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Ground-based TeV γ-ray Astronomy in India

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The ground-based γ-ray astronomy activity in India was initiated as early as 1969 with 2 large area search light mirrors. Over the years the concerned groups have improved the sensitivity of their setup and lowered the γ-ray energy threshold by constantly upgrading their telescopes. At present an array of 25 telescopes operates at Pachmarhi to detect Cherenkov showers through wave-front sampling technique while another 4 element array operates at Mt. Abu which use the imaging technique for the detection of γ-rays. The threshold energy of primary γ-rays that trigger these set-ups is about a TeV. At these energies only a few γ-ray sources are detected where as the satellite-based EGRET has detected about 270 sources at energies below 10 GeV. Efforts were made world-wide to reduce the energy threshold of ground-based set-ups to few tens of GeV. In this direction, plans were made for new generation experiments in India using the high altitude and low night sky background of a site in the Himalayas to advantage. A new γ-ray observatory comprising a large stereo imaging Cherenkov telescope and an array of wave-front sampling telescopes are being set up at Hanle, in Ladakh region of the Himalayas, at an altitude of about 4200m above mean sea level. The two telescope systems could detect very high energy γ-rays in the important region of the 10s of GeV energy range and have overlaping observations with future satellite-based detectors like GLAST, both in energy and time. This article traces a brief history of Indian activities in this field and highlights the present set-ups and future plans.

1. Introduction

Very high energy γ- rays and cosmic rays produce an electromagnetic (E-M) cascade in the atmosphere known as extensive air showers (EAS). Relativistic electrons and positrons form main component of these air showers and they produce detectable Cherenkov radiation as they propagate down the atmosphere. This radiation is coherent, beamed in the forward direction and could be detected at ground level during moonless clear nights. Thus ground-based γ-ray astronomy is carried out through the detection of Cherenkov radiation produced in the atmosphere by the relativistic charged particles of the E-M cascade initiated by the primary γ-ray. Cosmic rays constitute the main background of noise limiting the minimum measurable γ-ray flux.

In India the ground-based γ-ray astronomy was pioneered by a group from the Tata Institute of Fundamental Research (the TIFR group) led by Prof. B.V.Sreekantan and P.V.Ramanamurthy who plunged into this field as early as 1969. Another group from Bhabha Atomic Research Centre (the BARC group), led by Dr. H. Razdan and the late Dr. C.L.Bhat also actively pursued this field. As the techniques for the detection of γ-rays using ground-based setups improved calling for large area sophisticated third generation setups, these groups have joined hands forging an active collaboration. At present, the collaboration involving 3 institutes (groups from the Indian Institute of Astrophysics, BARC and TIFR) is involved in setting up a new high altitude γ-ray observatory at Hanle in the Himalayas.

In this article, we shall trace a brief history of our past activities in this field, describe the present set-ups and point to the future direction of the Indian group.

2. Early History

The TIFR group started the field of ground-based γ-ray astronomy in India in 1969, soon after the announcement of the discovery of pulsars in 1968. Pulsars were proposed to be the site of origin of high energy cosmic rays and hence the sources of ultra high energy γ-rays. They searched for pulsed emission of γ-rays from 5 pulsars with the same periodicities as observed at radio frequencies [1].

The Cherenkov light was detected by 2 large search light mirrors (f/0.45 mirrors of 90 cm dia) focused onto fast (56 AVP) photo-multipliers (PMT) placed at their foci. The full field of view of each mirror was 3°. The approximate collection area of high energy γ-rays was $3 \times 10^4\ cm^2$ and the threshold energy of detection $\approx 10\ TeV$. The mirrors, mounted on an orienting platform, tracked each pulsar for about an hour when it is close to meridian transit. Observations were made on clear nights in the years 1969 and 1970 at Mukurthi located at an altitude of 2.2 km above mean sea level in the Nilgiri Hills in South India. Not having found any significant flux of γ-rays from any source they placed upper limits on the flux of γ-rays of the order of $10^{-11}\ photons\ per\ cm^2\ per\ s$ [2].

This activity was revived after a hiatus of 5 years with more number of mirrors and improved detection methods. For 10 years, an array of Cherenkov telescopes with a total mirror area of about 20 m^2 was operated in and around Ooty (Now called Udhagamandalam) in southern India ($76^\circ.71E$, $11^\circ.42N$, 2.3 km altitude). A photograph of the set-up is shown in figure 1. Later, this set-up was moved in the year 1986 to Pachmarhi ($22^\circ.47N$, $78^\circ.43E$, 1075 m altitude) in the state of Madhya Pradesh, in central India, where the sky conditions for night sky observations are better than that at Ooty. A very systematic search for pulsed emission of γ-rays was made on a number of isolated pulsars [3] and X-ray binaries [4] using these set-ups at Ooty and.Pachmarhi. Crab, Vela, PSR0355+54, Geminga and Her X-1 showed positive signals on several occasions [5, 7, 6, 8, 9, 10, 11].

Figure 1. Compact array at Ooty

The BARC group started observing the night sky in the mid seventies at Gulmarg in Kashmir ($34^\circ.5N$, $74^\circ.3E$, 2743 m altitude) using two bare faced PMTs (EMI 9545B) separated by 1 m and pointing up-wards in the sky (which may be likened to a wide angle telescope with a viewing angle of 50° w.r.t. zenith) in the drift scan mode. In this mode the telescope is kept stationary, and the sky is scanned as Earth rotates. They reported [12] a non-random component in the arrival times of cosmic ray events for time separation of $< 40\ s$. Later following the TIFR group, they too installed [13] a similar set-up at Gulmarg, consisting of 6 equatorially mounted parabolic search light mirrors of 0.9 m diameter divided into 2 banks of 3 mirrors each. This set-up is shown in figure 2. Using this system they observed a few X-ray binaries (Cyg X-3, Her X-1, 4U0115+63), pulsars (Geminga, PSR 0355+54) and cataclysmic variables (Am Her) and other sources [14, 15, 16].

More details on historic account of above activities are documented in the literature [17, 18].

Figure 2. Set-up of 6 telescopes at Gulmarg

3. Present set-ups

The detection of atmospheric Cherenkov showers is usually done by 2 complimentary ways. In one method, the lateral distribution of Cherenkov photons is sampled. In another method, the image of Cherenkov light in the atmosphere is obtained at the focal plane of the telescope with an array of photo detectors, essentially sampling the longitudinal development of the shower. The former method is known as the wave-front sampling method while the later is referred to as imaging technique in the literature. The new generation of ground-based set-ups (that are being constructed or just operational), like HESS, MAGIC, CANGAROO and VERITAS adopt both these techniques to form an array of imaging telescopes. Such telescopes have become powerful tools in the exploration of very high energy γ-ray universe [19].

3.1 PACT, the wave-front sampling array at Pachmarhi

The recently commissioned Pachmarhi Array of Cherenkov Telescopes (PACT) consists of 25 Cherenkov telescopes arranged as 5×5 matrix spread over an area of 80 m × 100 m [20]. Each telescope consists of 7 parabolic F/1 mirrors of 90 cm diameter made from 6mm thick float glass. Each mirror is viewed by a fast PMT (EMI 9807B) at its focus with 3° field of view aperture. The total reflector area of each telescope is 4.45 m^2. Each telescope is on an equatorial mount and is independently steerable ($\pm 45°$ in E-W and N-S directions). The movement of telescopes is remotely controlled by an automated telescope orientation system[21]. High voltages of individual PMTs are controlled through a computerized automated rate adjustment and monitoring system. The array is divided into 4 sectors of 6 telescopes each with independent data acquisition system for each sector. The analog signals from 7 PMT's of a telescope are linearly added to form a telescope trigger pulse. A coincidence of any 4 telescope pulses initiate the data recording in each sector. A real time clock (RTC) synchronized with a GPS clock records the absolute arrival time (up to μs) of Cherenkov shower. Data regarding 'timing' and 'amplitude' (Charge) of PMT pulses are recorded for each event together with telescope information using a CAMAC based system operating under Gnu/Linux platform. Digital informations like the arrival time of photons at the telescopes, trigger status, event arrival times etc. from all 4 stations are also recorded in the central control room. A portion of PACT is shown in figure 3. PACT has energy threshold of $\sim$ 800 GeV for $\gamma-$rays incident in the vertical direction and the corresponding collection area is $\sim 10^5 m^2$.

Figure 3. One of the Telescopes of PACT array (2 of the remaining 24 telescopes are seen in the background)

The observations are usually carried out in a stretch first either ON-source and followed by OFF-source region or vice versa during same night. The OFF-source region is chosen to have the same declination as that of source but offset in RA such that same zenith angle range is covered for both ON-soure and OFF-source runs. Typical run duration is about 1 to 3 hours. Data with all telescopes pointing to the zenith is used for calibration purposes. The relative time of arrival of Cherenkov photons is fitted to a plane shower front to obtain the direction of arrival of shower for each event. Thus 'space angle' between the direction of arrival of shower and the source direction is obtained for each event. Cuts are applied on the number of telescopes with valid 'timing' data as well on the quality of fit parameter (using χ^2 for the fit).

3.2 TACTIC, the imaging telescope at Mt. Abu

The BARC group also moved to a better site than Gulmarg and set up an imaging telescope called TACTIC (TeV Atmospheric Cherenkov Telescope with an Imaging Camera) at Mt Abu ($24^\circ.62N$, $72^\circ.75E$, 1257 m altitude) in 1994. The 4 element array, shown in figure 4, is arranged in a triangular configuration (one element at the centroid and 3 elements at the vertices of an equilateral triangle of side 20 m). The telescope deploys a F/1 type tracking light collector of $\sim 9.5\ m^2$ area made up of $34 \times 0.6\ m$ diameter, front coated spherical glass facets which have been pre-aligned to produce an on-axis spot of $\sim 0^\circ.3$ diameter at the focal plane. The central imaging telescope uses a 349-pixel, PMT (ETL 9083UVB) based imaging camera with a uniform pixel resolution $\sim 0^\circ.3$ and a field of view $\sim 6^\circ \times 6^\circ$ to take a fast snapshot of the atmospheric Cerenkov events produced by an incoming cosmic ray particle or a γ-ray photon with an energy above 1 TeV. The focal plane instrumentation of all vertex elements is designed to study linear polarization state, time-profile, spectral content etc. of the recorded events. The back end signal processing hardware of the telescope is based on in-house developed medium channel density NIM and CAMAC modules. The data acquisition and control system of the telescope has been designed around a network of PCs running the QNX (version 4.25) real-time operating system. The innermost 121 pixels (11×11 matrix) are used for generating the event-trigger based on the 3 Nearest Neighbor Non-Collinear Triplets (3NCT) topological logic by demanding a signal $\sim 7\ pe$ for the 3 pixels which participate in the trigger generation. The telescope has a pointing and tracking accuracy of better than $3'$. The details about of the various subsystems of the telescope are discussed in [22, 23, 24].

Figure 4. 4 element Imaging Telescope system TACTIC at Mt Abu

The crab nebula has been observed with TACTIC γ-ray atmospheric Cherenkov imaging telescope for a period of $\sim$ 103 hours during 2003-04. They have detected a strong signal of 960 ± 87 γ-rays at a statistical significance of $\sim 11\sigma$. The measured energy spectrum $\sim (3.18 \pm 0.41) \times 10^{-11} (E/1TeV)^{-2.65 \pm 0.11}\ cm^{-2}\ s^{-1}\ TeV^{-1}$ is in agreement with observations by other groups [25]. Their result is shown in figure 5.

4. Future directions

The satellite-based EGRET, which has given a wealth of data below 10 GeV, has detected about 270 point sources of γ-rays. On the other hand, the ground-based atmospheric Cherenkov experiments have detected much fewer sources at $> 200\ GeV$. A good number of sources detected by EGRET are AGN's. Most of these AGN's with large redshifts have not been detected by ground-based experiments presumably due to either a cutoff in the emission spectrum at the source itself or attenuation of γ-rays by the intervening IR

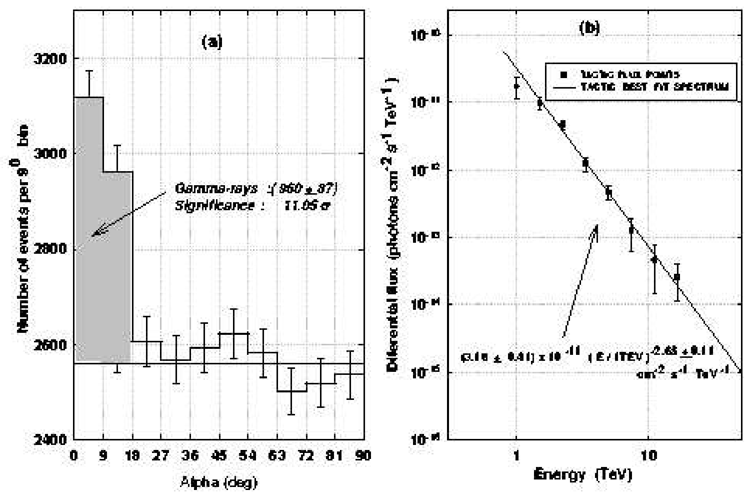

Figure 5. (a) γ-ray Signal and (b) Energy spectrum of CRAB nebula from TACTIC at Mt Abu

background radiation. But such a cutoff due to attenuation of γ-rays by background radiation is not expected for galactic sources like pulsars, SNR's etc. Therefor the energy spectrum of most of these galactic objects must steepen in the energy range 10 to 200 GeV. This energy region still remains to be explored and is also a viable energy region to study GRBs as the γ-ray universe is more transparent at low energies. Therefore, it is imperative to conduct experiments in this energy range for a full understanding of processes in these interesting celestial objects. Thus, there is a strong scientific motivation for lowering energy thresholds of ground based experiments to few tens of GeV and have overlap with satellite based detectors. This will enable the study of spectral cutoffs in AGN spectra and will also allow addressing various issues regarding pulsed emission from pulsars [26].

There were several attempts to reduce energy thresholds of ground-based experiments world-wide. Recently, based on stereoscopic technique, HESS Collaboration has produced several exciting results [27] by lowering the energy threshold to about 100 GeV [28, 29]. MAGIC experiment using very large size light collector is expected to reach energy threshold of about 30 GeV [30, 31]. Similarly experiments like CELESTE, STACEE etc. used large arrays of mirrors to achieve lower energy threshold. These low threshold energies can be attained either by increasing the light collector area of the telescopes or installing them at higher altitudes where the photon density of atmospheric Cherenkov events is higher [32, 33]. The Indian groups have forged an active collaboration between the Indian Institute of Astrophysics, Bangalore, Tata Institute of Fundamental Research, Mumbai and Bhabha Atomic Research Centre, Mumbai, to set up the Himalayan Gamma Ray Observatory (HIGRO) at Hanle ($32°.8N$, $78°.9E$, 4200m asl) in the Ladakh region of Northern India to address this important energy range using the two techniques of imaging and wave-front sampling for the detection of atmospheric Cherenkov photon showers produced by cosmic γ-rays. The site offers an average of about 260 uniformly distributed spectroscopic nights per year which is a major advantage in terms of sky coverage for source observations. The Cherenkov photon density at Hanle is a factor of about 4 -5 more than at sea level [33] as the high altitude site is located closer to the shower maximum. This increase in photon density along with the low background light level at the site help in lowering the threshold energy of the Cherenkov telescopes being set up there. At this site, a 2 m class optical telescope is also operating for the last several years and it can provide concurrent optical/IR monitoring of the objects of interest.

4.1 HAGAR telescope array

The HAGAR (High Altitude GAmma Ray) experiment [34] will deploy 7 alt−azimuth mounted telescope elements at the centre and corners of a hexagon of 50 m side as shown in figure 6. Each element comprises 7 paraxially mounted front-coated glass F/1 mirrors of 90cm diameter each with a PMT (XP2268B) at its focus. Each of the axes of the telescope is driven by a stepper motor through a chain of gears with the reduction ratio of about 3000:1 for azimuth drive and 3200:1 for elevation drive. The telescope movement control system comprises of two 17 bit Rotary encoders (Heidenhain, ROC 417), two stepper motors with motor drives (Slo-Syn make) besides the Microcontroller-based Motion control interface Units(MCIU). This control system has been developed to achieve the steady-state pointing accuracy of the servo of ± 10 arc-sec with the maximum slew rate of 30°/minute for each axis. The resulting blind-spot size while tracking the stars near zenith is $\sim 1.2°$. The telescopes' movement is maneuvered by the control software developed under Linux. The detailed point-run calibration by sighting large number of stars is being carried out to establish pointing model of the telescope to improve pointing accuracy further. High voltages of individual PMTs are controlled using C.A.E.N. controller model SY1527. Pulses from individual PMTs are brought to the control room through coaxial cables of type LMR-ultraflex-400. The signals from the 7 PMTs in each element will be added linearly before amplitude discrimination to yield a suitable count rate. The PC based data acquisition (DAQ) and recording system use CAMAC instrumentation and software written in C under Gnu/Linux environment. Linux device drivers are developed to accomplish interrupt driven DAQ system.

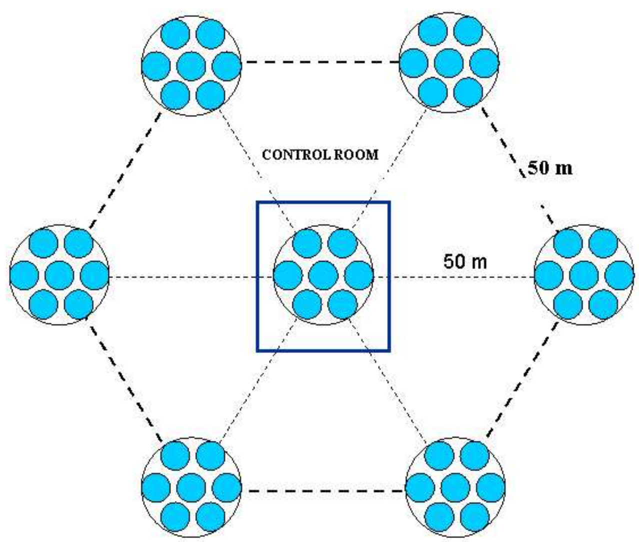

Figure 6. Layout of 7 telescope HAGAR array

Studies for the HAGAR experiment have been carried out with the CORSIKA [35] air shower simulation code.

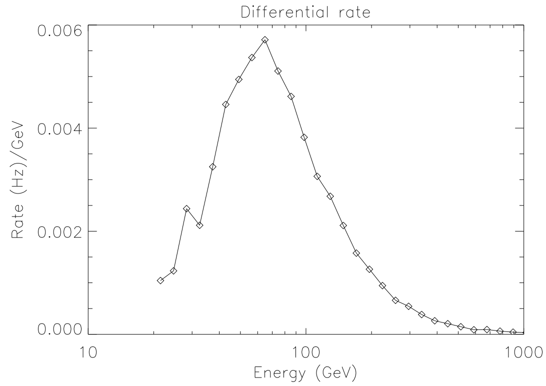

Figure 7. Expected differential γ-ray count rate spectrum from Crab nebula.

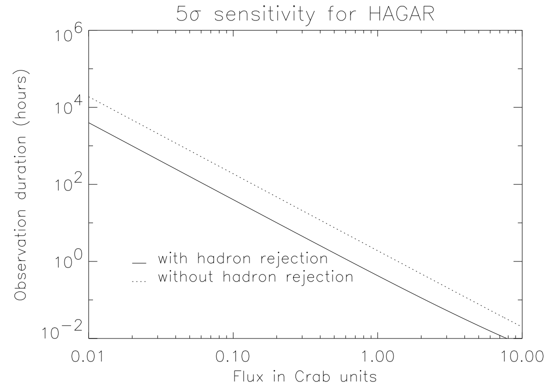

Figure 8. Sensitivity of HAGAR array ($\approx 7.7\sigma/\sqrt{hour}$ for 1 Crab)

Showers initiated by gamma rays, electrons, protons and alpha particles incident vertically at the top of the atmosphere were simulated using appropriate spectral shapes. The differential γ-ray count rate expected from the Crab nebula is shown in figure 7. The peak of the distribution at $\sim 60\ GeV$ defines the energy threshold of the telescope for vertically incident showers. The event rate for a coincidence trigger based on 4 out of 7 telescope elements is expected to be about 55 Hz from protons, 16 Hz from alpha particles, 1.3 Hz from electrons and 0.8 Hz from γ-rays from the Crab nebula.

Monte-Carlo simulation studies for assessing the segregation potential of various parameters along with their dependence on observation height has been investigated. The results indicate that while the radius of curvature of the Cherenkov light front is more sensitive to primary species as compared to lower observation altitudes, the relative timing jitter remains almost constant as a function of observation height. Further more it is also found that the Cherenkov pulse delay time which is more sensitive to the presence of hump is relatively less sensitive to the primary species compared to that at lower observation altitudes. Thus using relative timing jitter and pulse decay time in tandem it is expected that about 98% proton showers will be rejected while retaining about 35% γ-ray showers [36, 37]. Use of parameters based on Cherenkov photon density including local and medium range photon density fluctuations have also yielded promising results to discriminate γ-ray events from the more abundant cosmic ray events. The expected sensitivity of HAGAR is shown in figure 8. The 5σ sensitivity of HAGAR is shown as 'Dotted line' and corresponds to the case without any additional rejection of cosmic rays apart from that obtained from 4 out of 7 telescope trigger logic. The solid line corresponds to additional rejection of triggered events (98% rejection of cosmic ray showers and 35% acceptance of γ-ray showers). This corresponds to the detection of Crab at 5σ level within a duration of ~25 minutes.

4.2 Stereo MACE imaging telescope

The MACE (Major Atmospheric Cherenkov Experiment) telescope is planned to be a system of two high resolution imaging Cherenkov telescopes operating in a stereoscopic mode for γ-ray investigations in the sub TeV energy range. As depicted in figure 9, each telescope element will be based on the track and wheel design concept and will deploy an alt-azimuth mounted parabolic light collector of 21 m diameter. The drive control system of the telescope is being designed around electronically commutated motors using digital controllers, PC compatible hardware and software and Ethernet connectivity for remote monitoring and control. The light collector will be made of 356 panels of $984\ mm \times 984\ mm$ size with each panel consisting of $4/9$ spherical mirror facets of 488 mm $\times$ 488 mm / 323 mm $\times$ 323 mm size. Each aluminium alloy (Al-6063T6) facet is diamond turned to a mirror finish yielding a reflectivity of $> 85\%$ in the visible band. The focal length of the facets which increases to-wards the periphery will range from 2109 cm to 2245 cm. The use of graded focal length mirrors reduces the D95 spot size (defined as the diameter of the circle within which 95% of the reflected rays lie) of the light collector to $\sim$ 29 mm ($= 0^{\circ}.08$) for on-axis incidence and $\sim$ 85 mm ($= 0^{\circ}.23$) for incidence angle of 1°. The Davies Cotton design on the other hand, although found to yield slightly better off-axis characteristics at incidence angles beyond $0^{\circ}.75$, introduces a time spread of $\sim$ 9 ns which can lead to a contamination of the genuine Cherenkov signal from unwanted light of night sky background. Each of the 356 mirror panels will be equipped with motorized orientation controllers for aligning them to form a single parabolic light collector. The hardware and software requirements of the system have been worked out and image processing algorithms for mirror alignment based on the use of alignment lasers and star image methods have been evolved [38].

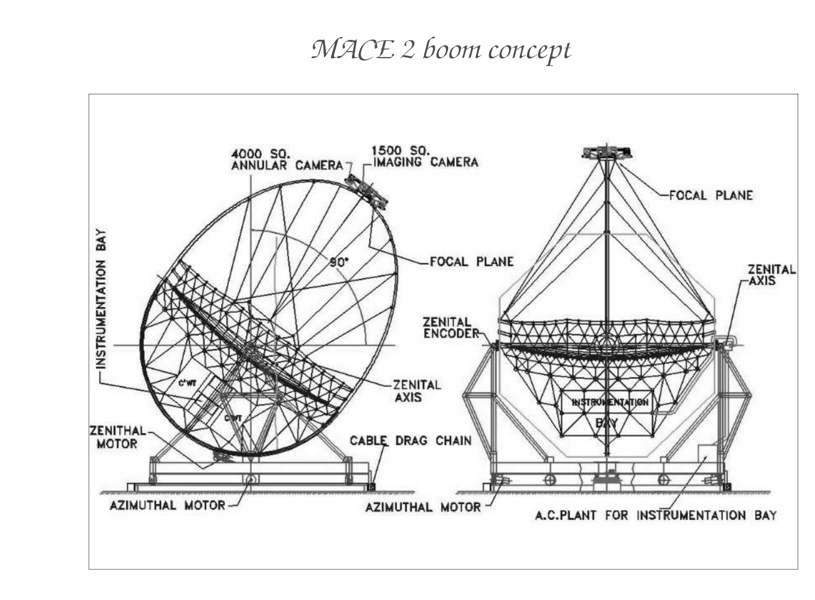

Figure 9. A schematic of the MACE γ-ray telescope planned to be set up at Hanle

The focal plane instrumentation will comprise 832 pixels imaging camera providing a field of view of $4^{\circ} \times 4^{\circ}$. While the inner 576 pixels covering a field of view of $2^{\circ}.4 \times 2^{\circ}.4$ will have a pixel resolution of $0^{\circ}.1$ for generating the event trigger, the surrounding 256 pixels will have a coarser resolution of $0^{\circ}.2$. The PMTs will be provided with acrylic front-aluminized light cones for enhancing the photo-sensitive area of the camera. The signal processing instrumentation will also be housed within the camera and the digital data will be sent over optical fibers to the computer network in the control room for processing and archiving. Preliminary simulation studies using the CORSIKA air shower simulation code have been conducted to evaluate the expected performance parameters of the MACE telescope. Based on the measured value of the night sky background and a coincidence gate width of $\sim$ 10 ns, the single pixel threshold was evaluated to be $\sim$ 4 pe at a single channel rate of $\sim$ 26 KHz using the Nearest Neighbour Quadruplet (NNQ) trigger. As shown in figure 10, the γ-ray threshold energy of a single MACE element works out to $\sim$ 15 GeV and $\sim$ 25 GeV at zenith angles of

10° and 30° respectively while the proton threshold is $\sim 60\ GeV$ and $\sim 80\ GeV$ respectively [39]. Detailed simulation studies which include the stereo-mode operation of the MACE are in progress.

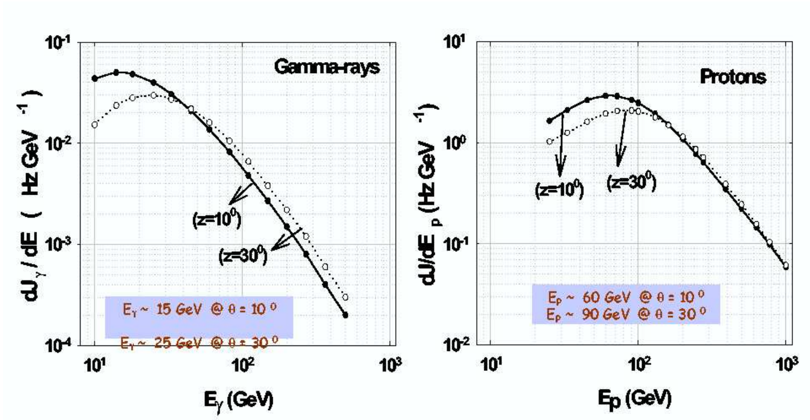

Figure 10. Differential detection rate of events as a function of the primary energy. The left panel is for γ-ray and right panel for proton primaries.

Figure 11. First element of 7 Telescope HAGAR array at Hanle

5. Epilogue

The first element of the HAGAR array has been recently installed at the site and is shown in figure 11. Engineering and preliminary functional tests of this unit have been successfully carried out. The second unit is also at the site but awaits installation. The remaining five elements of the array are being fabricated and scheduled to be in place in the next one and a half years. The complete array is expected to be operational by early 2007.

The detailed engineering and structural design of the MACE telescope is scheduled to begin soon and it is anticipated that the mechanical structure of one element will be installed at site by 2008. The first imaging element is expected to be fully operational by 2010 and will subsequently be augmented by a stereo element.

The initial emphasis will be on observations of pulsars including Crab and Geminga. Pulsed emission has been detected from seven pulsars by EGRET below 10 GeV [40, 41, 42] while at energies above few hundred GeVs only non-pulsed emission from nebula is detected [43]. Detection of pulsed emission and its spectral cutoff in the energy range covered by GLAST and ground-based set-ups would enable the much awaited differentiation between polar cap [44, 45] and outer gap [46, 47] models regarding the emission of γ-rays in pulsars.

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