VERY HIGH ENERGY GAMMA-RAY ASTRONOMY

An Indian Perspective

*R.C. Rannot

In the last two decades or so, the field of gamma-ray astronomy has gained the maturity level required to become a branch of astronomy and astrophysics. VERITAS (Very Energetic Radiation Imaging Telescope Array System)[1], HESS (High Energy Stereoscopic System)[2] and MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes)[3] collaborations have played a major role in bringing the field to the present level wherein the TeV source catalogue (http://tevcat.uchicago.edu) contains more than 245 various types of gamma-ray sources. The field is emerging as a powerful probe to study a variety of cosmic objects, energy fields prevailing in galactic and intergalactic space and possibly will throw light on the physics beyond the standard model as well. Apart from this, the use of contemporaneous observational data of high energy gamma-ray telescopes along with those at lower band of electromagnetic spectrum, data from neutrino and gravitational wave observatories in a coordinated manner will certainly enhance our understanding of the extreme environments and physical processes at work close to neutron stars and black holes.

The gamma-ray photons are produced under extreme relativistic conditions at the source by non-thermal emission mechanisms like inverse Compton scattering of low energy photons by accelerated charged particles, synchrotron emission from charged particles in the presence of magnetic field, π^0 decay etc. The extreme relativistic conditions are encountered in the environments of the cosmic objects such as supernovae remnants, pulsars, binary systems and Active Galactic Nuclei (AGN) which are suitable for the production of gamma-rays through non-thermal processes in the following way; the objects accelerate charged particles to energies more than 100 TeV possibly through shock wave acceleration mechanisms. These particles then interact with various energy fields like magnetic field, photons and surrounding matter close to the cosmic accelerator and produce gamma-ray photons in an enormously wide spectral range.

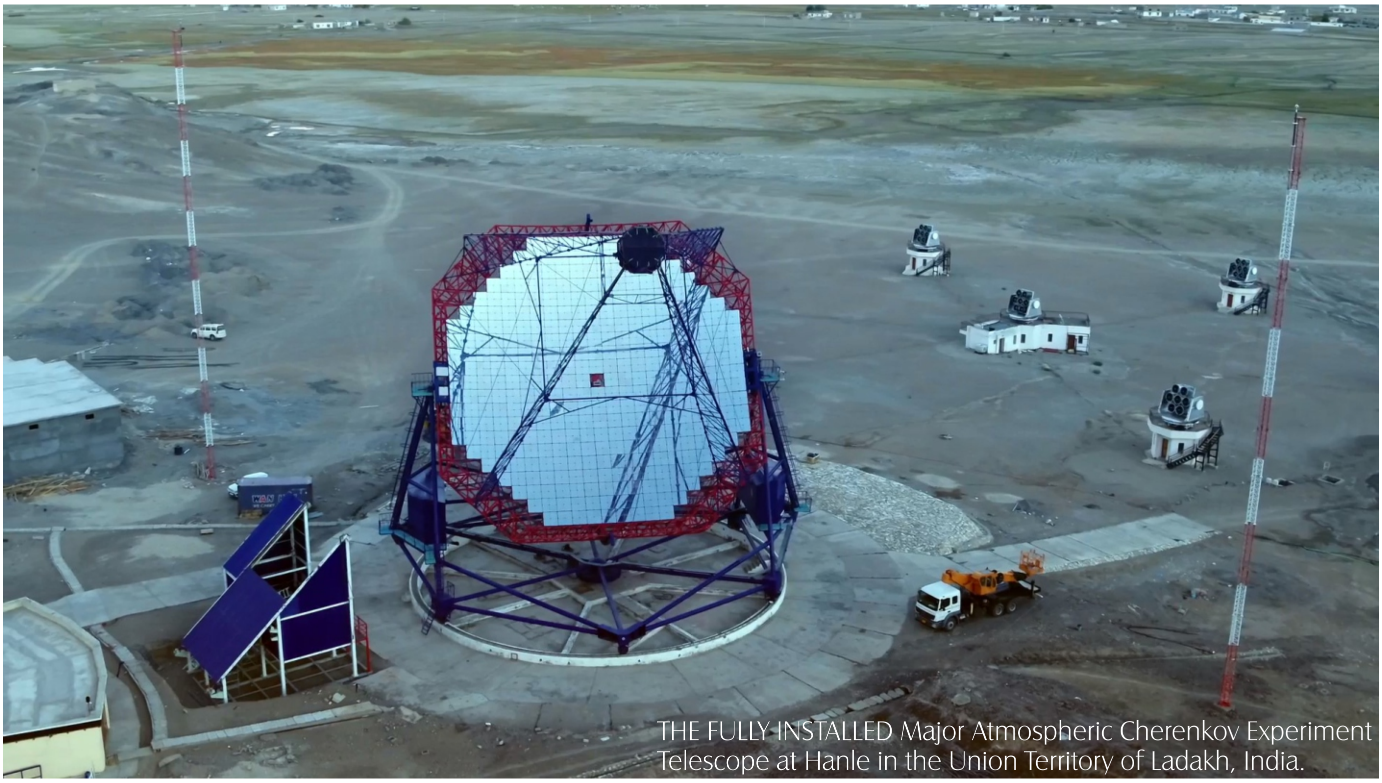
The accelerated charged particles' spectrum at source cannot be measured with direct experiments, as the charged particles' arrival directions are randomized by the presence of galactic and inter-galactic magnetic fields which the particles encounter while travelling from the source to the earth. In contrast, the gamma-rays so produced set out their journey along a rectilinear path and hence preserve their source directional information. The VHE photons provide a lot of indirect information about their progenitors and enable us to study a variety of non-thermal processes involving relativistic particles, energy fields and violent phenomena undertook during various past epochs at astrophysical objects of our known Universe.

On reaching the earth, the gamma-ray photons encounter earth's atmosphere which is opaque to gamma-rays and hence they cannot be detected directly using the ground-based detectors. At lower part of the gamma ray regime, up to few 10s of GeV energies or so, where the photons' flux is relatively more and detectable by using satellite based detectors, an impressive progress has been made in the last few decades.

For example, the satellite-based Fermi LAT detector has published 4FGL catalogue containing more than 5000 gamma-ray sources above 4σ significant in the energy range from 50 MeV to 1 TeV[4] with a variety of sources such as pulsars, pulsar wind nebulae, supernova remnants, globular clusters, star-forming regions, high and low mass binary systems, active galactic nuclei, radio galaxies, Seyfert galaxies and starburst galaxies. The catalogue also contains a significant number of the sources not associated with the known astrophysical objects.

Above few 10s of GeV energies, it is also termed as VHE (up to 100 TeV) gamma-ray domain wherein the cosmic gamma-ray flux falls sharply. This is mainly because of the power law nature of gamma-ray spectra produced through various gamma-ray emission mechanisms involving surrounding matter, accelerated particles, magnetic fields and photons, operating at cosmic accelerators' environments.

Consequently, it becomes increasingly difficult for the satellite-based gamma-ray detectors to sustain the gamma-ray detection sensitivity at very high energies to acceptable values rather it falls to a very poor level, thereby VHE gamma-ray experiments at satellite altitudes become unviable to carry out. However, the VHE gamma-ray sources are observed indirectly, by using the ground-based detectors wherein the earth's atmosphere acts as a transducer with a very large detector's effective collection area ($\sim 10^4$ m^2) making the atmospheric Cherenkov based detectors much more sensitive to the VHE gamma-rays as compared to the satellite-based detectors.



THE FULLY INSTALLED Major Atmospheric Cherenkov Experiment Telescope at Hanle in the Union Territory of Ladakh, India.

Atmospheric Cherenkov Technique (ACT)

When a VHE cosmic ray particle or photon impinges on the top of the earth's atmosphere, it produces an Extensive Air Shower (EAS) of relativistic particles some of them reach the ground level at higher altitudes. The EAS develops in the downward direction with a shower core aligned in the arrival direction of its progenitor. The relativistic charged particles of EAS emit Cherenkov radiation which is coherent, forward beamed, last for few nanoseconds and is detectable using ground-based detectors during cloudless and moonless dark nights in the presence of background of the night sky light. The ground-based gamma-ray telescopes make use of this atmospheric Cherenkov radiation, produced by the relativistic charged particles of the EAS initiated by the primary gamma-ray photon, to observe the VHE gamma-ray sources. This VHE gamma-ray detection method is known as the Atmospheric Cherenkov Technique and it offers a very large detector's effective collection area as mentioned earlier.

The ACT could be divided into two types: (1) Imaging Atmospheric Cherenkov Technique (IACT) which uses an array of Photo-Multiplier Tubes (PMTs) at focal plane of a large light collector to records the images of EAS and (2) the wave front sampling technique wherein a number of detectors are used to record Cherenkov photons' density on the ground. The examples of the former type of the Indian gamma-ray telescopes are TACTIC at Mt. Abu (Rajasthan) and MACE at Hanle in Ladakh, they use the differential EAS's development details which is present in shape and orientation parameters of the recorded images. An example of the latter type is HAGAR array at Hanle in Ladakh which uses the wave front sampling technique. The main advantage of such an array is that it is a low budget VHE gamma-ray detector but with limited sensitivity to gamma-ray flux when compared to the imaging telescope with same light collector area. Further, the particle detectors placed in a large array at high altitudes also detects EAS initiated by both cosmic- rays and gamma- rays by recording data of secondary particles reaching detector level produced during the EAS development. Such detectors offer much less sensitivity to photons' initiated showers owing to small effective detector area as compared to that of the IACT.

It is worth mentioning here that the IACT offers much better photons' detection sensitivity in VHE range of gamma-ray spectrum, hence is more popular worldwide and have led to many discoveries of variety of galactic and extra-galactic gamma-ray sources and breakthrough [5] in the field. Accordingly, global collaborative efforts in the field of VHE domain have led to the setting up of two large arrays (more than 100 telescopes) of Cherenkov imaging Telescopes at different locations, one in the northern hemisphere in La Palma in Spain to cover northern part of the sky and the second in the southern hemisphere in Chile to cover the southern potential gamma-ray sources and is known as Cherenkov Telescope Array

THE VERY HIGH ENERGY Gamma-Ray sources are observed indirectly by using ground-based detectors. The earth's atmosphere acting as a transducer with a very large effective collection area ($\sim 10^4 m^2$), it makes atmospheric Cherenkov based detectors highly sensitive to the VHE gamma-rays as compared to satellite-based detectors.

▲ THE FIRST GENERATION gamma-ray telescope at Ooty in Tamil Nadu.

▼ THE FIRST GENERATION gamma-ray telescope at Gulmarg in Jammu and Kashmir.

(CTA, https://www.cta-observatory.org/). When fully operational its gamma-ray flux sensitivity is expected to be two orders of magnitude more than the present generation instruments in energy range from 50 GeV to 100 TeV.

Indian First Generation ACT based VHE Gamma-ray Experiments

The Indian scientists traditionally persuaded astronomy programmes with great interest and vigour almost in the entire electromagnetic spectrum from radio to gamma-ray bands using the instruments mostly designed and developed within India. In the following, the historical perspectives of our VHE gamma-ray astronomy programme are briefly described. In India, the first-generation ACT based gamma-ray telescope which is shown in the figure, was set up by the TIFR group[6] in the seventies at Ooty (in Tamil Nadu now known as Udhagamandalam) by using search light mirrors, each having a focal length of 40 cm, diameter of 90 cm and using fast PMTs at their foci. The TIFR group also enthused BARC group working that time in Srinagar (Kashmir) to install a similar first generation gamma-ray telescope at Gulmarg in J&K. Consequently, the Gulmarg telescope [7] shown in the figure was set up and commissioned in 1984 by the BARC group in collaboration with TIFR. In 1985, the Ooty setup was moved to Pachmarhi in Madhya Pradesh[8] with upgraded detectors shown in Figure owing to a relatively better atmospheric conditions prevailed that time at Pachmarhi. By using the above mentioned three first generation ACT based gamma-ray telescopes, the following potential galactic TeV gamma-ray sources; Crab nebula[9], Vela [10], PSR0355+54[11], Geminga[12], Her X-1[13], 4U0115+63 [14,15], Am Her[16] and Cyg X-3[17,18] were observed. Results obtained in terms of their light curves, estimated gamma-ray fluxes or upper limits at 3σ statistical level on their integrated flux and pulsed gamma-ray signal search were reported in various national and international journals. These works using the first generation telescopes has indeed helped India to earn its place on the global map of the VHE gamma-ray astronomy field.

GLOBAL COLLABORATIVE efforts in the field of VHE domain have led to the setting up of two large arrays (more than 100 telescopes) of IACTs at various locations.

India's Maiden IACT based Gamma-ray Telescope

With a reasonably good success of the first-generation telescopes and by then, the BARC group had recognized the power of the IACT in terms of sensitivity to weaker fluxes as compared to that of the first-generation and wave sampling technique based telescopes, the group shifted its VHE gamma-ray astronomy programme to Mt. Abu (24.6° N, 72.7° E, 1300m above sea level) in Rajasthan, during mid-nineties. The new site was selected for setting up of the India's first Imaging gamma-ray telescope TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera, shown in Figure), on the basis of cloud pattern studies, the data for which were provided by the Indian Metrological Department. This is because as mentioned earlier, dark, cloudless and moonless nights, and away from civilisation site qualifications are required to set up atmospheric Cherenkov telescopes. The telescope uses F/1 type tracking light collector of 9.5 m^2 area which is made up of 34 x 0.6-m-diameter front-coated spherical glass facets which have been pre-aligned to produce an on-axis spot of ~0.22° diameter at the focal plane. It is equipped with a 349 PMTs (ETL 9083UVB) based imaging camera with a uniform pixel resolution of ~0.3° and a field-of-view of ~6° x 6° to record images of development of extensive air showers. The trigger is based on the 3NCT (Nearest Neighbour Non-Collinear Triplets) logic. The detailed description of the telescope can be found in[19].

The TACTIC was also upgraded by replacing the first generation Circular Opening Light Guides (COLG) with superior designed hexagonal opening light guides having much better light collection efficiency and much less dead space between the PMTs as compared to the COLG. In addition, some of the hardware components like Charge to Digital Converters (CDC) were also replaced with the branded CDC and software components were also optimized in terms of image cleaning parameters and dynamic cuts to segregate gamma-ray induced shower images. These changes has resulted in a substantial improvement in the telescope's flux sensitivity to a level at which now it detects gamma-rays from a standard candle source Crab nebula at 5σ significance in ~10 hours as compared to ~25 hours earlier of on-source observations.

Following potential VHE gamma -ray sources namely Crab nebula[20], Mrk421[21-30], Mrk501[31,32], 1ES2344+514[33], H1426+38[34], 1ES1218+304 [35], B2 0806+35[36], IC 310[37] and NGC 1275[38] have been observed and studied using the telescope's data and multi-wavelength data obtained from various telescopes at lower energies. The nearby blazars Mrk 421 and Mrk 501 were also detected in high emission states on a number of observational spells. An example of the former source which was found to be in a high state and was studied using multi-wavelength data at lower energies during the year 2010 is briefly described below.

Light curve (a plot depicting the variation of gamma-ray flux as a function of time) of Mrk 421 recorded using the TACTIC during its high gamma-ray emission state during the year 2010 in energy range from 1 TeV to 10 TeV is shown in the figure along with the contemporaneous multi-wavelength source light curves at lower energies. The light curve is an indicative of a variable or quiescent nature of source emission state and if observed contemporaneously in different wavelength bands, their correlation and modeling studies could throw light on how the source switches from a quiescent emission state to a high and variable emission state and also helps to understand the physics behind such flaring episodes.

In the present example, it is clearly seen from the figure that the source has exhibited a high emission state or a flaring activity from gamma-ray to X-ray energies. Whereas in V band a similar high emission feature is missing. We carried out variability and correlation studies of all shown light curves. The former study was made using a temporal profile function with an exponential rise and decay and it was observed that the variation in the one-day-averaged flux from the source during the flare is characterized by sharp rise and slow decay which is clearly seen in the figure. The latter study has revealed a strong correlation between the TACTIC TeV gamma-ray flux and X-ray flux, suggesting in favor of the synchrotron self-Compton VHE gamma-ray and X-ray production mechanism operating at the source. The observed gamma-ray and X-ray light curves were modeled by numerically solving the kinetic equations describing the evolution of particles' energy distribution in the emission region. The injection of particles' distribution into the emission region, from the putative acceleration region, was assumed to be a time–dependent power law. The synchrotron and synchrotron self-Compton emission from the evolving particle distribution in the emission region were used to reproduce the gamma-ray and X-ray high emission state successfully.

This work has suggested that this high state of Mrk 421 could be a result of an efficient acceleration process accompanied with an increase in underlying non-thermal particle distribution. These results have been published in[26].

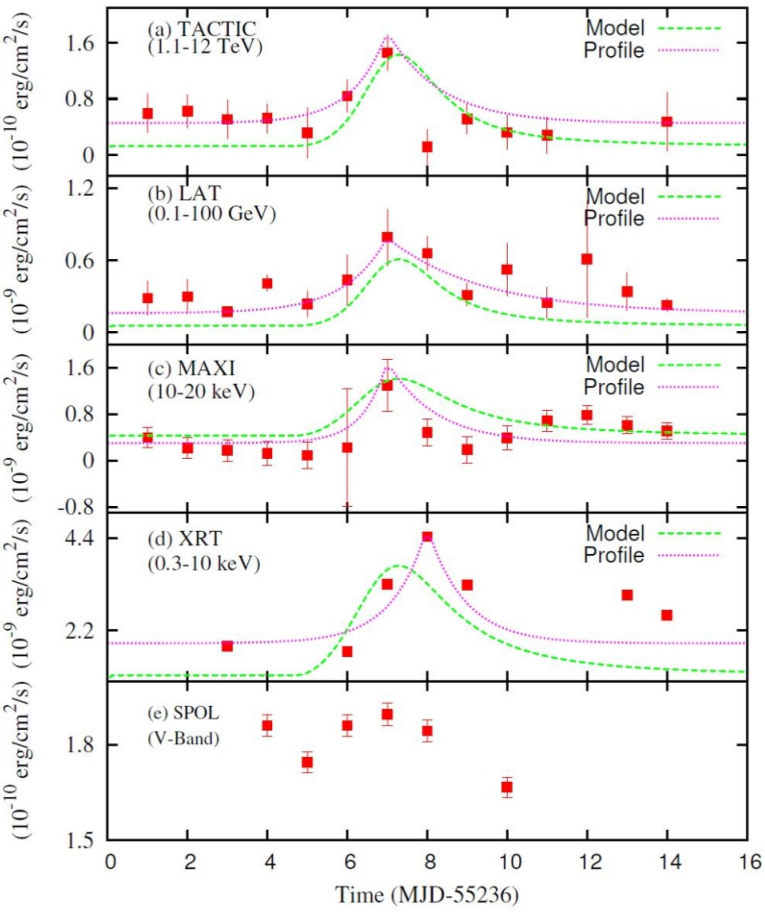
▼ THE gamma-ray telescope at Panchmarhi in Madhya Pradesh.

HAGAR (High Altitude Gamma Ray) Telescope Array

The HAGAR array has been designed and developed to realise gamma-ray detection energy threshold of ~200 GeV by the TIFR group and is based on wave-front sampling technique. The array is located at Hanle in Ladakh (latitude: 32.8° N, longitude: 78.9°E, altitude: 4200 m) and measures arrival time of Cherenkov shower front and Cherenkov photon density at various locations in the Cherenkov pool by using seven small telescopes with six telescopes at the corners of hexagon and one telescope located at the centre as shown in the figure. The array has been monitoring various potential VHE gamma-ray sources since 2008 the details of results obtained by the group are given in[39] and references therein.

THE FIRST generation telescopes have indeed helped India to earn its due place on the global map of VHE gamma-ray astronomy.

▲ INDIA'S FIRST imaging atmospheric Cherenkov telescope at Mount Abu in Rajasthan.



▲ MULTI-WAVELENGTH LIGHT CURVES of Mrk 421 observed during February 10-23, 2010 from various ground and satellite-based detectors and their physics modeling[35].

MACE Gamma-ray Telescope

The MACE, a low energy threshold gamma-ray telescope (shown in the figure) with an improved point source flux sensitivity as compared to the TACTIC telescope, has been recently installed at Hanle (32.8° N, 78.9° E, 4270 m above sea level) in Ladakh region of the Himalayan range of the North India at an altitude of 4270 m above sea level that is highest for any existing IACT in the world. The telescope has a longitudinal advantage in terms of its possible deployment in the global IACT's network mode to study flaring sources by recording continuous and short time scale variations of gamma-ray signal. It is also the second largest IACT in the northern hemisphere. This Very High Altitude (VHA) of the Himalayan desert offers an annual average of more than 260 uniformly distributed dark nights, leading to an excellent duty cycle of the telescope as the gamma-ray observations are made during cloudless and moonless nights. The VHA of the site at Hanle and large MACE light collector size contribute significantly in realizing the targeted low threshold energy of the MACE. When compared with the TACTIC, the MACE site is closure to the EAS maxima where the Cherenkov photons emitted by the relativistic charged particles reach the detector level almost un-attenuated and the MACE is also equipped with more than 35 times geometrical collection area of the TACTIC. This combination of large collection area and VHA of Hanle indeed helps to increase MACE imaging system triggering probability by few GeV gamma-ray initiated EAS unlike in the case of the TACTIC telescope.

The telescope deploys a large 21m diameter parabolic multifaceted light collector with an altitude-azimuth mounted drive system[40]. MACE's light collector consists of 356 mirror panels each having size of 1 m x 1 m. Further, each panel comprises 4 diamond turned spherical metallic honeycomb mirror facets having size of 0.5m x 0.5m and were indigenously developed in Mumbai. The total light collection area of the telescope is ~340m^2 with a mean value of reflectivity of 85%. In order to ensure a small on-axis spot size at the focal plane of the telescope, mirror facets with graded focal lengths varying from 25m to 26.5m from the centre of light collector to its periphery were used. This design has produced a spot size of ~25.4 mm at the focal plane which is much less than the pixel size.

MACE modular imaging camera with its back-end electronics mounted at the focal plane deploys 68 Camera Integrated Modules (CIM) each having 16 PMTs, also called as pixels, with a single PMT diameter of 38 mm. All the PMTs in the CIM are coupled with Hexagonal Compound Parabolic Concentrators (HCPC) to maximize the light collection efficiency. The entry apertures of the HCPC have a uniform angular size of 0.125° and provide a total optical field of view of 4.36° x 4.03°. The camera deploys a total number of 1088 PMTs and the innermost 576 of them (36 CIM) with a field of view of 2.62° x 3.02° are being used for event trigger generation based on a predefined trigger criterion. A programmable trigger configuration with a selectable feature of close-cluster nearest-neighbour trigger participating number of pixels between two and six has been implemented in the MACE camera hardware. Each CIM of the camera has its signal processing electronics built into it. The camera also uses an analogue switched capacitor array DRS-4 operating at 109 Hz for continuous digitization of the signal from the PMTs.

Simulation studies have also been carried out to predict the performance of the MACE using CORSIKA package[41]. The results obtained indicate that the gamma-ray trigger energy threshold of the telescope is expected to be 20 GeV in the low zenith angle range of 0°–40° and this value increases to 173 GeV for large zenith angle of 60°[42] with trigger rates varying from ~700 Hz to 305 Hz as the telescope track the sky from lower to large zenith angles. MACE integral sensitivity is estimated to be 2.7% of the Crab unit at the analysis energy threshold of 38 GeV at 5° zenith angle[43] when the Random Forest method is used for gamma-hadron segregation. It is found that the MACE telescope has a lower analysis energy threshold and is likely to be more sensitive below <150 GeV to gamma-rays as compared the MAGIC–I telescope, this is mainly because the MACE is located at very high altitude where the Cherenkov photon density is relatively better as compared to that at lower altitudes for low energy primaries. Further, the simulation studies has also yielded values of energy and angular resolutions of the telescope as a function of the primary photon's arrival zenith angle and energy. MACE energy resolution is

▲ THE HAGAR TELESCOPE ARRAY at Hanle in the Union Territory of Ladakh, India.

expected to vary from 40% to 20% as the primary photon energy increases from 30 GeV to 1 TeV, whereas its angular resolution is expected to vary from 0.35° to 0.1° from 30 GeV to 1 TeV energies at lower zenith angles, the details of these results are given in [44].

The MACE is presently being operated to fine tune its various parameters in order to attain the expected low energy threshold and integrated flux sensitivity to VHE gamma-ray photons. The telescope has detected gamma-rays from the standard candle source Crab nebula at more than 5 sigma statistical level during four observational spells in 2021, thereby possibly achieving the reproducibility feature which is crucial to attain the required stability in terms of prompt coincidence rates, chance rates and cosmic ray triggers but with lower sensitivity to gamma-rays than its expected value. After this validation operating mode, the telescope will be used to observe a variety of astrophysical objects such as pulsars, SNRs, binary systems, AGN and some of the unidentified LAT sources and will also be deployed in discovery mode.

The low energy threshold of the MACE is also likely to enable us to observe the distant sources beyond redshift z>2 and monitoring of astrophysical transients like gamma-ray bursts, in addition to the study of variety of galactic sources, as at lower energies gamma-ray sources emit more gamma-ray photons owing to the power law nature of their production mechanisms and their absorption probability due to photon-photon interaction is also much less as compared to the photons with energies around 1TeV. The MACE with an analysis energy threshold of~30 GeV (for TACTIC it is ~900 GeV), is suitable and likely to play an important role in the pulsars' study, which are believed to have a separate GeV-TeV gamma-ray emission mechanism.

These capabilities of the MACE, place it a generation ahead as compared to the TACTIC telescope at Mt. Abu. When both the telescopes are operated concurrently to observe a particular potential source, the dynamic energy range of the combined observed data would be possibly extended up to ~20 TeV or so, which would help us to study energy dependent gamma-ray emission features of the VHE gamma-ray sources. These observations are also likely to throw light on some of the open questions such as origin of the cosmic rays, the Extragalactic Background Light photons' density, intergalactic-magnetic-field's strength and possibly probing the nature of dark matter.

Indeed, the MACE is going to be a great addition to the Indian astronomy programme and is likely to contribute significantly to the field of VHE gamma-ray astronomy and astrophysics in the coming years. Further enhancement of MACE capability, in terms of its energy resolution, angular resolutions and gamma-ray flux sensitivity might be required however, in order to seek answers to the above stated open questions. For this, another MACE like system if installed near the existing MACE and when both are used in a stereoscopic mode, then the Indian VHE gamma-ray community would be better equipped and placed to address the questions.

Summary and Future Outlook

Using the ground-based and satellite- based gamma-ray detectors, the field of high energy astronomy and astrophysics has made unprecedented progress during the last two decades with discovery of a variety of astrophysical objects that are sources of accelerated charged particles, high energy and VHE gamma-rays. The objects include; pulsars, pulsar wind nebulae supernova remnants, globular clusters, star-forming regions, high and low mass binary systems, Active Galactic Nuclei, Radio galaxies, Seyfert galaxies, starburst galaxies and unidentified sources. Indian's VHE atmospheric Cherenkov based experiments have also contributed to the VHE gamma-ray astronomy right from the first generation experiments onwards which were conducted at Ooty in Tamil Nadu, Gulmarg in J&K, and Pachmarhi in Madhya Pradesh, during seventies and eighties. Later on these VHE experiments with

SCIENTISTS from various universities and research centres are expected to come onboard MACE activity to contribute positively to the overall understanding of the phenomena associated with the cosmic gamma rays.

improved detectors were shifted to Mount Abu and Hanle in Ladakh as better sky conditions conducive to such experiments prevailed at these locations. India's first imaging gamma-ray telescope TACTIC was indigenously installed at Mt. Abu in Rajasthan during the mid-nineties and has been since then monitoring nearby active galactic nuclei and has recorded interesting high gamma-ray emission state features of Mrk 421 and Mrk 501 on many occasions.

Further, the TIFR and BARC groups have consolidated their activities in the field at Hanle with the setting up of the HAGAR and MACE telescopes respectively. During the last decade the scientists of BARC, TIFR and IIA have been working in close coordination and a number of young scientists have joined these groups. An experience gained by the BARC group while setting up the TACTIC and developing new data analysis techniques, has indeed helped and encouraged the group to take the leading role in designing and developing a low energy threshold and more sensitive MACE telescope. As the MACE goes into the mode of regular observations scientists, from various Universities and research centres will be invited to join the programme. It may be noted that Hanle has the unique distinction of having an IACT, a wave-front sampling gamma-ray telescope and a 2m optical telescope located on the same campus. This unique feature along with the use of GMRT and the ASTROSAT can be effectively utilized for multi-wavelength studies of variety of astrophysical objects.

Finally, it will be desirable to convert the MACE system into a stereoscopic MACE by installing a similar telescope at an appropriate distance (the exact value of the distance will be known from simulation studies) from the present MACE location. This is mainly because the stereoscopic system possesses an enhanced capability in terms of its energy resolution, angular resolution, gamma-ray flux sensitivity and quality factor that would possibly help us to come closure to find answers to the open questions in the field.

*The author is from Astrophysical Sciences Division
Bhabha Atomic Research Centre
Trombay, Mumbai- 400085

rcrannot@barc.gov.in

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