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OBSERVATIONAL FACILITIES

Gamma-ray astronomy with the imaging atmospheric Cherenkov telescopes in India

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Abstract. Ground-based γ-ray astronomy (GRA) using atmospheric Cherenkov techniques has emerged as a mature field during the last three decades in modern high-energy astrophysics. Advent of the imaging atmospheric Cherenkov telescopes (IACTs) for the indirect detection of the cosmic γ-ray photons has played a very important and leading role to understand the non-thermal Universe in the GeV–TeV energy band. In this paper, we present a topical review of the field with a special focus on the two Indian IACTs namely TeV atmospheric Cherenkov telescope with imaging camera and major atmospheric Cherenkov experiment. We also describe the present status and future scope of the GRA using IACTs in India.

Keywords. High energy astrophysics—γ-ray astronomy—imaging atmospheric Cherenkov telescopes—TACTIC—MACE.

1. Introduction

The field of ground-based γ-ray astronomy (GRA), also referred to as TeV astronomy, is concerned with the study of cosmos at very high energies (VHE $>$ 20 GeV) lying at the uppermost end of the electromagnetic spectrum. The emission process associated with the production of the VHE γ-ray photons in the astrophysical sources is not completely understood until now and remains an open question. Moreover, it is commonly believed that the astrophysical VHE γ-rays are produced from the interaction of relativistic particles (mainly electrons and protons) with the ambient photon, matter or magnetic fields. Main goal of the observation of VHE γ-ray sources is to explore the crucial and unique information about the most violent and energetic processes at different epochs in the Universe. Important questions that GRA attempts to answer include: the origin of cosmic rays, radiative processes in the GeV–TeV γ-ray emission, acceleration of particles to relativistic energies in the astrophysical environments, intergalactic magnetic field and extragalactic background light, photon-axion like particle oscillation, dark energy and nature of dark matter. This is also expected to solve fundamental physics problems like quantum gravity effects (Lorentz invariance violation) and physics beyond the standard model of the elementary particles. Development of the state-of-the-art imaging atmospheric Cherenkov telescopes (IACTs) around the globe over the last three decades has immensely benefitted the field with the discovery of more than 220 sources of GeV–TeV γ-rays in the Universe (Ong 1998; Aharonian *et al.* 2008; Hillas 2013; Funk 2015; Holder 2015; Di Sciascio 2019; Singh & Yadav 2021). Different classes of the Galactic and extragalactic sources such as blazars, radio galaxies, galaxy clusters, pulsars and pulsar wind nebulae, supernova remnants, compact object (white dwarf, neutron star, black hole) binary systems and γ-ray bursts have been identified as the GeV–TeV emitters using the ground based γ-ray observations (http://tevcat.uchicago.edu/). Similar to other branches of astronomy from radio to X-ray, TeV measurements with IACTs are playing an active and leading role in

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the multi-messenger probe to the Universe along with the recent additions of neutrino and gravitational wave observations.

After the first detection of the TeV γ-ray emission from the Crab Nebula using an IACT in 1989 (Weekes *et al.* 1989), ground-based GRA experienced steady and slow growth during 1990–2000 due to several negative factors including the indirect nature of the experimental technique, innovative instrumental development, involvement of only a few groups in the world, financial and infrastructural deprivations, etc., (Fegan 1997). However, the field has matured significantly with a firm experimental footing over the last two decades, thanks to the advent of several new generations of ground-based γ-ray observatories around the globe. In this contribution, we mainly emphasize the development of ground-based GRA using IACTs in India. The structure of the paper is as follows: in Section 2, we describe the experimental principle of an IACT. In Section 3, we describe the GRA in India using the TeV atmospheric Cherenkov telescope with imaging camera (TACTIC) and major atmospheric Cherenkov experiment (MACE) telescopes. An outline of the future roadmap of the GRA program in the country is discussed in Section 4. Finally, we conclude in Section 5.

2. Experimental principle of IACT

The γ-ray emission from astrophysical sources is typically described by a differential energy spectrum of the falling power-law form. This leads to very low photon statistics at higher energies and therefore challenges their direct detection by the space-based observatories equipped with small collection area detectors. The cosmic γ-ray photons with extremely low flux enter the Earth's atmosphere (which is opaque to VHE photons) and predominantly produce energetic electron-positron pairs due to their interaction with the atmospheric molecules. This is followed by the development of an extensive air shower (EAS) of secondary charged particles in the atmosphere at an altitude of ~ 10 km above sea level. These relativistic charged particles move towards the Earth with speed faster than the phase velocity of light in the medium and radiate Cherenkov light (Galbraith & Jelley 1953). This leads to the formation of a uniformly illuminated Cherenkov light pool on the ground with a circular diameter of ~ 250 m centered on the EAS core. It corresponds to an effective area of $\sim 10^5$ m^2 for a ground-based telescope. The IACTs are designed to record the image of an EAS by detecting the Cherenkov photons in the light pool as illustrated in Figure 1. An EAS survives for $\sim 10^{-4}$ s in the atmosphere and the Cherenkov light emitted from the EAS reaches the ground in the form of a faint flash of ~ 10 ns duration. Also, the Cherenkov light spectrum peaks in the UV-blue wavelength region and escapes major atmospheric absorption. Therefore, an IACT equipped with a suitable arrangement of focusing mirrors and an array of fast photodetectors such as photomultiplier tube (PMT) or avalanche photodiode (APD) at the focal plane can be effectively used for the indirect detection of the VHE γ-rays emitted from the astrophysical sources. Unfortunately, hadronic showers produced by the cosmic ray particles (protons, electrons, alpha, etc.) in the Earth's atmosphere outnumber the EAS initiated by the GeV–TeV γ-rays by several orders of magnitude. Therefore, the γ-ray signal detected by an IACT has to be extracted against a huge and isotropic cosmic ray background within the field of view of the telescope. Formulation of an effective approach for separating the images of γ-ray showers from those of the cosmic ray showers is very important for the success of the IACT observations.

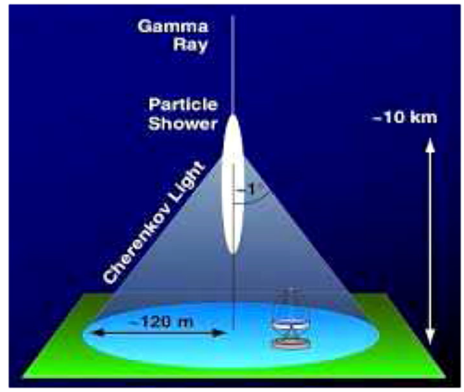

Figure 1. Schematic of the Cherenkov light emission from the EAS initiated by an astrophysical γ-ray photon and the light pool on the ground for IACT observations (image credit: http://www.isdc.unige.ch).

A Cherenkov light flashes from an EAS, initiated by a γ-ray photon or cosmic ray particles, is detected as the signal (S) by the camera of an IACT if the integration time of the photodetector is greater than the duration of Cherenkov flash during the moonless dark nights. However, this is affected by the isotropic light of the night sky or night sky background comprising the zodiacal light, light of bright stars, airglow, fluorescent light and artificial ambient light. The spectrum of night sky background peaks at infrared wavelength and its contribution increases with increasing zenith angle. Therefore, contributions of the light of the night sky are the main source of noise for observations with IACTs and the Cherenkov flash should be detected above the random Poisson fluctuation dominated noise (B). The signal-to-noise ratio is defined as

$$\frac{S}{N} = \frac{S}{\sqrt{B}} \propto \rho \left(\frac{\eta A}{\tau \Omega \phi} \right)^{1/2}, \qquad (1)$$

where ρ is the Cherenkov photon density on the ground, A is the area of light collector/reflector in an IACT, η is the quantum efficiency of the photodetector in the camera, Ω is the solid angle subtended by the photodetector, τ is integration time of the Cherenkov light flash and ϕ is the flux of night sky background which varies from site to site of the IACTs. Within the Cherenkov pool, ρ (number of Cherenkov photons per unit area) is proportional to the energy of primary γ-ray (E) initiating the shower, i.e.

$$\rho = y_\gamma E, \qquad (2)$$

where y_γ is a scaling factor for the Cherenkov photon yield. An EAS can be easily detected as the Cherenkov photon density (ρ) is sizeable and its arrival time can be measured by employing a simple arrangement of focusing mirrors with photodetectors at their focal plane. Salient design features of an IACT are briefly described below:

- *Energy threshold:* It describes the ability of an IACT to detect the smallest Cherenkov light pulse (a measure of the minimum energy of the γ-ray photon initiating the shower) against fluctuations in the night sky background. The smallest Cherenkov pulse or the lowest Cherenkov photon density, that can be detected from an EAS, corresponds to $S/N = 1$ and is inversely proportional to the signal-to-noise ratio. Therefore, the energy threshold ($E_{\rm th}$) of an IACT is defined as

$$E_{\rm th} \propto \frac{1}{y_\gamma} \left(\frac{\tau \Omega \phi}{\eta A} \right)^{1/2}. \qquad (3)$$

  This implies that the collection area (A) of an IACT should be maximized to get the lower energy threshold which is generally desirable in the design of an IACT. IACTs with reflector diameter >15 m are expected to have $E_{\rm th} < 100$ GeV. Conventionally, the energy threshold of an IACT is quoted as the energy at which the differential detection/trigger rate peaks for typical power-law spectra of γ-ray emission from the Crab-Nebula like source.
- *Sensitivity:* Apart from the Poissonian fluctuations in the night sky background noise, the γ-ray detectability of an IACT is greatly affected by the overwhelming cosmic ray background. The sensitivity of an IACT is related to its capability to discriminate between the images of γ-ray and cosmic ray showers. Therefore, it is governed by the minimum number of γ-rays detected in a given exposure time and this γ-ray signal should be statistically significant above the Poisson fluctuations in the cosmic ray background events detected by the telescope. Conventionally, the sensitivity of an IACT is defined as the minimum flux level of a source with Crab-Nebula like the spectrum that gives a γ-ray signal with 5σ (σ being the standard deviation of the fluctuations in the cosmic ray background events detected during source observation) statistical significance in 50 h. Alternatively, the sensitivity of an IACT is expressed as the minimum time required to detect the γ-ray emission from a Crab-Nebula like source at 5σ significance level. Important factors that govern the sensitivity are $E_{\rm th}$, Ω, observational time (T), spectral index of the γ-ray source and that of the cosmic ray background. The γ-ray signal and cosmic ray background increase linearly with T for a steady source and therefore statistical significance of the γ-ray signal is proportional to $\sqrt{T}$. Then, the ratio of significance to $\sqrt{T}$ is a measure of sensitivity which does not depend on T but the flux level of the source. A distinction between differential and integral sensitivity is made depending on the photon energy spectrum of the source under consideration.
- *Angular resolution:* It is a measure of the ability of an IACT to effectively localize the γ-ray source in the sky. Canonically, the angular resolution of an IACT is defined as the angular distance around the source encircling 68% of the detected γ-ray like events and is determined from the two-dimensional distribution of the reconstructed arrival directions of the γ-ray photons. For an IACT, the angular resolution is energy-dependent with a typical value of $\sim 0.1^\circ$ at 1 TeV.
- *Signal extraction:* Besides the light of the night sky, hadronic showers initiated by cosmic rays represent the dominant background for high energy γ-ray observations with an IACT. The images of EAS are recorded at a rate of several hundred Hz by the IACTs and the majority of

these images (>99%) correspond to the showers initiated by protons and electrons (in the GeV energy band). Therefore, extraction of γ-ray signal by rejecting the overwhelming cosmic ray background is very important and challenging task even today. Images of γ-ray and e^-/e^+ initiated EAS appears as a compact, elongated ellipse in the camera plane of an IACT and the major axis of the ellipse indicates the direction of the γ-ray source. On the other hand, images of cosmic ray hadron-initiated showers are wider and show an irregular complex shape. More importantly, the γ-ray images are oriented towards the camera center as the telescope is pointing to the source whereas the cosmic ray (hadronic and e^-/e^+) images have no preferred orientation in the camera plane as they arrive isotropically. Michael Hillas in 1985 proposed that the cleaned images recorded by an IACT can be analyzed by using moment analysis of the recorded pixel signal amplitudes (Hillas 1985). The set of shape and orientation parameters that roughly characterize the images as an ellipse is referred to as *Hillas parameters*. γ-ray like events are segregated from the hadronic background based on cuts on the Hillas parameters derived from the Monte Carlo simulations. In principle, each IACT requires its own set of Hillas parameters with optimized cut values based on preferred parameters for effective γ/hadron segregation. The statistical significance of the γ-ray signal is finally estimated using the well known Li & Ma (1983) formula. If the γ-ray signal from a source is established at statistical significance of 5σ or above, the differential energy spectrum of the detected γ-ray events is derived for further astrophysical studies. In case, the statistical significance level is $< 5\sigma$ for a source, the upper limit on the γ-ray flux at appropriate confidence level is estimated (Helene 1983).

3. GRA in India with IACTs

Ground-based GRA in India was pioneered by two groups, one from the Tata Institute of Fundamental Research (TIFR) under the leadership of Prof. B. V. Sreekantan and another led by Dr H. Razdan from the Bhabha Atomic Research Centre (Mumbai) in early 1970. The TIFR group installed the first atmospheric Cherenkov telescope in the country at Ooty (11.4° N, 76.7° E, 2300 m asl: above sea level) in 1969 for detecting the celestial TeV γ-rays immediately after the discovery of the Crab pulsar. In 1974, the BARC group made a modest start in the field of GRA by setting up an atmospheric scintillation experiment at Gulmarg (34.5° N, 74.3° E, 2700 m asl) to search for γ-ray emission from the supernovae explosions. This was followed by successful commissioning of a multi-mirror atmospheric Cherenkov telescope in Gulmarg for detecting possible TeV γ-ray emission from several candidate sources in 1984 (Koul *et al.* 1989). With over 20 years of experience and contemporary global trends in the budding field of GRA, the BARC group embarked on a very ambitious project GRACE (Gamma-Ray Astrophysics Coordinated Experiments) to establish an international class astronomical facility in Mount Abu (24.6° N, 72.7° E, 1300 m asl) by the side of the already existing infra-red observatory of the Physical Research Laboratory (PRL) in 1992. A comprehensive site survey suggested Gurushikhar in Mount Abu as the best location for the air-Cherenkov experiment (Kaul *et al.* 1994). This site also offers a significantly high observing time with clear and dark moonless nights more or less evenly spaced throughout the year except during monsoon from June to October. Moreover, Mount Abu is located in the same longitude zone Tien Shan, Tibet, Hanle (Ladakh), Pune and Ooty. This longitude clustering by chance greatly enhanced the prospects for undertaking time-coordinated observations on the candidate γ-ray sources. The principal objective of the GRACE project was comprehensive coverage of the wide γ-ray window from one location to investigate: (i) temporal and spectral properties of the γ-ray emission from the Galactic and extragalactic sources, (ii) cosmic-ray energy spectrum and mass-composition around the knee region, (iii) the metagalactic radiation field, (iv) dark matter candidates and (v) feasibility of using horizontally viewing Cherenkov telescopes for detection of ultra-high energy neutrinos (Razdan & Bhat 1997).

3.1 *TACTIC*

The TeV atmospheric Cherenkov telescope with imaging camera (TACTIC) telescope is the first IACT in Asia built under the GRACE project (Koul *et al.* 2007). It was proposed and installed at GOALS (Gurushikhar Observatory for Astrophysical Sciences), Mount Abu within a few years of the real breakthrough which occurred in 1989, when the Whipple Observatory detected TeV γ-rays from the Crab Nebula at 9σ statistical significance level for the first time using imaging Cherenkov technique (Weekes *et al.* 1989). The TACTIC comprises a compact array of four elements disposed of in a triangular configuration as shown in Figure 2. The central telescope, equipped with an effective light collector of area ~ 10 m^2 and a PMT-based camera at the focal plane, is used as an IACT. The remaining three telescopes at the corners of the equilateral triangle of side 20 m are referred to as the vertex elements with their design identical to the central imaging element. Each of the vertex elements utilizes appropriate focal plane instrumentation for recording the spectral, temporal and polarization state of an atmospheric Cherenkov event.

The TACTIC imaging element had first light in 1997 using the prototype 81-pixel camera leading to a field of view of $\sim 2.8° \times 2.8°$ with a pixel resolution of 0.31°. The data collected with the imaging element within a few days of its first light, produced strong evidence for the occurrence of the TeV γ-ray flares from the well known active galactic nuclei (blazar) Mrk 501 (Protheroe *et al.* 1997). This was the unique result from the first science operation of the TACTIC telescope because of the almost synchronous detection of the flaring event by the other five γ-ray telescopes operating around the globe. In 2000, the prototype 81-pixel imaging camera was upgraded to the final camera configuration of 341-pixels leading to a field of view of $\sim 5.9° \times 5.9°$ with a uniform pixel resolution of 0.31°. The TACTIC telescope has been operational since then as a stand-alone IACT in India. The design features of the TACTIC imaging telescope along with its important scientific achievements so far are discussed below:

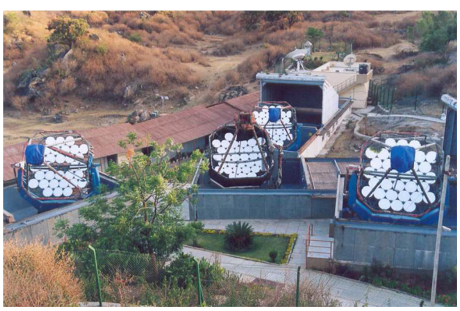

Figure 2. The TACTIC telescope array at GOALS, Mount Abu. The central element of the array is used as a single IACT for the GeV–TeV γ-ray observations.

- *Salient features:* The TACTIC telescope is among the few first-generation IACTs developed in different parts of the globe in early 2000 (Table 1). Out of all the first generation IACTs listed in Table 1, only TACTIC is operational at present to monitor the TeV γ-ray sky. It deploys a computer-based two-axes drive system with an altitude-azimuth mount which provides a tracking accuracy of better than 3 arc-min for a potential γ-ray source across the sky. The weight of the moving part of the telescope is ~ 6 tons. The light collector with ~ 4 m diameter and ~ 3.8 m focal length is a tessellated structure made of 34 high-quality spherical glass mirror facets each of 60 cm diameter and 20 kg weight. The mirror facets have been suitably mounted on the telescope basket to generate an overall light collector surface which approximates a Davies-Cotton optical configuration with an effective focal length of ~ 4 m. The optimum focal plane distance of 3.85 m is found to give the lowest possible spot size of 20 mm diameter. Thus, the f/d-ratio of the TACTIC reflector is close to unity. A coating of SiO_2 is used for protecting the mirror facets from weathering effects.

  The 349-pixel PMT based imaging camera at the focal plane is provided with appropriate instrumentation and backup electronics to detect

Table 1. Summary of the first generation IACTs in the world.

Observatory	Location	Light collection area (m^2)	Energy threshold (GeV)	First light
Whipple	USA (31.5° N, 110.5° W, 2.3 km asl)	75	400	1985
HEGRA	Spain (28.7° N, 17.8° W, 2.2 km asl)	8.5	500	1995
CAT	France (42.5° N, 1.9° E, 1.7 km asl)	18	250	1996
SHALON	Russia (42.8° N, 74.6° E, 4.8 km asl)	11	800	1996
TACTIC	India (24.6° N, 72.7° E, 1.3 km asl)	9.5	850	1997
CANGAROO	Australia (31.2° S, 136.8° E, 220 m asl)	57	400	2000

the Cherenkov pulses in time-coincidence. The key requirements of the PMT in the camera are two-fold: fast response and high gain. A compound parabolic concentrator (CPC) is employed over each PMT to compensate for the dead space between the array of circular pixels. Apart from compensating for the dead space, the CPCs also function as *anti-albedo screens* around the primary light collector for preventing the non-Cherenkov light from reaching the PMT array in the focal plane. The pixel resolution of 0.31° or 18 arc-min is consistent with the spot-size of the light collector for on-axis incident rays. The high voltage requirement of the PMTs (as photon counting device) is ensured by a Zener-diode based hybrid voltage divider network. The high speed associated with the PMT pulses resulting from the registration of an atmospheric Cherenkov light flash is handled by a back-end signal processing electronics based on NIM & CAMAC standards. An interrupt-driven distributed data acquisition and control system has been developed for the TACTIC imaging element.

The TACTIC telescope has dynamic operational energy of 0.85–20 TeV and sensitivity of detecting the Crab Nebula at 5σ significance level in 12 h with a measured TeV γ-ray rate of 15 per hour (Tickoo *et al.* 2014). Extraction of γ-ray signal from the huge cosmic ray hadronic background using artificial neural networks (Dhar *et al.* 2013) and random forest (Sharma *et al.* 2015) based strategies has significantly enhanced the performance of the TACTIC telescope. An artificial neural network-based energy estimation procedure for the γ-ray events detected by the TACTIC telescope yields an energy resolution of $\sim$26% at 1 TeV (Dhar *et al.* 2009). The angular resolution of the telescope is $\sim$0.23°.

- *Scientific achievements:* The astronomical site at GOALS offers about 1200 h of effective observation time every year for monitoring potential TeV γ-ray sources. The TACTIC telescope is deployed for regular observation of the standard candle Crab Nebula before starting the monitoring of potential target γ-ray sources every year since 2001. The time-averaged differential energy spectrum of the TeV γ-ray photons detected by the TACTIC imaging element from the Crab Nebula is described by a simple power-law of the form (Tickoo *et al.* 2014)

$$\frac{dN}{dE} = (2.66 \pm 0.29) \times 10^{-11} \times \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.56 \pm 0.10} \mathrm{ph\,cm^{-2}\,s^{-1}\,TeV^{-1}}. \quad (4)$$

This is in excellent agreement with the Crab Nebula spectrum obtained from other contemporary IACTs like Whipple (Mohanty *et al.* 1998) and HEGRA (Aharonian *et al.* 2000). The artificial neural network methodology for energy reconstruction has led to determine the Crab Nebula energy spectrum upto $\sim$24 TeV (Dhar *et al.* 2009). Apart from the regular Crab Nebula observations for the calibration and performance evaluation, the TACTIC telescope has monitored the TeV γ-ray emission from many sources over the last 20 years. A catalog of the potential sources observed with the TACTIC is reported in Table 2. A historical detection of the TeV γ-ray events from the blazar Mrk 501 was claimed by the newly commissioned TACTIC telescope at the statistical significance of $\sim 13\sigma$ in about 50 h of observation time in 1997 (Protheroe *et al.* 1997). A relatively high γ-ray emission state of Mrk 501 had been detected by the TACTIC during 22–27 May 2012 and the emission spectrum of the source in the energy range 0.85–17 TeV was described by a power-law function (Chandra *et al.* 2017).

TeV γ-ray signal from another blazar Mrk 421 was observed at a statistical significance of 6.8σ in about 79 h of observation time in 2004 by the TACTIC telescope. Subsequently, the TACTIC telescope detected statistically significant TeV γ-ray emission from Mrk 421 at several occasions during its flaring episodes (Chandra *et al.* 2010; Singh *et al.* 2015a, 2018; Rannot *et al.* 2018) as well as long-term monitoring in quiescent states (Yadav *et al.* 2007; Chandra *et al.* 2012; Ghosal *et al.* 2017; Yadav *et al.* 2019). A first model of the multi-wavelength light curve of blazars was proposed using the results from the TACTIC observations of the remarkable February-2010 flare of Mrk 421 (Singh *et al.* 2012, 2017). A short-term TeV γ-rayflaring activity of Mrk 421 on the night of 28 December 2014 with a minimum variability timescale of

Table 2. TeV γ-ray source catalog from the TACTIC observations since 2001.

Name	Type	Redshift (z)	References
Mrk 501	Blazar	0.034	Protheroe *et al.* (1997)
			Godambe *et al.* (2008)
			Chandra *et al.* (2017)
1ES 2344 + 514	Blazar	0.044	Godambe *et al.* (2007)
H 1426 + 428	Blazar	0.129	Yadav *et al.* (2009)
Mrk 421	Blazar	0.031	Rannot *et al.* (2005)
			Yadav *et al.* (2007)
			Chandra *et al.* (2010)
			Chandra *et al.* (2012)
			Singh *et al.* (2015a)
			Singh *et al.* (2017)
			Ghosal *et al.* (2017)
			Singh *et al.* (2018)
			Yadav *et al.* (2019)
			Rannot *et al.* (2018)
1ES 1218 + 304	Blazar	0.182	Singh *et al.* (2015b)
B2 0806 + 35	Blazar	0.083	Bhattacharyya *et al.* (2018)
IC 310	Radio-Galaxy	0.018	Ghosal *et al.* (2018)
NGC 1275	Radio-Galaxy	0.017	Ghosal *et al.* (2020)

less than 1 day was used to constrain the emission region parameter space of the source (Singh *et al.* 2018). Results from the TACTIC observations of the TeV γ-ray emission from different sources are also extensively used by researchers in the world for blazar emission modeling and other astrophysical studies (Biteau & Williams 2015; Lin & Fan 2018; Lang *et al.* 2019; Dmytriiev *et al.* 2021).

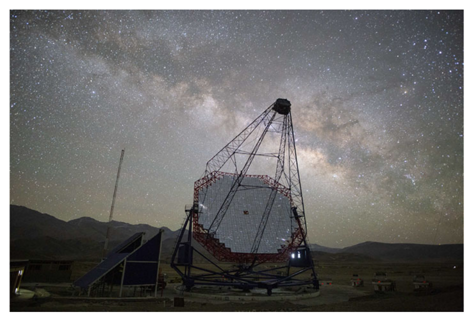

Figure 3. The MACE telescope, ready for its first light, at Hanle, Ladakh.

3.2 *MACE*

Scientists from Bhabha Atomic Research Centre, Mumbai have taken a lead role in setting up a second IACT called the major atmospheric Cherenkov experiment (MACE) in the country as a part of ongoing global efforts to lower the energy threshold of ground-based γ-ray telescopes (Koul 2017). The MACE telescope (depicted in Figure 3) has been successfully installed at Hanle, Ladakh in October 2020. The Hanle site, at an altitude of $\sim$4.5 km in the Himalayan desert region of Ladakh, is emerging as a potential astronomical observatory hub in the country. Apart from the MACE telescope, other infrastructures that exist at Hanle are: (i) 2 m Himalayan Chandra optical/NIR telescope (Indian Institute of Astrophysics, since 2003), (ii) HAGAR TeV γ-ray Array (Tata Institute of Fundamental Research and Indian Institute of Astrophysics, since 2008) and (iii) GROWTH-India 0.7 m robotic telescope (Indian Institute of Astrophysics and Indian Institute of Technology Bombay, since 2018). The MACE telescope will be operated by the HiGRO (Himalayan Gamma Ray Observatory) collaboration between Bhabha Atomic Research Centre, Tata Institute of Fundamental Research and Indian Institute of Astrophysics. New upcoming facilities at Hanle include a large national solar telescope, a 10 m class optical/IR telescope, and a submillimeter-wave astronomy observatory. An annual average of about 260 uniformly distributed spectroscopic nights available at Hanle leads to a good year round sky coverage for γ-ray observations with an excellent duty cycle. This is one of the important criteria for the selection of the MACE telescope site at Hanle. Important features and expected performance of the MACE γ-ray telescope are described below:

- *Design features*: The MACE telescope is equipped with a light collector of 21 m diameter and 25 m focal length. The quasi-parabolic design of the MACE reflector with *f/d*-ratio of $\sim$1.2 helps in reducing the optical aberrations of the telescope. Such a large light collector with area $\sim$340 m^2 has been achieved by segmenting the MACE reflector into 356 mirror panels of size 0.986×0.986 m each with varying focal lengths. These mirror panels are mounted on the telescope basket in the order of gradually increasing focal length from the center towards the periphery. Each panel comprises four square-shaped spherical metallic honeycomb mirror facets of size 0.488×0.488 m each with a similar focal length. All the 1424 mirror facets employed in the MACE reflector have been indigenously developed using diamond turning technology. The reflectance of these mirrors is more than 85% in the wavelength range 280–600 nm. Due to its large size, the MACE telescope is not protected by a dome and the mirrors are continuously exposed to the environment. Therefore, the reflecting surface of each mirror facet is coated with a thin (100–150 nm) layer of SiO_2 for protecting the optical quality of mirrors and ensuring their longevity. Indigenously developed actuators are used for the alignment of the mirror panels to obtain the optimal point spread function. The minimum spot size at the focal plane for the Pole star is measured to be $\sim$45 mm.
The telescope deploys a 1088-pixel imaging camera with a pixel resolution of 0.125° and an optical field of view of $\sim 4.36° \times 4.03°$ at the focal plane. Low gain PMTs with 38 mm diameter are used in the camera for detection of Cherenkov photons. Each PMT/pixel is provided with a hexagonal front-coated CPC of size 55 mm for enhancing the light collection efficiency by collecting the Cherenkov photons incident in the dead space between adjacent pixels. This indicates that the minimum spot size of $\sim$45 mm measured for the Pole star is in good agreement with the size of one pixel in the imaging camera of the telescope. The unique feature of the MACE camera is its modular design comprising 68 camera integrated modules (CIM). Each CIM has 16 PMTs with in-house front-end electronics. A compact and finely programmable, efficient multi-channel high voltage supply is used for the close gain matching of pixels and low power requirement of the camera electronics. An active voltage divider base has been designed to reduce the gain non-linearity of PMTs due to varying count rates. The pixel signal acquisition for the MACE camera has been implemented using an analog memory buffer followed by a high-speed analog to digital converter. A domino ring sampler (DRS-4) developed by Stefan Ritt, Paul Scherrer Institute, Switzerland, is used to achieve a high event rate of $\sim$1 GHz for continuous digitization of the signal from the PMTs. The entire electronics and data acquisition for MACE camera is mounted in the camera itself at the focal plane. The drive system of the 180-ton MACE telescope is based on an altitude-azimuth mount. The positions of two axes (azimuth and zenith) are monitored by 25-bit absolute optical encoders with a tracking accuracy of better than 20 arc-sec. On the world map, the MACE telescope belongs to the family of current generation state-of-the-art IACTs with extremely large aperture-diameter (Table 3). It is the second-largest IACT in the northern hemisphere and fills the longitudinal gap among major IACT around the globe.
- *Performance and science case*: The MACE telescope has been set up at an altitude of

Table 3. Current generation extremely large IACTs in the world.

Observatory	Location	Aperture-diameter (m)	Energy threshold (GeV)	First light
MAGIC	Spain (28.7° N, 17.8° W, 2.2 km asl)	17	30	2004
HESS-II	Namibia (23.2° S, 16.3° E, 1.8 km asl)	28	10	2012
LST-1	Spain (28.7° N, 17.8° W, 2.2 km asl)	23	20	2020
MACE	India (32.8° N, 78.9° E, 4.3 km asl)	21	17	2021

Table 4. Science case for the MACE telescope.

Target	Science
GeV spectrum	γ-ray emission processes and particle acceleration in jets
High redshift observations	Exploring the deep extragalactic Universe
Pulsar and Supernova	γ-ray emission and Galactic astronomy
Cosmic γ-ray horizon	Extragalactic background light, cosmology
Dark matter	Nature of weakly interacting massive particles and relic density

$\sim$4.3 km (highest in the world for existing IACTs) to address the unexplored energy region of 10–200 GeV and beyond in the electromagnetic spectrum. Detailed simulation studies using the CORSIKA package (Heck *et al.* 2012) for the expected performance of the MACE suggest that the telescope has an energy threshold of $\sim$17 GeV and a total γ-ray trigger rate of $\sim$6 Hz in the low zenith angle range up to 40° for a power-law spectrum of the standard candle Crab Nebula (Borwankar *et al.* 2020). The energy threshold increases to $\sim$30 GeV for a log-parabola spectrum whereas the total γ-ray trigger rate decreases to $\sim$2.2 Hz. The total trigger rates for the cosmic ray background proton, electron and alpha particle are $\sim$840 Hz, 20 Hz and 170 Hz respectively. It is expected that the MACE telescope can achieve an integral flux sensitivity of $\sim$2.4% of the Crab Nebula flux at an energy threshold of $\sim$31 GeV. Thus, the MACE telescope has a lower energy threshold than the single MAGIC (MAGIC-I) telescope and is more sensitive for γ-ray energies below 150 GeV (Carmona *et al.* 2008). This is justified by the choice of high altitude site for the MACE to achieve a lower energy threshold. The angular resolution of the MACE telescope for a γ-ray source in the sky is estimated to be $\sim$0.21° in the energy range 30–47 GeV and it improves to $\sim$0.06° in the energy range 1.8–3.0 TeV. The energy resolution is expected to be $\sim$40% at $\sim$31 GeV and it improves to $\sim$ 20% in the high energy range of 1.8–3.0 TeV.

A comparison of the expected performance of the MACE telescope with the single MAGIC telescope suggests that the performance of both the IACTs is rather similar, though MACE has a comparatively low analysis energy threshold. The improved sensitivity and lower energy threshold of the MACE telescope provide an excellent opportunity for effectively exploring the γ-ray sky to understand the mysteries of the Universe. A summary of the plausible science cases using the MACE telescope is given in Table 4.

4. Future of Indian GRA program

The successful operation of the TACTIC telescope over the last two decades has made very significant contributions in the field of ground-based GRA. The experience gained from the TACTIC has greatly helped in setting up the MACE telescope which is currently under the commissioning phase (Yadav *et al.* 2021). The engineering runs conducted to verify the telescope performance and optimize the operating parameters are completed and results from its first light are expected very soon followed by regular science observations starting this year. Therefore, the journey of GRA in India using IACTs in the last 20 years has been very satisfying and heartening. A very bright future is inevitable for the Indian GRA program. An outline of the upcoming plans in the field of ground-based GRA in the country is given below:

- Major upgrade of the TACTIC imaging element hardware for lowering its energy threshold and improving the sensitivity. The telescope after the upgrade will be deployed for dedicated long-term monitoring of the TeV γ-ray emission from different astrophysical sources.
- Development of silicon photomultipliers (SiPMs) based imaging camera by TIFR group and its mounting in the focal plane of one of the vertex elements of the TACTIC observatory. After successful field testing of the camera, a small size ($\sim$4 m diameter) imaging telescope with a SiPM-based camera is planned at Hanle by the HiGRO Collaboration.
- Design and development of small size Schwarzschild–Couder telescopes for TeV γ-ray observations at GOALS Mount Abu.

- Installation of the second MACE telescope (MACE-II) at Hanle for stereoscopic observations.
- Participation in the multi-messenger observation programs within the country and the world.

5. Conclusion

The journey of ground-based GRA using IACTs in India over the last two decades has been very satisfying and encouraging on the whole. The period between the installation of the TACTIC telescope at GOALS Mount Abu in 1997 and setting up the world's second-largest IACT in the northern hemisphere, MACE, at Hanle in 2020 is the era of impressive technological and scientific advances in the country. From the development of an 81-pixel prototype camera for TACTIC to a 1088-pixel camera for the MACE telescope is the testimony of the advances made in the field of technology and resources in a very short time. The commissioning of MACE telescope has opened a new and exciting era for very fruitful research in the field of high energy astrophysics and has also shown a very bright path for multi-messenger astronomy in India.

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