPL and reading parts of the Massachusetts Institute of Technology (MIT) Radiation Laboratory Series, Govind put together the equipment over about 18 months. Thrown into the deep end, Govind came out on top, just as he learned to swim when pushed into the Ganges many years earlier! It is worth mentioning here that while research scholarship amounts in today's national laboratories and institutes are quite comfortable, Govind worked for about a year without any financial support from NPL as the Government had put a moratorium on new recruitment. He was to later take up the paid position of Secretary of the Radio Research Committee of CSIR located at NPL.

Let me describe briefly the somewhat deceptively named Radiation Laboratory, commonly referred to as Rad Lab, whose publications Govind used. It was established at MIT in 1940 and brought together experts from the United States and Britain for about five years to work on microwave electronics and radar technology to aid the war effort. The IEEE plaque, which it received in 1990, says it "made lasting contributions to microwave theory and technology, operational radar, systems engineering, long-range navigation, and control equipment". Its significant results were put together after the war in a 28-volume series, the MIT Radiation Laboratory Series, published by McGraw-Hill-New York.

NPL had managed to get these volumes which Govind used, and which are now available online at Jefferson Lab.

NPL and K. S. Krishnan would play a major role in shaping Govind's entry into the exciting world of radio astronomy, the first major window of the electromagnetic spectrum to be available for astronomical observations outside the optical band. After Karl Jansky's discovery of radio emission from the centre of our Galaxy, Grote Reber, the pioneer radio astronomer, built a radio telescope in his backyard in 1937. He made surveys of the sky, mapped the Milky Way and showed that the emission detected by Jansky increased at low frequencies, demonstrating that the emission is non-thermal in origin [13]. The field, however, remained largely dormant till after the war. Researchers who were working on radar related work during the war turned their eyes to radio astronomy. The major efforts at that time were led by Martin Ryle at Cambridge, Joseph Pawsey at the Division of Radiophysics, CSIRO, Australia, and Bernard Lovell who established the Jodrell Bank Observatory in the plains of Cheshire in 1945.

The exciting discoveries as the radio sky was being explored, were reported in meetings of the International Union of Radio Science (URSI). The tenth General Assembly of URSI, which was held in August 1952 in Sydney, brought together many well-known radio astronomers. K. S. Krishnan attended this General Assembly and learnt first hand the remarkable developments in this field. On his return, he gave a colloquium that kindled Govind's interest in radio astronomy. He went on to study the 30 odd papers or so published by the scientists of the Division of Radiophysics. Krishnan, interested in starting a radio astronomy program at NPL, recommended Govind for a scholarship under the Colombo Plan to spend two years working at the Division of Radiophysics (RP) of CSIRO, Australia. Govind set sail and reached Australia in March 1953. R. Parthasarathy from Kodaikanal Observatory was also selected that year under the Colombo Plan Fellowship to work in Australia.

4. Australia

The Division of Radiophysics which started as a secret centre for radar work in 1939, developed into a vibrant centre for astronomical research under the leadership of Joseph Pawsey. He attracted some of the most talented and dynamic persons to the existing talent and expertise at RP. These included Bernard Mills, Wilbur (Chris) Christiansen, John Bolton and Paul Wild, all of whom were involved in the war effort and went on to make fundamental contributions in radio astronomy. As Govind would mention later "There is nothing like working in a place where discoveries are taking place every few weeks! Even in the canteen there were discussions about what new had happened that week". Pawsey's approach was to build a strong group, an advice Homi Bhabha would give Govind a decade later while taking the first steps towards establishing radio astronomy in India.

Joe Pawsey decided that during the first year, Govind would work for three months each with the groups led by Wilbur Christiansen, Paul Wild, Bernard Mills and John Bolton, and during the second year would do a joint project with R. Parthasarathy. Although the headquarters of the Division of Radiophysics was at the University of Sydney, research activities were largely centred around the field stations led by the different team leaders for different projects. The field stations were chosen to be at radio-quiet locations. During the first year, he analyzed data, including making a two-dimensional map of the Sun from one-dimensional strip scans with a grating interferometer, and designed and made instruments for observations. During the second year, Govind and Parthasarathy decided to convert the 1420-MHz interferometer built by Christiansen to observe at 500 MHz. Their objective was to study limb brightening of the Sun, which was predicted by S. F. Smerd in Australia but not verified by H. M. Stanier at Cambridge. Govind and Parthasarathy found evidence of limb brightening contrary to the results of Stanier and also studied various components of solar radio emission.

The limb of the Sun appears brighter at radio frequencies due to contributions from the chromosphere and corona.

Meanwhile, Christiansen planned to build a cross-type radio telescope using bigger dishes and the Potts Hill interferometer was to be scrapped. On Govind's request, Pawsey and CSIRO agreed to donate the dishes to India under the Colombo plan. Govind wrote to Krishnan, who responded positively in February 1955: "I agree with you that we should be able to do some radio astronomy work even with the meagre resources available".

5. Back to NPL

Govind returned to India in 1955 along with R. Parthasarathy and joined NPL, eager to start off radio astronomy here. His plans centred on the arrival of the dishes of the Potts Hill array gifted by Australia. However, Australia wanted India to bear the transportation costs which CSIR was not prepared to do citing foreign exchange reserves. Meanwhile, a small radio astronomy group was being built up at NPL over the next few years which included T. Krishnan from Cambridge who had worked with Martin Ryle, R. Parthasarathy who shifted from Kodaikanal Observatory, Mohan Joshi, N. V. G. Sarma, who both joined after their M.Sc., and Mukul Kundu, who had studied solar radio astronomy in France. However, the dispute over the payment of transportation costs lingered on and the members of this nascent radio astronomy group at NPL began looking for other opportunities. Govind was offered the position of Research Associate at Harvard College Observatory to work at the Radio Astronomy Station at Fort Davis, Texas. He married Bina in June 1956, and both Bina and Govind left for the United States in July 1956. The Australians agreed later to bear the cost of transportation and the dishes arrived perhaps in late 1957. Although several members had left NPL, they would get together later to make India a world leader in radio astronomy.

6. United States

The Radio Astronomy Station at Fort Davis had a 28-foot parabolic antenna operating in the frequency range 100 to 580 MHz. A dynamic radio spectrograph was in operation, which Govind used to study solar radio bursts and possible association with flares under

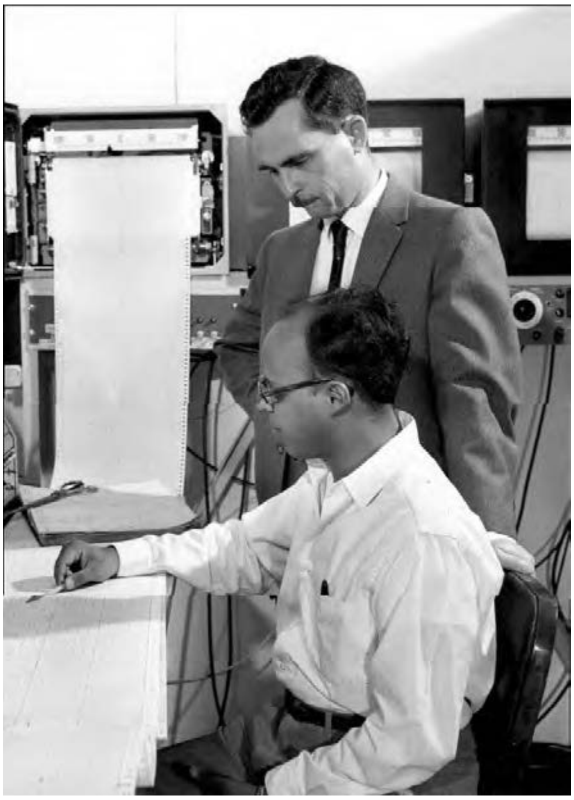

Figure 1. Govind Swarup and Ron Bracewell examining records of solar observations. Image credit: Stanford University Archives.

A dynamic spectrum plots intensity as a function of frequency and time. The U shape arises due to a stream of energetic electrons moving up the ascending part of a magnetic loop, with the plasma density decreasing with height. Hence lower frequency emission appears later in time, giving a negative frequency drift rate. As the stream moves down the descending leg, the plasma frequency increases resulting in a positive frequency drift rate.

the supervision of Alan Maxwell. He discovered a new type of solar burst in December 1956, which he called the U-burst.

In early 1957, Govind decided to work for a PhD degree in the USA and received favourable responses from Harvard, Caltech and Stanford, all of which were already active in radio astronomy. His mentor Joe Pawsey advised him: "Stanford is famous for radio engineering, Caltech for its physics and, of course, its astronomy research, and Harvard for its training in astronomy ... If you are returning to India, I should recommend to you to place great emphasis in electronics. It is a key to open many doors." Govind went to Stanford and worked under the guidance of Ronald Bracewell on solar microwave emission. He worked at the Stanford Cross antenna, which operated at 3260 MHz and consisted of 32 parabolic dishes, each of 3-m diameter. Rather than go through the tedious process of equalization of phases of the antennas for making images of the Sun, Govind and a fellow student K. Yang conceived of the concept of the round trip phase measurement scheme which was to become a standard procedure for radio interferometers across the world [14]. He submitted his thesis titled "Studies of solar microwave emission using a highly directional antenna" in December 1960 and joined Stanford as a faculty member in 1961. During his stay at Stanford he along with a Japanese astronomer, T. Kakinuma, wrote one of his most cited papers invoking gyrofrequency radiation in understanding the slowly varying component of the Sun [15]. Govind also made his first observations of an extragalactic object, Cygnus A, using the Stanford interferometer by adding two more dishes to improve the resolution. Extragalactic radio sources were to be one of his main areas of interest in later years, and it was a real pleasure working with him on a number of projects. Govind also discussed with Ron Bracewell a simpler way of making two-dimensional images from one-dimensional scans, which he did not pursue as he was preparing to return to India. This was later developed by Bracewell and Riddle [16] and had many applications, especially in medical imaging.

7. Initial Steps of Returning to India

Govind's mind was set on doing something innovative in India, although he took up a position at Stanford, and he began discussions with Mukul Kundu and Kochu Menon. They were both accomplished radio astronomers working in the United States, Mukul Kundu then at the University of Michigan and Kochu Menon at the National Radio Astronomy Observatory, USA. The trio was joined by T. Krishnan from RP in Australia, and they met during the General Assembly of the International Astronomical Union held at Berkeley in August 1961. This led to a proposal titled "Proposal for the formation of a radio astronomy group in India", which first involved using the dishes gifted by Australia to set up a solar radio observatory, and then moving on to build a high-resolution innovative telescope of novel design.

Their move was supported strongly by Govind's mentors in Australia, Joe Pawsey and Chris Christiansen. Five internationally renowned astronomers Bart Bok, Jean-Francois Denisse, Jan Oort, Joe Pawsey and Harlow Shapley were requested to write confidential referee reports on their proposal. One of them, Bart J Bok, wrote: "....it seems to me that their offer of returning to India as a group is a unique one and that should, by all means, be accepted and acted upon promptly. An offer like the present one comes only rarely in the history of a nation, which scientifically, is obviously coming of age." Of the five organizations that they sent their proposal to, Homi J Bhabha, Director of the Tata Institute of Fundamental Research, responded most positively. Bhabha cabled all four of them in January 1962: "We have decided to form a radio astronomy group stop Letter follows with offer". And in April 1962, Bhabha wrote to Govind, "If your group fulfills the expectations we have of it, this could lead to some very much bigger equipment and work in radio astronomy in India than we can foresee at present." Bhabha, the architect of India's atomic energy programme, also urged Govind to return early. Ron Bracewell referring to Bhabha, said, "This man means business, you better go".

8. Tata Institute of Fundamental Research

Govind resigned from Stanford and set off for India via Europe with his wife Bina and two little children Anju and Vipin, arriving at Bombay in March 1963. Govind joined TIFR in April 1963. In Europe, he met the legendary Jan Oort, Monique Pick, the solar physicist and Marcello Ceccarelli, the father of Italian radio astronomy, who was building a big parabolic cylindrical radio telescope at Bologna. Jan Oort showed him around and suggested building a telescope to observe the sky in neutral atomic hydrogen in the southern hemisphere, which was not possible to observe from The Netherlands. This was an important topic of the time, but Govind seems to have gone by his mentor Pawsey's advice to "keep off the fashionable stuff as far as possible. Be original. Try, if possible, to develop ideas which one or more of you have originated." Govind mentioned that he also turned down an offer from Merl Tuve of Carnegie Institution of Science to send an antenna to India to explore atomic hydrogen in the southern sky, saying "I was going back to my own country to do independent research" [7].

8.1 *Kalyan Radio Telescope*

Back in Mumbai, a small but dedicated group of young and talented persons soon joined Govind, initially J. D. Isloor and Vijay Kapahi, who were fresh graduates from the Atomic Energy Training School, followed by Ramesh Sinha and Durga Bagri. Around the same time Mohan Joshi and N. V. G. Sarma left NPL to join the group. On request from Bhabha, the dishes from Potts Hill soon arrived at TIFR, and these were put together as India's first radio interferometer at Kalyan in suburban Mumbai. Operating at a frequency of 610 MHz, the first results were published in *Nature* showing the degree of limb brightening to be consistent with theoretical predictions [17]. The Kalyan telescope operated from 1965 to 1968.

8.2 *Models of the Universe and the Ooty Radio Telescope*

Meanwhile, momentous developments were taking place in the world of astronomy. As Govind would recall, he was sitting in the TIFR library opening the pages of *Nature* as new discoveries were being promptly reported there. There were two papers in 1963, which heralded the discovery of quasars. One was by Cyril Hazard et al., who reported the accurate position and structure obtained from high-resolution lunar occultation observations of the radio source 3C273 from the third Cambridge catalogue. It was associated with a star-like object. Its emission-line spectrum was published by Maarten Schmidt in the accompanying paper who recognized it to be the redshifted Balmer spectrum corresponding to a cosmological redshift of 0.158. This was the largest redshift known at the time, and in today's cosmology, this corresponds to a luminosity distance of 760 Mpc. This implied a huge luminosity which could be achieved by accretion onto a supermassive black hole. Supermassive black holes range from $\sim 10^6$ to 10^{10} $M_\odot$ and provide a viable explanation for producing the energy in the most luminous active galaxies known.

Another controversy raging around that time was the model of our Universe, whether it followed the steady-state model or originated in a singularity derisively referred to as 'big bang' by Fred Hoyle. The counts of radio sources as a function of flux density suggested an evolving Universe in support of a big bang model of the Universe. Govind's approach has been to address big questions of the day and build the instruments to address those questions. However, versatile instruments are capable of addressing a number of other questions at the frontiers of knowledge as has happened with all major telescopes. The instruments which Govind and his team have built were no exception.

With this background, it occurred to Govind that the question of the steady-state vs big bang model of the Universe could be addressed by measuring the angular sizes of distant radio sources using the double-lobed radio sources as standard rods. Statistically, the luminous double-lobed radio sources, the structure of the archetypal example Cygnus A he had determined while at Stanford, would appear weaker when they are more distant. Also, they would appear smaller when more distant. The decrease in median angular size with redshift could be used to distinguish between the two contending models of the Universe. However, at low radio frequencies, which would be easier to build, the angular resolution for a single antenna given by $\sim \lambda/D$ where λ is the wavelength of observations and D is the size of the aperture would be inadequate. With the high angular resolution possible from occultation observations as seen for 3C273, that seemed the way to go. However, the distant sources would also be much weaker, requiring a huge collecting area. With knowledge of parabolic cylinders, one of which he had seen being constructed at Bologna, he conceived of the unique design of the Ooty Radio Telescope. It is a parabolic cylinder 0.53 km long and 30 m wide, innovatively located on a hill with the north-south slope being the same as the latitude of the place [5, 18]. This enabled sources to be tracked continuously with this equatorial mount as the sky rotated. After discussing this idea with M. G. K. Menon, who was then the Dean, he discussed with Homi Bhabha. In Govind's words, Bhabha "grilled me for a couple of hours about the scientific objectives and also the structural and mechanical details of the proposed telescope". Bhabha also reminded him, "Young man, do not waste your time writing a project report. Your main problem would be to collect a team. When you have managed that you can submit a project report and proceed with the design and construction."

The Ooty Radio Telescope was completely indigenously built by a very young team. Besides Govind, and Mohan Joshi and N. V. G. Sarma, who had joined from NPL, and S. S. Bhave, a mechanical engineer from TIFR, the rest of the team were largely young students. The authors of the *Nature* paper describing the ORT included the then youngsters S. Ananthakrishnan, D. S. Bagri, V. Balasubramanian, S. H. Damle, V. K. Kapahi and R. P. Sinha, in addition to the more experienced members of the team [18]. The Ooty Radio Telescope and some of the science it has produced are described in an accompanying article by Ananthakrishnan and Balasubramanian [5].

To mention briefly one key result, the angular size-flux density relationship found from Ooty showed that the linear sizes of sources, l, evolved with redshift, z, or cosmic epoch, $l = l_o(1 + z)^{-n}$ where $n \approx 1$, supporting the big-bang model of the Universe [19, 20]. Direct measurements of sizes of sources with measured redshifts also supported this picture. There was, however, controversy within TIFR itself as Jayant Narlikar was a strong proponent of the steady-state model of the Universe. Today, the overwhelming observational evidence and consensus of astronomers is that of a big-bang origin of the Universe.

Besides cosmology, the ORT contributed towards our understanding of extragalactic radio galaxies, pulsars, interplanetary medium, and the interstellar medium. Due to the vision of both Govind and Radhakrishnan, who had joined as the Director of Raman

Research Institute in 1972, the radio astronomy group at RRI pursued radio recombination lines and pulsars using the ORT. Even today, ORT continues to be a powerful instrument far more sensitive than in its early days with ongoing observational programs on solar wind, pulsars and detecting neutral atomic hydrogen at cosmological distances.

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The successful design and construction of the ORT completely indigenously had an important effect on the microwave antenna industry in the country. Rather than importing an antenna for overseas communication as was earlier planned, a 28.6-m antenna for satellite communication was fabricated indigenously by a firm in Mumbai and installed at Arvi, a village about 80 km north of Pune. Govind and Suresh Tapde, who was to later become the Project Manager of the Giant Metrewave Radio Telescope (GMRT), played a major role in this development.

8.3 *Moving Ahead, Thinking Big*

With the success of the ORT, Govind began thinking of the next major project. The first generation of Govind's students who had built the ORT had mostly finished their theses by the mid-1970s using data from the instrument they had built. This would have been a unique and extremely enriching experience, very different from many of us. When I had joined Govind as his student in August 1977, cosmological studies using radio sources was still a hot topic. His Presidential Address at the meeting of the Astronomical Society of India, published in 1977 [21], was titled *Extragalactic Radio Sources and Cosmology*. However, during the approximately 2-hour meeting with him on the day I joined, it was clear he was exploring a much wider canvas, both in terms of astrophysical problems and the instruments required to address these.

8.4 *Giant Equatorial Radio Telescope*

To detect fainter emission and probe further into the Universe than was possible with ORT, one needed an even larger collecting area. Govind conceived of a giant cylindrical antenna 2 km long and 50 m wide, which would be located on the equator while on his way back from Peru in 1975. Sam Okoye from Nigeria, who was a student of Anthony Hewish at Cambridge, T. R. Odhiambo from Kenya and Govind put together a proposal of forming an International Institute of Space Sciences and Electronics (INISSE) with the Giant Equatorial Radio Telescope (GERT) as its major project in 1978. This was to be located in Kenya through which the equator passes. A workshop was also held at Ooty, funded by UNESCO, which was attended by Govind's mentor in Australia W. N. Christiansen and Anthony Hewish, and Sam Okoye, who was often seen in his traditional colourful Nigerian dress.

Tata Consulting Engineers (TCE) had prepared plans for the large cylinder, as well as, ten smaller ones to form a synthesis telescope, which would have an effective area of 150,000 sq m, about 10 times that of ORT. It was a beautiful concept of developing countries working together in addition to the technical and astronomical objectives. However, the project did not progress after President Jomo Kenyatta's death. Alternative sites at the equator were pursued. Although a site was identified in Indonesia, there were concerns about the area being seismic prone. An earlier attempt to connect with Brazil did not elicit a response. Although this particular project did not fructify, it showed the dynamic and innovative mind of Govind, which would go on to build greater things.

8.5 *Ooty Synthesis Radio Telescope (OSRT)*

Meanwhile, with the large collecting area of the ORT, a synthesis radio telescope was built at Ooty in the late 1970s and early 1980s. Besides the ORT, it consisted of 7 parabolic cylinders up to a distance of about 4 km and operating at 327 MHz. This led to the discovery of a giant radio galaxy and an old, very steep-spectrum radio source in a cluster of galaxies, but most importantly, it was invaluable as a learning step towards building the Giant Metrewave Radio Telescope (GMRT).

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8.6 *Giant Metrewave Radio Telescope (GMRT)*

In addition to the renowned theoretical groups, TIFR has been at the forefront of experimental work, whether it be in the physical or biological sciences. The proton decay experiment in Kolar gold fields, construction of the first computer—the TIFR Automatic Calculator (TIFRAC)—which put Indian scientists only a few years behind in the early 1960s [22], cosmic ray experiments and the ORT are a few of the examples in the physical sciences. With this background, as Govind recalled, B. V. Sreekantan, then Director of TIFR, asked Govind in May 1983 to think of something really innovative. This was followed by several brainstorming sessions within the group.

The big question of the day Govind wanted to address was the formation of galaxies via the detection of redshifted neutral hydrogen. Do galaxies form 'top-down' via the collapse and fragmentation of large clouds of gas, or do they form 'bottom-up' via hierarchical clustering? [23] The signal is expected to be weak, and a telescope with a large collecting area would be required to detect it. By this time, the Very Large Array (VLA) consisting of 27 antennas, each of 25-metre diameter, located in the shape of Y and operating largely at cm wavelengths had come into operation. The antennas could be moved to different locations along the arms of a Y via railway lines varying the resolution of the array over four major configurations, A, B, C and D, with the A-array providing the longest spacing of ∼27 km. Improved image processing algorithms incorporating self-calibration routines were beginning to produce high dynamic range images from short or snap-shot observations. Govind had also spent some time at the VLA while on sabbatical leave, which he took in 1979 after 16 years at TIFR, and observed many 3CR radio sources studying hotspots and jets in these.

Keeping in mind the scientific goal, costs and available expertise, Govind's idea of a major telescope in India would have to be a low-frequency one with a large collecting area. Govind initially toyed with the idea of dividing the proposed GERT 2-km

Figure 2. Some of the pioneers of radio astronomy who have received the Grote Reber Gold Medal seen together on the occasion of Govind's 90th birthday celebrations. The Grote Reber Medal is the most prestigious medal in radio astronomy established by the Trustees of the Grote Reber Foundation for innovative contributions to radio astronomy. From left to right: Ron Ekers, Govind Swarup, Barry Clark and Alan Rogers. Image credit: Divya Oberoi and NCRA-TIFR Archives.

long parabolic cylindrical antenna into 34 parts, to be located in a Y-shaped configuration extending over ~25 km in India. The debate over whether to have parabolic cylindrical or parabolic dish antennas went on for a while, 'dash' vs 'dish' as Peter Wilkinson from Jodrell Bank Observatory would describe it to some of us. The 'dish' won the day with more steering flexibility, ease of changing frequency, and easier to handle polarization characteristics. Govind would bounce these ideas off anybody to get the best possible solution.

The GMRT has been accorded the prestigious IEEE Milestone status earlier this year. The citation said that it "pioneered new techniques in antenna design, receiver systems, and signal transport over optical fibre. GMRT has produced important discoveries in domains such as pulsars, supernovae, galaxies, quasars, and cosmology, greatly enhancing our understanding of the Universe."

Govind named it the Giant Metrewave Radio Telescope, which consists of 30 antennas, each of 45-metre diameter spread over a region of 25 km [24]. Unlike in the VLA, there was no possibility of moving these giant antennas, and these were located optimally to be sensitive to both large-scale structure with low angular resolution and small-scale structure with high angular resolution. The central square consisted of 14 antennas randomly located, while the remaining 16 formed the three arms of the Y. Given its unique design, some of us referred to GMRT as Govind's Masala Radio Telescope! The frequency ranges were 130–150, 230–235, 320–350, 590–620 and 1000–1450 MHz. The electronics for the first four frequency ranges were designed in house at NCRA, while for 1000–1450 MHz these were designed at the Raman Research

Institute overseen by N. V. G. Sarma, who had shifted from Ooty to Bengaluru well before that time.

Govind had been at the forefront of using innovative technology in the construction of radio telescopes. In the construction of GMRT too, he went and studied about optical fibres after receiving a letter from Alec Little on this theme for an Australian telescope. GMRT was the first major synthesis telescope to make extensive use of optical fibres for communication and signal transmission between the antennas and the control room. A novel design christened SMART (stretched mesh attached to rope trusses) was put in place to reduce costs compared with what the initial traditional dish design would have implied. The GMRT has recently been upgraded with new antenna feeds and receivers, almost seamless frequency coverage from ~130 to 1430 MHz, and wide bandwidths up to 400 MHz. Christened as uGMRT this has improved the sensitivity of GMRT by a factor of about 3 [25].

GMRT has made a major impact on the astronomical world and is being used by astronomers from about three dozen countries. It has produced a major survey of about 0.6 million radio sources at 150 MHz.

GMRT has made a major impact on the astronomical world and is being used by astronomers from about three dozen countries. It has produced a major survey of about 0.6 million radio sources at 150 MHz [11]. Govind's personal choice of highlights of results from GMRT and uGMRT include discoveries of double-double radio galaxies, the largest giant radio galaxy which still holds the record, surveys of clusters of galaxies, the youngest supernova remnant, polarized quasi-periodic microstructure emission in millisecond pulsars, the most distant radio galaxy, placing constraints on radio emission mechanism from Venus, and detection of neutral atomic hydrogen by stacking emission from galaxies initially at a redshift of 0.37 and more recently at a redshift of about 1 [11]. Detection of redshifted neutral atomic hydrogen was one of the goals of building the GMRT.

9. Eager to Teach, Eager to Learn

While constructing the major telescopes of the day, he also perceived the importance of trained personpower to not only help build these instruments but also to make optimal use of these.

Figure 3. Govind Swarup along with the academic community of NCRA on the occasion of the academic days in 2018 January. During the academic days held annually and spread over two days, the academic members give talks on their work. On this occasion, Govind close to 89 years of age participated in all the different sessions asking probing questions. Image credit: Shilkumar Meshram and NCRA-TIFR Archives.

Over the years, he had mentored hundreds, starting with some of the brightest young minds from the Atomic Energy Training School and elsewhere to build instruments and also to do cutting-edge science. As mentioned earlier, he was instrumental in initiating the astronomy and astrophysics summer schools in 1976, which continue to this day, and the Joint Astronomy Programme at the Indian Institute of Science, Bengaluru. Alumni from these two programs can be found in institutions across the country.

The opening up of the economy in 1991 provided many more lucrative job opportunities to bright young students. This, coupled with the lack of quality education in the sciences, appeared to affect the number of bright young students wanting to pursue a scientific career. Govind along with V. G. Bhide, former Vice-Chancellor of Pune University, prepared a detailed report on a proposed five-year integrated program, where after four years of science teaching, the fifth year is spent doing research projects at well-equipped national level laboratories. They impressed the importance of this to officials and ministers at the Government of India level. The proposal was finally approved in 2004 after about eight years. It evolved into the Indian Institutes of Science Education and Research (IISERs) at the initiative of C. N. R. Rao. These have grown to be among the premier institutions of our country in a relatively short span of time.

Govind's attempt to reach out was not confined to merely creating elite institutions. In consultation with the people living in Khodad, the nearest village to the GMRT, he was instrumental in setting up the Khodad Rural Science Centre. The objective was to encourage students to develop an interest in science doing hands-on experiments and interacting with visiting scientists. The Science Day celebrations at GMRT have had hundreds of students from rural schools in the neighbourhood exhibiting their projects and winning laurels for themselves and their institutions.

In tune with the overall culture of TIFR, the units of NCRA at both Ooty and Pune have provided opportunities for academic learning and skill development for staff members to progress in their careers. For example, youngsters who have joined soon after their undergraduate degrees as telescope operators or similar positions have learnt new skills, pursued higher degrees and become experts in different areas. Many have occupied key positions both in India and abroad. These are also important societal contributions of the institutions that Govind nurtured.

Govind himself was always eager to learn new techniques and tools. He persuaded several of us to teach him Astronomical Image Processing System, a software for analysing astronomical data, while in his 70s and made the transition from overhead projection to power-point presentations better than many of us. He never shied away from doing the routine and was always ready to check what we may have done with simple back of the envelope estimates. This is something he seems to have picked up from Paul Wild while in Australia. Govind would recollect later "Wild pulled out a plain paper and wrote simple equations analyzing the results. I realized that by simple equations, you could start interpreting data. Basic equations were the most important because you could pull them out anytime. You could use sophisticated theory later." Sometimes when all we had were pixel values of a brightness distribution, we have sat down together to painstakingly manually estimate flux densities of radio sources from these numbers! Today's world is a different one.

10. Concluding Remarks

People like Govind and Bhabha thought far ahead of their times, chalking their trajectories and pushing the frontiers of both science and technology with innovative ideas that have had a much wider impact. It is interesting to note that Homi Bhabha had planned for an Inter-University Centre at Ooty in the mid-1960s. Sadly this did not materialise due to Bhabha's tragic and untimely death. Interestingly, with the GMRT located near Pune, the Inter-University Centre for Astronomy and Astrophysics (IUCAA) was established at Pune by Jayant Narlikar nearly two and a half decades later, leading to a healthy academic and scientific collaboration between the two institutions.

Govind's legacy will live on. He has received numerous awards for his contributions, including election as a Fellow of the Royal Society and the Grote Reber Gold Medal. His everlasting smile and warmth, care and concern helped carve a special relationship with many and would live on with us. To several of us, his students, he would mention that if we had a wiki page, we could connect all the way to Newton through him! On a more serious note, ORT and GMRT were pioneering projects attempting to answer major questions of the day. For Indian science to progress rapidly, our country would require many more such men and women of science with innovative and creative minds to take on major projects, even high-risk ones in different fields.

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