Commissioning of the MACE gamma-ray telescope at Hanle, Ladakh, India

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The MACE telescope has recently been commissioned at Hanle, Ladakh, India. It had its first light in April 2021 with a successful detection of very high energy gamma-ray photons from the standard candle Crab Nebula. Equipped with a large light collector of 21 m diameter and situated at an altitude of ~4.3 km amsl, the MACE telescope is expected to explore the mysteries of the non-thermal Universe in the energy range above 20 GeV with very high sensitivity. It can also play an important role in carrying out multi-messenger astronomy in India.

Keywords: Gamma-ray astronomy, high energy radiative processes, non-thermal Universe, telescope.

IN the present era of multi-messenger astronomy, ground-based gamma-ray telescopes play an important role in probing the very high energy (VHE; $E > 20$ GeV) end of the electromagnetic spectrum. The first detection of VHE photons from the galactic source Crab Nebula was reported by the Whipple group in 1989 using the so-called imaging Cherenkov technique[1]. Subsequent development of the Imaging Atmospheric Cherenkov Telescopes (IACTs) for detecting VHE gamma-ray emission from astrophysical sources has revolutionized the field of ground-based astronomy over the last three decades[2–4]. This has led to installing various state-of-the-art IACTs in different corners of the world. These telescopes have played an important role in detecting more than 240 gamma-ray sources belonging to different astrophysical classes over a short period of about 30 years[5]. Results from these observations have

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greatly helped reveal the nature of non-thermal physical processes involved in the producing VHE gamma-rays from various galactic and extragalactic sources. However, the exact physical process for cosmic gamma-ray emission still remains elusive and offers an active area of experimental as well as theoretical research in the field of high-energy astrophysics. The VHE observations using IACTs are also employed to probe the mysteries of the Universe, such as the origin of cosmic rays, relativistic particle acceleration processes, nature of dark matter particle candidates, intergalactic magnetic field strength, density of low-energy extragalactic background light photons, transparency of the Universe and gamma-ray horizon, existence of new particles beyond the standard model and parameters of the expanding Universe.

The Earth's atmosphere is effectively opaque to the VHE gamma rays as the incident photons undergo pair production and initiate an electromagnetic cascade/shower in the atmosphere. The IACTs at high altitudes measure the Cherenkov light produced by the energetically charged particles in the cascade and indirectly detect the cosmic VHE gamma-ray photons from the ground. Therefore, the detection technique is rather simple, which requires only a large reflector for collecting as many Cherenkov photons as possible and an efficient photodetector at the focal plane[6,7]. Two competing requirements of an IACT are large field of view and a large aperture diameter. The large area of the light collector in turn defines the minimum energy of the VHE gamma rays detectable by an IACT. At present, various state-of-the-art IACTs equipped with an optical reflector of diameter in the range 4–28 m and a camera with a field of view of ~3°–6° are operational around the globe[8,9]. The reflectors in IACTs are made of glass or aluminum mirror facets of circular, square or hexagonal shape. The surface quality of mirrors in the IACTs is less important than that of the optical telescopes. The camera at the focal plane consists of an array of about 300–2000 fast photodetectors such as photomultiplier tubes (PMTs) or avalanche photodiodes (APDs). High-optical quality light concentrators are also mounted in front of the photodetectors in the camera to reduce the dead space between them as well as the contamination from ambient light. This arrangement helps drastically improve the Cherenkov photon detection efficiency of the camera. The IACTs offer an excellent capability of detecting the GeV–TeV gamma-ray photons by efficiently rejecting the huge cosmic ray background, a large field of view, a better angular resolution and an energy resolution of ~15%.

In India, the first IACT was installed at GOALS (Gurushikhar Observatory for AstrophysicaL Sciences), Mount Abu (24.6°N, 72.7°E, 1.3 km amsl), Rajasthan, by the Bhabha Atomic Research Centre (BARC), Mumbai, within a few years of the discovery of the imaging technique by the Whipple group[1]. The TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera) telescope had the first light immediately after its commissioning at Mount Abu in 1997, with the successful detection of the TeV gamma-ray flare from a well-known extragalactic source (Mrk 501) using only the prototype 81-pixel camera having a field of view of ~2.8° × 2.8°. This was the first time four different IACTs operating around the globe detected TeV gamma-ray emission from an extragalactic source. Therefore, the very first observational result from the TACTIC telescope was well received by the VHE gamma-ray astronomy community worldwide. Equipped with an altitude–azimuth-mounted light collector of ~4.0 m diameter and a camera field of view of ~5° × 5°, the TACTIC telescope started its regular science observations in early 2000. With an energy threshold of ~850 GeV, it has made significant contributions in the field of TeV astronomy over the last 25 years[10–12]. This has given confidence to the Indian gamma-ray astronomers to explore the possibility of setting up a world-class observatory with current-generation state-of-the-art telescope. Modern IACTs are designed with large optical reflectors so that their detection energy threshold can significantly be pushed down to sub-GeV in order to have sufficient overlap with the space-based gamma-ray observatories like the large area telescope (LAT) on-board the Fermi satellite[13]. The site altitude also plays an important role in reducing the gamma-ray energy threshold of ground-based gamma-ray telescopes. An IACT at a higher altitude has a lower energy threshold than a lower altitude with similar light collector. As part of ongoing global efforts to develop low-energy-threshold IACTs, BARC has taken the lead role in setting up a very large IACT called Major Atmospheric Cherenkov Experiment (MACE) at Hanle (32.8°N, 78.9°E, 4.3 km amsl) in the Union Territory of Ladakh, India. Here we report the on-site commissioning of MACE, which also has the distinction of being the largest IACT in Asia.

Salient features of the MACE telescope

The MACE telescope has been designed to achieve a lower gamma-ray energy threshold of ~20 GeV and a better sensitivity than the existing stand-alone telescopes in the world[14–16]. The main components of an IACT are the optical reflector (to collect the Cherenkov photons from the shower), an imaging camera (for converting the Cherenkov photons into an image of the shower) and a drive system (for fast repositioning of the telescope). Figure 1 shows the fully installed MACE telescope at Hanle site. Important features of the different hardware subsystems of the telescope are briefly described below.

Mechanical structure

The mechanical structure of MACE is designed to support its drive and optical subsystems by withstanding the wind, thermal, snow and seismic loads in all directions. The mechanical design aims to achieve stability of the telescope under observing (moderate wind load, temperature variations, self-weight, etc.) and survival (high wind, snow, seismic loads) conditions in the remote Himalayan desert region. The major structural sub-assemblies of the telescope are camera basket, boom structure, mirror basket, stiffening ring, elevation brackets, bull gear, middle/side trusses and mount structures. The overall weight of the telescope (~180 tonnes) is supported by six uniformly spaced wheels of 0.6 m diameter each on a 27 m diameter circular reinforced cement concrete (RCC) foundation of 0.6 m width and 3 m thickness. The camera basket is supported at a height of 42 m from the ground and 25 m above the basket by the boom structure made of planar trusses, which are held at designated positions using guy rod assembly. The boom structure is mounted on the 23 m diameter stiffening ring baskets. The mirror basket assembly, which forms a quasi-parabolic base, is a 3D space truss structure connected to the stiffening ring. The combined camera-boom–basket-stiffening ring assembly is supported on an elevation axis through elevation brackets, which in turn are supported by an alidade structure. A large bull gear, which rotates the basket in the meridian direction about the elevation axis, is connected to the stiffening ring and elevation brackets through side/middle trusses. The foundation structure of the telescope, consisting of a circular rail track and a central circular beam of 0.95 m diameter, supports the pintle bearing and alidade structure. The central pintle bearing enables azimuth motion of the telescope. An equipment room of RCC framed structure is constructed below the pintle bearing to house all control-system racks and associated equipment. The foundation structure has been designed according to IS 1893-2002 code for seismic loads.

Drive system

The altitude–azimuth drive system consists of two servo motors per axis in counter torque mode to eliminate backlash. The motors are coupled to gear-boxes. Servo system of the MACE telescope can support slew, position and track modes of operation. The slew mode is used to quickly reposition the telescope to the desired location while switching from one source to another in the sky. In position mode, precision encoders are used as feedback sensors for accurate positioning at the designated angle. The telescope can be held at the commanded position continuously while correcting for wind-induced disturbances. The track mode is the normal mode of operation, wherein demand angles are generated using the astronomical ephemeris of cosmic objects. The azimuth drive rotates the telescope from –270° to +270° about a vertical axis passing through the centre of the basket (azimuth axis), while the elevation drive rotates the telescope from –26° to +165° about a horizontal axis passing through the basket top (elevation/zenith axis). Precision absolute angle encoders for azimuth and elevation axes are used as angle sensors. For azimuth axis, a multi-turn solid shaft absolute encoder with 25-bit resolution per turn and 20 arcsec accuracy is used. Whereas a single-turn solid shaft absolute encoder with 25-bit resolution and 20 arcsec accuracy is used for the elevation axis. This enables the steering of large and heavy telescope structure for pointing and tracking a gamma-ray source with an accuracy of about 1 arcmin in the presence of wind blowing at a speed of up to 45 km/h. The telescope can be quickly repositioned in any direction in the sky within a minute to monitor transient astronomical events like gamma-ray bursts. The peak speed of azimuth drive of the MACE telescope is observed to be ~0.35°/sec.

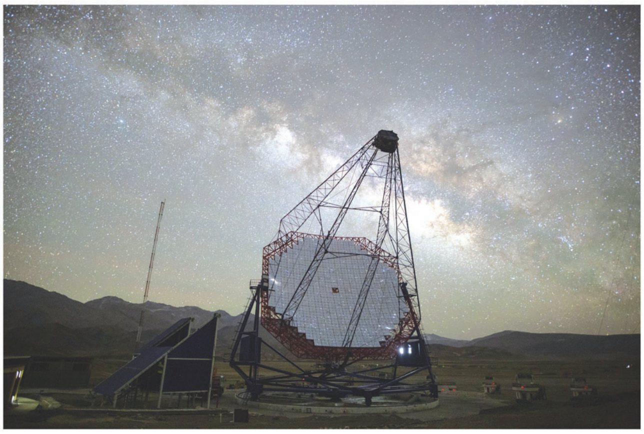

Figure 1. The MACE telescope operational at Hanle, Ladakh, India.

Light collector

The MACE telescope is equipped with a large, 21 m diameter quasi-parabolic optical reflector with *f*-number of ~1.2. The quasi-parabolic design of such a large reflector helps in reducing optical aberration and has virtually no time dispersion. This provides a total light collector area of ~339 m^2 and an effective focal length of ~25 m. Such a large collection area is achieved using the tessellated structure for the telescope reflector. In the case of MACE, the reflector is segmented into 1424 small square spherical mirror facets of size 0.488 m × 0.488 m each, with varying focal lengths between 25.0 and 26.25 m. Four such mirror facets with similar focal length, mounted on a single panel of size 0.984 m × 0.984 m are manually aligned to obtain a single reflecting surface. The position of the panel in the telescope basket is optimized for the best parabolic approximation. Thus, the MACE light collector has a total of 356 mirror panels with focal lengths gradually increasing from the centre of the basket towards the periphery. This varying focal length arrangement of spherical mirror facets helps minimize the on-axis spot size and temporal spread in a spot at the focal plane. An active mirror alignment control system employing linear actuators and diode-lasers fitted on each panel is designed to obtain optimum focusing in all orientations of the basket. More than 1500 metallic mirror facets made up of aluminum alloy have been indigenously developed using the diamond turning technology[17]. These metallic mirrors, supported by a honeycomb structure, not only reduce the telescope weight significantly, but also overcome most of the challenges associated with the glass mirrors employed in the field instruments. The reflecting surface of the mirror facets used in the MACE light collector is coated with a layer of SiO_2 of thickness ~120 nm for environmental protection. The coated surfaces have an average reflectance of ~85% in the visible wavelength band.

Imaging camera

The optical system of MACE efficiently focuses the Cherenkov light collected from the atmospheric showers on a multipixel, high-resolution camera placed at the focal plane of the telescope and forms the shower image. The MACE camera has an optical field of view of ~4.36° × 4.03° and a uniform pixel resolution of 0.125°. It is custom-designed, event-driven system with state-of-the-art technologies for in-house signal processing electronics and high-speed data acquisition. The camera comprises 1088 PMTs with high quantum efficiency (above 30%) and medium gain (~10^4), organized in 68 modules. Each module has 16 PMTs with compound parabolic concentrators of hexagonal cross-section as light guides. A high-voltage for each PMT is provided by a specially designed programmable high-voltage supply. In order to reduce the gain nonlinearity of PMTs due to varying count rates, an active voltage divider base is employed, which imposes a minimal load burden on the high-voltage bias supplies. The detection of short duration (5–10 ns) Cherenkov events is implemented in a highly efficient two-stage digital trigger generation system which detects and validates the occurrence of an event in real time as a close cluster coincidence, so that data (charge and profile) can be acquired by the acquisition system. In the first level trigger (FLT), the occurrence of full or partial coincident clusters in a 16-pixel segment of the camera is detected. The second level trigger (SLT) analyses individual FLT outputs and generates the final trigger at the camera level, which is distributed over the entire data acquisition system. It also validates the trigger based on full hit pattern received from the camera to filter out triggers generated by disjoint clusters. The complete trigger generation and distribution process happens in ~110 ns and the validation process takes an additional 400 ns. The trigger generation is blocked for a programmable time interval following every valid trigger to allow the completion of the event data acquisition. The trigger system also generates regular periodic sky calibration pulse trains to acquire night-sky background during observations. The real-time event processing requirement is achieved by a field-programmable, gate array-based digitization module that processes the data sampled at 1 GSPS (giga samples per second) using a DRS4 (digital ring sampler version 4) chip. The event rates, single-channel rates and validation rates are acquired periodically from the triggers system as part of telemetry data. The occurrence of each event is tagged with a time stamp synchronized with a global positioning system to an accuracy of 1 μs.

Data archival system

A large data volume of ~50 GB is generated during every hour of observation with the MACE camera. A data archival storage system with a capacity of 80 TB is housed in the control room at the telescope site for safe and secure storage of the MACE data. It serves in the archiving and retrieval of raw data generated by the camera, telemetry data from different subsystems of the telescope and processed data from various analysis tools. The on-site data from ~1000 h of telescope operation can be retained for two years at the Hanle control room. The data archival storage system has been developed using standard off-the-shelf commodity hardware, open-source software components and in-house software. It consists of solid-state drives, hard-disk drives and tape drives. Bulk storage is realized using tape and hard drives in a redundant manner, whereas solid-state drives are used only at critical stages. The data archival storage system of MACE also offers a data retrieval facility. For *in situ* use at the Hanle site, data are available over the network file system only on the servers, which are part of the archival system. For systems which are external to the MACE data archival storage system, data download is available via MACE-Explorer or at AMBAR-Project share. MACE-Explorer is a web-based application developed for querying and retrieving observation event data through various parameters. It only provides an interface for querying and downloading, and does not store or tag the data or allow any upload. AMBAR is a centralized storage service developed by Computer Division at BARC to keep data safe and secure. The MACE data archival server at Hanle is synched with AMBAR over ANUNET, supporting the feature of automatic back-up and data-sharing among the users. Using the AMBAR facility, MACE data can be accessed from any machine on the BARC Intranet. The MACE data project share is available as a network drive that can be mapped onto a Windows or Linux machine.

Remote operation

The MACE telescope is also equipped with a remote operation facility using ANUNET over GSAT 18 satellite network. It provides multiple concurrent operation consoles for coordinating control and monitoring activities from different geographical locations. A single operation console can perform the role of controller and the rest is available for simultaneous observers with a provision of dynamic entry of new clients. For an effective interface, client-server architecture is adopted during the remote operation of the telescope. The command and data servers run on-site, whereas clients can connect to the server from any remote location in India.

ANUNET is a private wide-area network interconnecting all major units of the Department of Atomic Energy, Government of India, to provide communication infrastructure. It has a robust four-layer connectivity architecture, viz. National Knowledge Network links, leased links, dedicated fibre and VSAT links. The MACE telescope is connected to ANUNET through a VSAT link of 3 Mbps throughput.

Weather monitoring system

As an important subsystem of the MACE telescope, the weather monitoring system consists of a datalogger, a sky-quality meter, a pyrometer, an anemometer, and a fish-eye camera. It is integrated with the MACE operator console for monitoring various weather parameters in real-time. The datalogger records temperature, humidity, wind speed, etc., provides parameter visualization in the form of graphs, calculates hourly-averaged weather parameters and stores them for future use during data analysis. The anemometer is included to obtain the values of wind speed and direction more accurately. The sky-quality meter measures sky brightness and the pyrometer provides information about the clear sky. The fish-eye camera gives a measurement of near-solar ground radiation. These parameters are also used as an interlock for the telescope operation. Alarms and warnings are generated if the weather is not favourable for the safe operation of the telescope.

Commissioning and first light

Individual subsystems of MACE have been indigenously developed and debugged in different laboratories at BARC and Electronics Corporation of India Limited (ECIL), Hyderabad. In the initial phase, trial installation of the telescope mechanical structure was carried out at ECIL. The camera electronics was also installed in the camera structure and tested. After ensuring the compliance of the telescope subsystems and operations, the structure was dismantled and transported to Hanle for smooth installation at the remotely located site in Ladakh. The final installation work proceeded as follows:

- Construction of a 240 kW solar power station for fulfiling the power requirements of the telescope operation as well as other site activities, including local livelihood in the Himalayan desert.
- Completion of the civil works related to the 27 m diameter rail track and installation of the first layer of the adelade structure with six wheels.
- Mounting and alignment of four mirror facets with similar focal lengths on a single honeycomb panel using a suitable arrangement of in-house-designed ball-and-socket adapters for holding the facets.
- Assembly of mechanical structure and mirror basket. A total of 356 mirror panels were designed on the ground and subsequently mounted on the telescope basket in 11 predefined focal length zones to obtain a quasi-parabolic reflector of 21 m diameter.
- The 356 mirror panels on the telescope basket were individually equipped with linear actuators and servo motors for their realignment to achieve the desired optical point spread function of the telescope reflector in any direction. Figure 2 shows an image of Polaris (pole star) at the focal plane of the MACE telescope after the successful alignment of the full optical system. A CCD camera along with a lens of 18 cm focal length was mounted at the centre of the telescope basket to capture the optical image of the star formed by the reflector at the focal plane. The 80% containment diameter of the pole star image was estimated as ~46 mm after performing a Gaussian fit to intensity distribution in the image. This meets the design specification of the MACE optical system with a point spread function of less than or equal to 55 mm or 0.125°. It is important to note that the offset between the centroid of the pole star image and optical axis of the telescope is ~1.5 arcmin or 0.025°. This indicates that the mispointing in the absolute direction of the telescope is well within its optical point spread function.
- Finally, the fully wired 1088-pixel imaging camera structure was placed at the focal plane of the telescope. A number of engineering and technical trial runs were conducted to optimize the performance and operation of the camera along with the complete data acquisition system by exposing it to the night sky. They mainly involved charge uniformity of the whole camera, charge resolution of each pixel in the camera, time resolution with a test pulse and calibration laser. A homogeneous response of the camera was achieved by adjusting the high voltages for all pixels or PMTs to get the same charge output against the calibration pulse input from a laser, as each PMT has a different gain at a given high voltage. Figure 3 depicts the uniformity of the triggered

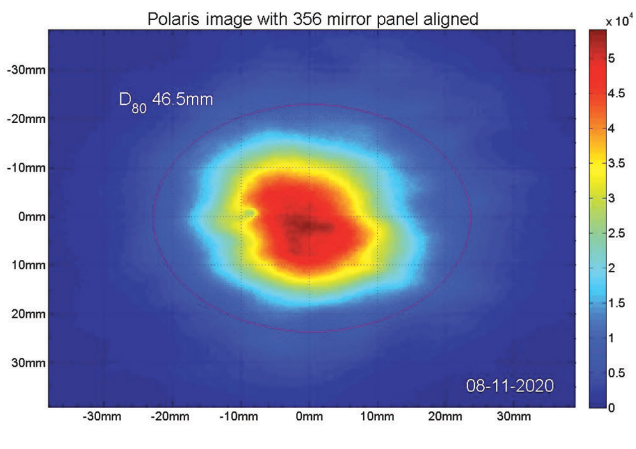

Figure 2. Optical image of the pole star in the focal plane of the MACE telescope recorded by a CCD camera.

pixels in the trigger region covering 576 inner pixels in the MACE camera. It is evident that pixels in the trigger region of the camera (inner 24 × 24 pixels) are homogeneously triggered during one of the observation events. Flat-fielding of the PMT gains is regularly done during observations in order to avoid the spread of gains from the manufacturing process.

- A software pipeline called MAP (MACE data Analysis Package) has been developed in-house to process and analyse the MACE data. MAP is a collection of data-processing algorithms based on C++ and ROOT frameworks. The main input of MAP is raw data written to disk by the data acquisition system of the MACE camera. After performing various intermediate steps based on the standard data analysis procedure of IACTs, MAP provides the gamma-ray signal and its statistical significance for a given source direction. Events corresponding to the huge cosmic-ray hadronic background are detected by the IACTs at a much higher rate than the gamma-ray events during observation of a potential target source and therefore challenge the gamma/hadron segregation in the data. The images of hadronic showers formed in the telescope camera are irregular and wider than their gamma-ray counterpart. This feature is effectively used in the IACT data analysis to segregate gamma-ray events from hadronic events using the method first proposed by Hillas[18] in 1985 based on the moment analysis of the Cherenkov light distribution corresponding to the clean shower images. Due to the isotropic nature of cosmic rays, the hadronic shower images are randomly oriented in the camera plane, whereas gamma-ray shower images are oriented towards the source position in the camera. Consequently, when an IACT tracks a gamma-ray source in the sky, the signal builds up as an excess of gamma-ray-like events aligned with the camera centre. This orientation of events in the telescope is characterized by the Hillas parameter ALPHA[18]. From the detailed Monte-Carlo simulation studies, ALPHA is defined to be in the range 0°–10° for gamma-ray events detected by the MACE camera and cosmic-ray events have no preferred orientation due to their isotropic arrival. Therefore, the frequency distribution of the ALPHA parameter of all the detected events by the camera of an IACT can be used as an effective tool to discriminate the gamma-ray and cosmic-ray-induced air shower images after applying appropriate cuts on a set of other Hillas parameters[18]. An extensive Monte-Carlo study has been performed to obtain the optimized ranges of Hillas parameters for gamma/hadron segregation in MAP. The statistical significance of gamma-ray signals was estimated using the methodology proposed by Li and Ma[19] for analysis of results in gamma-ray astronomy.
- After performing engineering trial runs of more than 350 h, the MACE telescope was at first deployed to observe the standard candle Crab Nebula on the night of 1 April 2021. The observations were carried out at high zenith angles above 40° for about 1 h. The data were analysed using tools of MAP software. Standard data quality checks were applied to estimate the good time interval after rejecting the raw data affected by bad weather/atmospheric conditions, hardware malfunction, unusual background rates, etc. This resulted in an effective or live time of ~47 min. Figure 4 shows results from the final data analysis. An excess of events is apparent at low ALPHA values up to 10°, generally referred to as gamma-ray domain or ON-source region. Beyond 10°, the distribution is relatively flat, which indicates the cosmic-ray background domain or OFF-source region. This corresponds to a signal-to-noise ratio of greater than 5 and provides clear evidence for the detection of plausible gamma-ray signals from the direction of the Crab Nebula at ~5.3σ statistical significance level. This marked the first successful light of the MACE telescope. These preliminary results were presented at the 37th International Cosmic Ray Conference (ICRC 2021) to update the status of MACE among the international

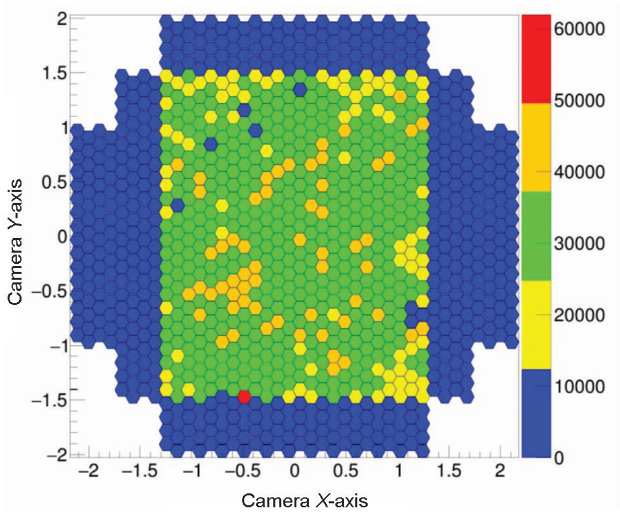

Figure 3. MACE camera geometry with 1088 pixels and the hit pattern of pixels in the trigger region (inner 576 pixels) during a trial run.

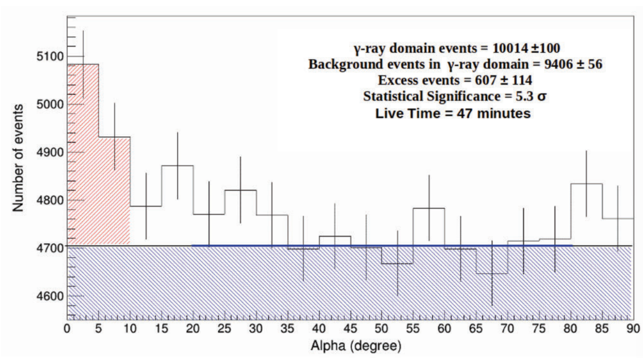

Figure 4. Results from the observation of Crab Nebula with the MACE telescope on the night of 1 April 2021.

community of high-energy astrophysics research, especially the gamma-ray astronomers[20]. Based on the first successful detection of statistically significant gamma-ray signals from the standard candle Crab Nebula, the telescope was officially commissioned in September 2021.

- Subsequently, MACE was further deployed for Crab Nebula observations in order to optimize and fix the operational parameters of the telescope before taking up regular science observations. Interestingly, gamma-ray signals above 5σ confidence level were repeatedly detected by the MACE telescope from the direction of the Crab Nebula. These post-commissioning results helped in characterizing the consistency in the telescope performance. Figure 5 shows results from the recent observation of the Crab Nebula with MACE on the night of 29 January 2022. The source was monitored for more than 270 min. Clean data with a live time of ~235 min yielded the detection of gamma-ray signals at $\sim 8.7\sigma$ statistical significance level. The preliminary differential energy spectrum of the detected gamma-ray photons was approximately described by a log–parabola function of the form: $dN/dE = f_0(E/E_0)^{-\alpha + \beta \log(E/E_0)}$, where f_0 is the normalization factor at energy E_0, and α and β are the spectral index and curvature parameter respectively. Figure 6 presents the spectral flux points estimated from the MACE observations in the energy range 32–400 GeV along with the best-fit parameters of the log–parabola function. The decorrelation energy (E_0) was fixed at 300 GeV during the fitting of the spectrum. The Crab Nebula spectrum obtained from the MACE observations was consistent with the MAGIC-I spectrum within statistical uncertainties[21]. It is important to note that the single MAGIC-I telescope measured the Crab Nebula spectrum in the energy range above 60 GeV, whereas the MACE telescope can measure the same spectrum at energies above 30 GeV. This highlights the importance of the lower energy threshold of the MACE telescope.

Science cases

The MACE telescope operational at Hanle has unique geographical and astronomical advantages on the world map. It has the distinction of being an extremely large IACT located at the highest altitude in the world. Also, it appropriately fills the longitudinal gap among different gamma-ray observatories operating around the globe. In particular, the performance of MACE is comparable with the single MAGIC telescope, though the former has a lower energy threshold and better sensitivity in the range 20–150 GeV. Monte-Carlo simulation studies suggest that the telescope can achieve an integral sensitivity of ~2.4% of the Carb Nebula flux in 50 h at an energy threshold of ~20 GeV (ref. 15). The energy resolution of MACE is estimated as ~40% at ~20 GeV and ~19% in the high-energy range above 1 TeV. The angular resolution for a gamma-ray source in the sky is expected to be ~0.21° at energies up to 50 GeV and ~0.06° in the energy range above 1 TeV. Equipped with the above unique features, the MACE telescope provides an excellent opportunity for exploring the mysteries of the Universe such as: (i) high-energy radiative processes and particle acceleration in the jets of extra-galactic sources; (ii) gamma-ray emission from pulsars and supernova remnants in the Milky Way galaxy; (iii) gamma-ray propagation effects of the high-energy photons over cosmological distances; (iv) nature of dark matter candidate particles and their relic density, and (v) association of unidentified gamma-ray sources reported in the Fermi catalog. Due to its lower energy threshold, the MACE telescope has the potential to explore gamma-ray emission from the deep Universe up to a redshift of $z \sim 2.5$ (ref. 22). This has implications for probing the cosmological evolution of the extra-galactic background radiation in ultraviolet/optical/infrared wavebands and constraining their photon density[23]. Apart from the above scientific motivations, MACE is expected to play a major role in the field of multi-messenger astronomy in India and abroad. Therefore, results from the regular science operation of the MACE telescope may help in addressing outstanding

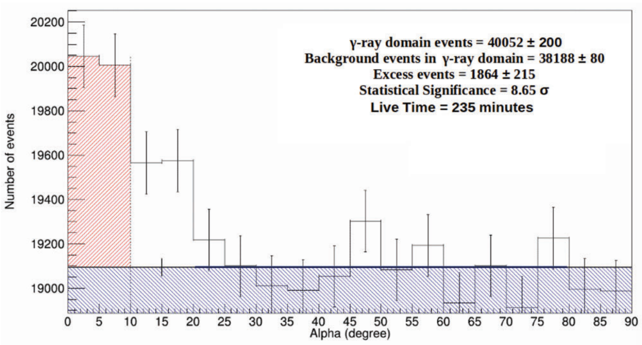

Figure 5. Results from the monitoring of Crab Nebula by the MACE telescope on the night of 29 January 2022.

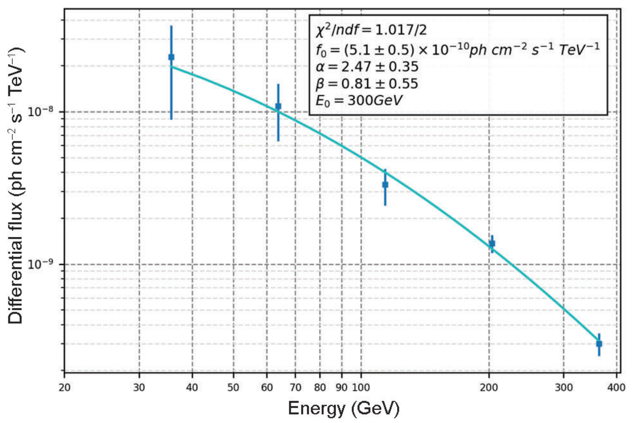

Figure 6. Differential energy spectrum of the Crab Nebula measured by the MACE telescope on the night of 29 January 2022.

problems in the fields of high-energy astrophysics, astroparticle physics and observational cosmology.

Summary and outlook

The MACE telescope is the first of its kind to be fully designed, developed and commissioned in India. It was fully installed at Hanle site in October 2020 after passing the primary trial runs at ECIL. It immediately started collecting on-site engineering trial run data for optimization of the operation of its various subsystems. After a rigorous operation of the telescope for more than 350 h, it was deployed collect first light commissioning data from the direction of the standard candle Crab Nebula. The MACE telescope had its successful first light on the night of 1 April 2021, when it detected statistically significant gamma-ray signals from the source. Subsequently, it was officially commissioned in September 2021. The measurement of Crab Nebula spectrum in the energy range above 30 GeV with the MACE telescope is unprecedented in the field of ground-based very high-energy gamma-ray astronomy. MACE is now fully operational and has been deployed for collecting science data since its commissioning. It is deemed that the telescope would provide path-breaking results in the high-energy astrophysics research over the next decade.

This is the first major step in developing the Hanle site as a world-class astronomical observatory in India. A stereoscopic MACE system with three similar telescopes has been proposed for ground-based astronomy with enhanced sensitivity, improved energy resolution and better angular resolution.

1. Weekes, T. C. *et al.*, Observation of TeV gamma rays from the crab nebula using the atmospheric Cerenkov imaging technique. *Astrophys. J.*, 1989, **342**, 379–395.
2. Ong, R. A., Very high energy gamma-ray astronomy. *Phys. Rep.*, 1998, **305**, 93–202.
3. Hillas, A. M., Evolution of ground-based gamma-ray astronomy from the early days to the Cherenkov Telescope Arrays. *Astropart. Phys.*, 2013, **43**, 19–43.
4. Chadwick, P., 35 Years of ground-based gamma-ray astronomy. *Universe*, 2021, **7**, 432.
5. http://tevcat.uchicago.edu (accessed on 15 July 2022).
6. Fegan, D. J., Topical review: γ/hadron separation at TeV energies. *J. Phys. G.*, 1997, **23**, 1013–1060.
7. Aharonian, F. *et al.*, High energy astrophysics with ground-based gamma ray detectors. *Rep. Prog. Phys.*, 2008, **71**, 096901.
8. Holder, J., Atmospheric Cherenkov gamma-ray telescopes; arXiv: 1510.05675.
9. Di Sciascio, G., Ground-based gamma-ray astronomy: an introduction. *J. Phys., Conf. Ser.*, 2019, **1263**, 012003.
10. Koul, R. *et al.*, The TACTIC atmospheric Cherenkov imaging telescope. *Nucl. Instrum. Methods Phys. Res. A*, 2007, **578**, 548–564.
11. Singh, K. K. and Yadav, K. K., 20 Years of Indian gamma ray astronomy using imaging Cherenkov telescopes and road ahead. *Universe*, 2021, **7**, 96.
12. Singh, K. K., Gamma-ray astronomy with the imaging atmospheric Cherenkov telescopes in India. *J. Astrophys. Astron.*, 2022, **43**, 3.
13. Ajello, M. *et al.*, Fermi large area telescope performance after 10 years of operation. *Astrophys. J. Suppl.*, 2021, **256**, 12.
14. Borwankar, C. *et al.*, Simulation studies of MACE-I: trigger rates and energy thresholds. *Astropart. Phys.*, 2016, **84**, 97–106.
15. Borwankar, C. *et al.*, Estimation of expected performance for the MACE γ-ray telescope in low zenith angle range. *Nucl. Instrum. Methods Phys. Res. A*, 2020, **953**, 163182.
16. Sharma, M. *et al.*, Sensitivity estimate of the MACE gamma ray telescope. *Nucl. Instrum. Methods Phys. Res. A*, 2017, **851**, 125–131.
17. Dhar, V. K. *et al.*, Development of a new type of metallic mirrors for 21 meter MACE γ-ray telescope. *J. Astrophys. Astron.*, 2022, **43**, 17.
18. Hillas, A. M., Cerenkov light images of EAS produced by primary gamma rays and by nuclei. In 19th International Cosmic Ray Conference, San Diego, CA, United States, 1985, vol. 3, p. 445.
19. Li, T. P. and Ma, Y. Q., Analysis methods for results in gamma-ray astronomy. *Astrophys. J.*, 1983, **272**, 317–324.
20. Yadav, K. K. *et al.*, Status update of the MACE gamma-ray telescope. In Proceeding of Science, 37th International Cosmic Ray Conference, Berlin, Germany, 2021, p. 756.
21. Albert, J. *et al.*, VHE gamma-ray observation of the Crab Nebula and its pulsar with the MAGIC telescope. *Astrophys. J.*, 2008, **674**, 1037–1055.
22. Tolamatti, A. *et al.*, Feasibility study of observing γ-ray emission from high redshift blazars using the MACE telescope. *J. Astrophys. Astron.*, 2022, **43**, 49.
23. Singh, K. K. *et al.*, Probing the evolution of the EBL photon density out to $z \sim 1$ via γ-ray propagation measurements with Fermi. *Astrophys. Space Sci.*, 2021, **366**, 51.

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