MACE gamma-ray telescope – a status update

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A 21 m diameter imaging atmospheric Cherenkov telescope is being installed at the high-altitude astronomical site at Hanle in the Ladakh region of North India. When operational by 2018, it will have the distinction of being the largest gamma-ray telescope in the northern hemisphere and the second largest in the world. Operating at a trigger threshold energy of <20 GeV, it will play an important role in understanding very high energy processes in the Universe.

Keywords: Gamma-ray astronomy, galactic and extragalactic sources, high-energy processes, imaging atmospheric telescope.

Introduction

VERY high energy (VHE) gamma-ray astronomy has made impressive progress during the last two decades, from a few well-established sources to nearly 200 galactic and extragalactic sources of various types catalogued presently[1,2]. Most of these sources have been detected in the >100 GeV energy range by large (>10 m diameter) ground-based gamma-ray telescopes like VERITAS, MAGIC and HESS. The smaller (~3 m diameter) telescopes like TACTIC, HAGAR and FACT are also complementing these efforts by monitoring flaring episodes of nearby active galactic nuclei in the energy range ≥400 GeV (refs 3–5). The >100 MeV catalogue has also expanded from the 270 sources detected by EGRET detector on-board the Compton satellite observatory to more than 3000 sources picked up by the Fermi satellite observatory which was launched in 2008 (ref. 6). The Fermi satellite has detection capability up to 300 GeV; however, its sensitivity beyond 10 GeV is limited because of its small detection area of about 1 sq. m. The energy band of 10–100 GeV which has remained largely unexplored got a fill-up with the recent release of the first Fermi-LAT catalogue of >10 GeV, which lists 514 sources[7]. As the detailed temporal and spectral studies of highly variable sources like blazars are limited by the sensitivity constraint of the Fermi detector, exploring the gamma-ray sky in the tens of gegaelectronvolt energy range with low threshold ground-based atmospheric Cherenkov imaging telescopes continues to be an important research area. The recent detection of pulsed gamma ray emission above 20 GeV from Vela pulsar opens up another interesting area of understanding the nature of pulsars at gegaelectronvolt energies with ground-based gamma-ray telescopes[8].

In order to address the unexplored energy region of 10–100 GeV and beyond, the Himalayan Gamma Ray Observatory (HiGRO) collaboration formed by BARC, TIFR and IIA is setting up a large area imaging atmospheric Cherenkov telescope MACE (Major Atmospheric Cherenkov Experiment) at Hanle, in the Ladakh region of North India. Hanle (32.8°N, 78.9°E, 4270 m amsl) is a high-altitude dark astronomical site in the Himalaya, which offers an annual average of about 260 uniformly distributed spectroscopic nights, leading to a good year round sky coverage for source observations. The 2 m diameter Himalayan Chandra Telescope (HCT) set up by IIA has been in operation at Hanle since 2000 and offers an opportunity of concurrent VHE and optical–infrared (IR) observations. The location also has the advantage of extending the longitudinal coverage of atmospheric Cherenkov telescopes in the northern hemisphere by filling the gap between the MAGIC and VERITAS telescopes. Located closer to the shower maximum, the Cherenkov photon intensity at Hanle is about a factor of ~2 more than at MtAbu (1300 m amsl), where the TACTIC gamma-ray telescope has been operating for more than a decade[9]. The reduced atmospheric attenuation effects at higher altitudes combined with the geometrical aspects of atmospheric Cherenkov light contribute substantially to the enhancement of the Cherenkov photon density at Hanle. The high altitude of Hanle and the large 21 m diameter light collector of MACE are used to advantage to lower the gamma-ray trigger threshold of the telescope to ~20 GeV.

Telescope design concept

The overall design concept of the telescope was evolved with the main target of lowering the trigger energy threshold to ~20 GeV with indigenous design and development. The three major subsystems of the telescope were identified as the mechanical structure, including its altitude–azimuth drive system, light collector optics, and the multi-pixel camera and its data acquisition system. The number of photons required for the generation of an unambiguous signal from the photomultiplier-based camera at the focal plane of the light collector was used as a

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parameter to optimize the light collector specifications to ~21 m diameter and 25 m focal length. The optimization of the pixel size and number of pixels went through a series of iterations before being finalized as 0.125° (7.5 arcmin) and 1088 respectively. In order to overcome the problem of signal attenuation through long lengths of coaxial cables, it was decided to house all the signal-processing electronics at the focal plane of the telescope with only power and data cables going to the control room. During a series of technical reviews it was decided to install two instrumentation shelters on the alidade structure of the telescope. One of these shelters was designated to house the dual rack drive control system, while the other will house the 48V power supply required for the camera electronics and the controllers of the mirror alignment system. An additional specification of quick pointing towards any direction in the sky in a maximum duration of 60s was also incorporated for monitoring gamma-ray burst events. In order to reduce the weight of the telescope structure the use of composites was investigated, but in view of the limited expertise available in the country on composite materials, mild steel of EN-24 grade was chosen as the main structural material for the telescope. This material retains good impact strength at low temperatures of –30°C experienced at Hanle during the winter months. Diamond-turned aluminium honeycomb mirrors, whose 30 cm diameter prototypes were developed indigenously, were selected for use on the telescope. The detailed design work for the various telescope subsystems was started in 2008.

Simulation studies

After defining the main specifications of the telescope, detailed simulation studies were carried out with the CORSIKAv6.735 (Cosmic Ray Simulations for KAscade) simulation package to understand its expected performance[10]. A database of a million showers each for gamma rays, protons, electrons and alpha particles at each of the zenith angles of 0°, 20°, 40° and 60° was used for the study. A total of 16 million showers in the energy range 5 GeV–10 TeV was generated for the simulation study. The night sky background measurements taken at Hanle during 2003–08 by HCT were used to compute the contribution of the night sky background to the Cherenkov event[11], which turns out to be ~0.29 photoelectrons/ns. In order to ensure that the actual after-pulsing rate of the photomultiplier tubes is also considered in the determination of the single-pixel threshold, laboratory measurements of a few gain-calibrated photomultiplier tubes were taken by exposing them to the light intensity which gives rise to the anode current magnitude expected at Hanle. Various close cluster nearest neighbour (CCNN) trigger schemes were also investigated and it was determined that the best performance was obtained with 4 CCNN trigger along with a single pixel threshold of nine photoelectrons. Using the Random Forest technique we have estimated the integral sensitivity of the MACE telescope. Figure 1 depicts Its comparison with MAGIC-I sensitivity. Details of simulation studies and sensitivity estimation are given in the litereture[12,13]. The preliminary sensitivity estimates of the telescope suggest a 5σ detection of a source with 2.7% Crab Nebula flux in 50 h of observation.

Mechanical structure and drive system

The MACE telescope deploys a 21 m diameter quasi-parabolic light collector on an altitude–azimuth tracking structure. In order to ensure stability of the structure, a track and wheel design is followed for the azimuth movement. The 180 tonne telescope is supported on uniformly spaced 6 × 60 cm diameter and 100 mm wide wheels on a 27 m diameter circular track whose planarity has been maintained to within ± 0.75 mm. The track is formed of 25 machined interlocking sections which are clamped to the sole plate anchored to the 600 tonne RCC circular foundation of 0.6 m width and 3 m thickness. The first layer of the alidade structure connects the six wheels and the central pintle-bearing housing. Two diametrically opposite A-frame structures rise to a height of 15 m to support the two elevation brackets which house the spherical roller bearings of 148 mm inner diameter. These brackets in turn support the 23 m diameter stiffening ring (SR) from which the mirror basket is suspended. The SR also supports the four planer booms which in turn hold the 1.5 tonne camera assembly at a distance of 25 m from the mirror surface. The two-layer mirror basket follows a rod and knot design and has a square pitch of 1008 mm on the front surface where the 984 mm × 984 mm mirror assemblies are to be installed. Figure 2 shows a photograph of the trial assembly of the telescope

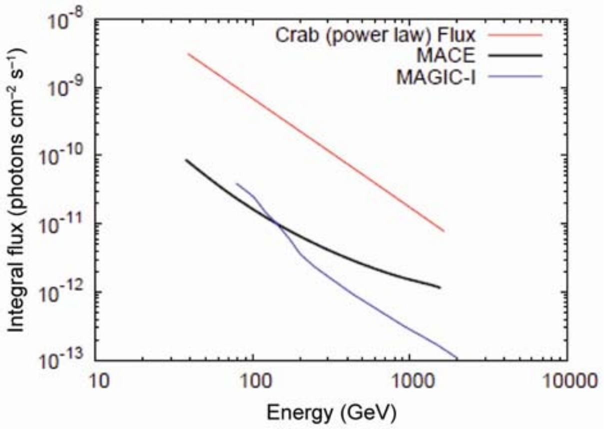

Figure 1. Comparison of the integral sensitivity of the MACE and the MAGIC-I telescopes at 5° zenith angle. The Crab Nebula power law spectrum is also plotted for reference.

structure. Two azimuth drive-wheels are coupled to three phase, permanent magnet brushless AC servo motors through multi-stage gearboxes for providing azimuth movement. The elevation movement is provided through a gear box coupled to the 13-section bull-gear assembly of ~11.6 m radius. All the drives have counter torque capability to avoid gear backlash errors. The motors are driven by pulse width-modulated drive amplifiers powered by 480V DC derived from a solar photovoltaic array-based power station. The positions of the two axes are monitored by 25 bit absolute optical encoders with 20 arcsec accuracy. Both the azimuth and elevation gear boxes have also been provided with high speed options to move the telescope at $3°s^{-1}$ to quickly point in the direction of interest on receipt of a satellite alert for events like a gamma-ray burst. The drive system can ensure tracking accuracy of better than 1 arcmin in wind speeds of up to 30 km h^{-1}. At sustained wind speeds of >40 km h^{-1}, the telescope is automatically brought to the parking position. The telescope structure is designed for survival at wind speed of 150 km h^{-1}.

Light collector optics

The 21 m diameter mirror basket of the telescope has 356 square mirror panels of 984 mm × 984 mm fixed on it. Each mirror panel comprises 4 mm × 488 mm × 488 mm spherical mirror facets pre-aligned to give a spot size of <4 mm diameter at its focus for a parallel beam of on-axis light. A structurally rigid mirror blank is made by sandwiching a 26 mm thick HEXEL aluminium honeycomb structure between a 5 mm thick aluminium alloy plate of Al 6161 T6-grade and a 1 mm thick aluminium sheet with structural adhesives followed by curing. The 5 mm thick aluminium plate is subsequently diamond-turned to a mirror finish with the required radius of curvature. After characterization and acceptance of the mirror facet for use on the telescope, a protective layer of SiO_2 of ~100 nm thickness is deposited on its reflecting surface. In order to ensure that the integrated spot size of the 21 m diameter light collector is <27 mm diameter (half of the pixel diameter), mirrors with increasing focal length of 25–26.16 m are deployed from the centre of the mirror basket to its periphery. Each of the mirror panels is supported on three ball joints. Two of these are provided with motorized linear actuators with a travel range of ± 20 mm, which are used for the purpose of aligning the individual mirror panels to form an integrated quasi-parabolic light collector surface. The mirror alignment system uses 712 brushless DC motors and their drive electronics is controlled by an elaborate algorithm to ensure reliability.

Figure 2. Trial assembly of the mechanical structure of the MACE telescope at ECIL, Hyderabad in June 2014. A set of eight aligned mirror panels can be seen of centre of the mirror basket.

Imaging camera and data acquisition system

The 1088 pixel imaging camera has a resolution of 0.125° and covers a field of view of 4.3°× 4°. Also, 38 mm diameter, six-stage photomultipliers (ETE, UK-make 9117 WSB) arranged at a triangular pitch of 55 mm are used for the detection of the few nanoseconds duration, fast Cherenkov light flash produced by the interaction of the incident VHE gamma-ray photons, protons and other progenitors with the Earth's atmosphere. The photomultipliers are provided with hexagonal front-coated light concentrators for enhancing their light collection efficiency by collecting the photons which fall in the dead space between adjacent photomultipliers. The light collection efficiency of these light concentrators has been determined experimentally to be ~85% in the wavelength range 240–650 nm. The camera is modular in design and comprises of 68 camera instrumentation modules (CIM) of 16 channels each. A fully assembled CIM shown in Figure 3 houses the photomultipliers, high-voltage

Figure 3. A fully assembled 16 channel camera instrumentation module of the MACE telescope. The 16 photomultiplier tubes can be seen in the front, while the fast signal processing electronics is fixed at the rear of the module.

generators, signal-processing electronics, first-level trigger generation logic and signal digitization circuitry for the 16 channels. Figure 4 shows the partially assembled camera and its power supply rack. An analogue switched capacitor array DRS-4 developed by PSI, Switzerland is being used as an analogue ring sampler at 1 GHz speed for continuous digitization of the photomultiplier signals. These digitized values are stored only for channels which have triggered. In order to ensure a large dynamic range, the photomultiplier signal is simultaneously amplified by a gain of 14 and 140. If the high gain output saturates, then the low gain output is used for further processing. The amplitude discriminator output of each channel is used for monitoring its single channel rate and also for generating the first-level trigger from an individual CIM. The first-level triggers from all the modules are collated in a second-level trigger generator where proximity of the triggered pixels in adjacent CIMs is checked. After the generation of the second-level trigger, the data from all the 68 modules are collated by the data concentrator, which in turn sends then to the data acquisition computer in the control room through optical fibres. The innermost 576 pixels (24 × 24) are used for generating this trigger according to predefined logic. As mentioned earlier, the topological trigger scheme uses CCNN patterns which are predefined for nearest pairs, triplets, quadruplets, etc.

Figure 4. The partially assembled imaging camera of the MACE telescope at ECIL, Hyderabad in June 2016. The central 19 CIM modules can be seen along with the two motorized front shutters. The 48 V power distribution rack connected to the camera can be seen and the left of the photograph.

Figure 5. The status of the telescope installation at Hanle in December 2016. The two instrumentation shelters are mounted on the alidade structure. The solar photovoltaic panels deployed for providing electric power to the telescope on the left of the photograph.

About 50 GB of data will be stored during every hour of observation. Quick-look algorithms will do a preliminary analysis of the data and archive then. A copy of the data will also be archived in a Data Centre at BARC, Mumbai, from where it will be made accessible to the astronomy community. The data acquisition and archiving system along with the telescope drive control system have been designed for internet-based remote operation. In the first phase remote operations from BARC and TIFR over the Anunet network, operated by the Department of Atomic Energy (DAE), will be established. Subsequently, connectivity will be established with other collaborating institutes.

Implementation status

The trial assembly of the mechanical structure of the telescope was completed at ECIL, Hyderabad in June 2014. Eight mirror panels were also installed on the telescope basket and the automated alignment of these mirror panels using a distant light source was successfully demonstrated. The azimuth and zenithal drive systems were also tested for various sequences of operation for a duration of about 40 h spread over 10 days. Subsequently, the telescope was disassembled and most of its subsystems were packed and transported to Hanle by road. The installation of the circular track and the first layer of the alidade structure, including its six wheels was completed by the end of 2014. The partially assembled imaging camera shown in Figure 4 was also tested at ECIL, Hyderabad during June 2016. The assembly and testing of all the CIM modules is likely to be completed by June 2017. As can be seen in Figure 5, by December 2016 the major part of the mechanical structure of the telescope, including the mirror basket was assembled at Hanle, and it is expected to be fully assembled and tested by June 2017. Subsequently, with the installation of the mirror panels and the imaging camera commissioning trials will be started towards the end of 2017. It is proposed to observe the Crab Nebula during the commissioning trials for checking the integrity of the complex hardware and software of the telescope. According to our simulation results, it should be possible to detect a 5σ signal of gamma rays from the source in a few minutes of observation with the MACE telescope.

Summary

The mechanical structure of the MACE telescope is at an advanced stage of installation at Hanle. The altitude and azimuth drive systems of the telescope have been extensively tested at Hyderabad. More than 1400 spherical mirror facets required for the telescope have been manufactured indigenously and characterized. Most of the associated mirror alignment hardware is also ready for deployment. A major part of the camera electronics has been tested at ECIL, Hyderabad, while the rest of it is at various stages of production. The elaborate software for data acquisition and archiving has also been tested extensively. The commissioning trials of the MACE telescope are expected to start towards the end of 2017, when installation of all the telescope hardware and software is expected to be completed.

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