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Review Article

Gamma Ray Astronomy from High Altitudes: HAGAR

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High Altitute Gamma Ray (HAGAR) experiment, an array of seven atmospheric Cherenkov telescopes, is installed at Hanle in Ladakh, at an altitude of 4300 m, in 2008. This experiment is designed to study very high energy gamma rays from astronomical sources. Taking advantage of high altitude location HAGAR has achieved energy threshold of about 200 GeV. Design details and performance parameters of HAGRA are discussed here. Also preliminary results for Crab nebula, which is a standard candle, are discussed.

Key Words : Gamma Ray Astronomy; Atmospheric Cherenkov Technique

1. Introduction

Study of Very High Energy (VHE) gamma ray emission from celestial sources is carried out using ground based atmospheric Cherenkov technique. In this technique gamma rays from astronomical sources are detected indirectly. Gamma ray interacts at the top of the atmosphere by pair production, in presence of air nucleus. Electron and positron formed here lose part of their energy in the form of gamma ray photon by Bremsstrahlung. With successive pair-production and Bremsstrahlung, a cascade of lower energy gamma ray photons and charged particles develops in the atmosphere. These charged particles moving at relativistic speeds cause atmosphere to emit bluish Cherenkov light. This light comes as a flash of coherent radiation lasting for a few nanoseconds and is spread over a circular area of radius of about 100 m at ground level. Ground based atmospheric Cherenkov telescopes detect this Cherenkov light.

Present era of VHE gamma ray astronomy started in 1989, with statistically significant detection of signal from Crab nebula by Whipple observatory (Weekes *et al*., 1989). This experiment is based on imaging version of atmospheric Cherenkov technique. Imaging telescope consists of a large mirror with cluster of PMTs at its focus, with each PMT viewing different region in the field of view. Imaging telescope samples longitudinal development of shower. Other variant of atmospheric Cherenkov technique is wavefront sampling. In this version, using large arrays of telescopes, lateral distribution of Cherenkov light is sampled. Imaging technique was pioneered by Whipple and experiments including French experiment CAT, Russian experiment SHALON, BARC experiment TACTIC at Mt. Abu etc are based on this technique. Whereas experiments including French experiments Themistocle and CELESTE, STACEE and CACTUS in US, TIFR experiment PACT at Pachmarhi are based on wavefront sampling technique. By middle of 1990s, stereoscopic imaging technique was pioneered by German experiment HEGRA at La Palma. In this technique array of several imaging telescopes is used. This technique, in some sense, combines imaging and wavefront sampling technique. Many of the present generation big experiments like European experiment HESS in Namibia, MAGIC at La Palma, VERITAS

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in US and Australian-Japanese experiment CANGAROO in Australia are based on this technique.

Most of the experiments operated in 1990s had energy thresholds in the range of 300 GeV to 1 TeV. Satellite based experiment EGRET onboard Compton Gamma Ray Observatory operated during 1991-2000 and covered energy range of 20 MeV-30 GeV. So the region 30-300 GeV was largely unexplored. At the same time there was strong physics motivation to cover this energy range. For example, EGRET had detected pulsed emission from seven pulsars upto the energies of few GeVs, but none were detected by ground based experiments above 300 GeV. This indicates a cutoff in the pulsed component of the spectrum. This cut-off occurs in the unexplored window of gamma ray band and has important implications on models for pulsations. Also gamma rays from distant AGN are attenuated due to their interaction with extragalactic background light. As a result, experiments with energy threshold of about 1 TeV can detect gamma ray light from only nearby AGN with redshift within about 0.03. Whereas experiments with energy threshold of about 100 GeV can detect AGN with redshift as high as 1. So lower energy threshold experiments can detect larger number of AGN and also can give estimate of EBL based on detected spectra of AGNs with distances varied over wide range. Another important aspect is detection of gamma ray bursts by ground based atmospheric Cherenkov experiment. Most of the gamma ray bursts are at cosmological distances, so gamma rays from these distant objects are also attenuated by their interaction with extragalactic background light. There have not been any detections of GRBs by atmospheric Cherenkov experiments so far, but lowering energy thresholds of the experiments is likely to help detection of GRBs . Because of these reasons there is a global effort to reduce energy threshold of atmospheric Cherenkov experiments and cover part of hitherto unexplored gamma ray band.

2. HAGAR

2.1 Methods for Achieving Lower Energy Thresholds

There are several ways of reducing energy thresholds of atmospheric Cherenkov experiments. Energy threshold decreases with increase in mirror area. Experiments like MAGIC have adopted this

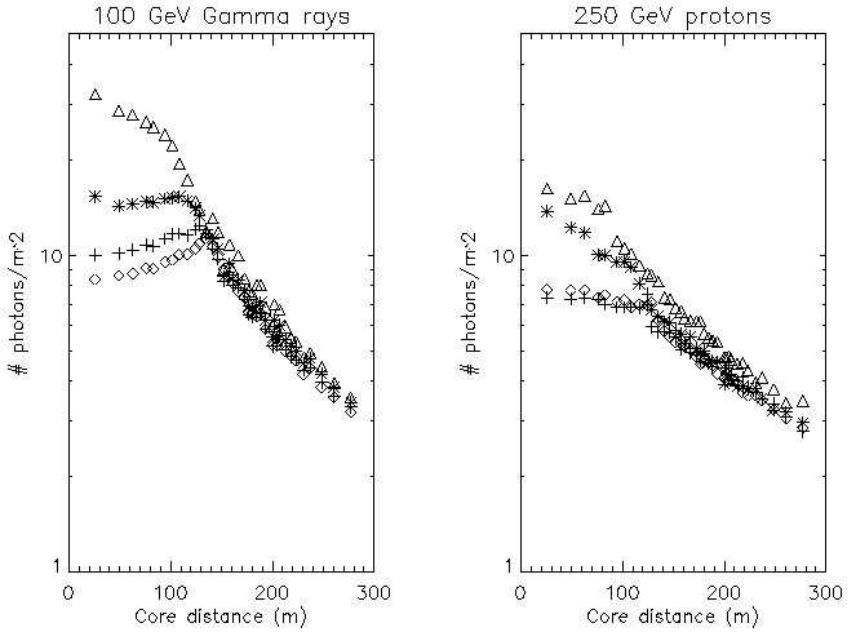

Fig. 1: Lateral distribution of Cherenkov photons, i.e. Cherenkov photon density vs distance from shower axis, for showers initiated by 100 GeV gamma rays and 250 GeV protons for various altitudes: sea level (diamond), 1 km altitude (plus sign), 2 km altitude (asterisk) and 4.5 km altitude (triangle)

approach of using large mirrors (17 m diameter mirror in case of MAGIC), to reduce energy threshold below 100 GeV. But this is an expensive method. Other cost effective way to decrease energy threshold of the experiment is to take the experiment to higher altitude. Cherenkov light is emitted in the form of a cone, with most of the light being emitted from vicinity of shower maximum. This shower maximum is at the altitude of typically 10 km above sea level in the case of showers initiated by 100 GeV gamma rays, incident vertically. At sea level, this light is spread over a circular region with radius of about 140 m. As one goes higher up in the atmosphere, size of this Cherenkov pool decreases. As a result, Cherenkov photon density increases but the collection area decreases. Hence it is possible to detect showers initiated by lower energy gamma rays with experiments at higher altitudes compared to similar experiments at lower altitudes. This is further clarified by Fig. 1 which shows lateral distribution i.e. variation of Cherenkov photon density vs distance from shower axis for showers initiated by gamma rays and protons at various altitudes : sea level, 1 km, 2 kms and 4.5 kms. Cherenkov photon density increases by factor of 4-5 near shower core at 4.5 kms altitude, compared to that at sea level. Also atmospheric attenuation of Cherenkov photons is much less at higher altitudes. It is about 14% at Hanle (4.3 kms altitude) compared to 50% attenuation at sea level. Based on these simulations High Altitude Gamma Ray (HAGAR) experiment was proposed.

2.2 Design Details of HAGAR

HAGAR was proposed in 2001. Simple design consisting of seven telescopes based on wavefront sampling technique was adopted for HAGAR. The reason for the simple design was to get the array ready in a short time. The extreme cold weather conditions prevailing at Hanle impose certain restrictions for civil work. At Hanle, civil work can be carried out only in summer period, i.e. from May to September months. Also HAGAR was planned in such a way that it should be operational when GLAST (named Fermi Gamma-ray Space Telescope after launch in 2008) is launched. The aim was to have simultaneous coverage for sources with Fermi telescope and HAGAR. HAGAR is situated at base camp of Hanle at altitude of 4.3 kms. The first telescope of HAGAR was installed in 2005 and the remaining telescopes were installed in next two years. For about an year, various engineering tests were conducted and science observations commenced in September, 2008 with the full array.

HAGAR is an array of seven telescopes with six telescopes forming a hexagon and one telescope at the centre (see Fig. 2). Spacing between

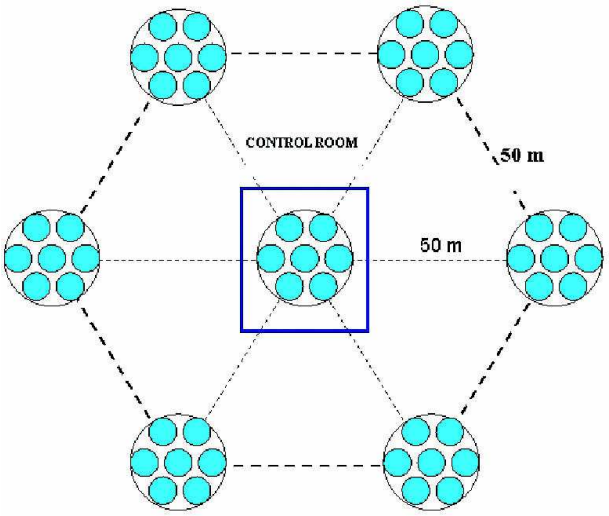

Fig. 2: Schematic of HAGAR array

neighbouring telescopes is 50 m. Each telescope consists of seven para-axially mounted parabolic mirrors of diameter 0.9 m each. The f/d ratio of these mirrors is about 1. The mirrors were fabricated by forming 10 mm thick float glass plates into parabolic shapes. The front surface is aluminised. At the focus of each mirror fast UV sensitive Photonis phototube of the type XP2268B is mounted (Acharya *et al.*,2008) Photograph of HAGAR after completing installation of all seven telescopes is shown in Fig. 3.

Telescopes have alt-azimuth mounts where each axis of the telescope is driven by a steppar motor. The telescope movement control system consists of two 17 bit Rotary encoders, two steppar motors and Microcontroller-based Motion Control Interface Unit (MCIU). Steady state pointing accuracy of the servo is ±10 arc-sec with maximum slew rate of 30°/minute.

Fig. 3: Photograph of HAGAR

The resulting blind-spot size while tracking the stars near zenith is ~1.2° . The movement of telescopes is maneuvered by the control software developed under Linux.

High voltages given to phototubes are controlled using C.A.E.N. controller model SY1527. Pulses from phototubes are brought to the control room situated below the central telescope via coaxial cables of types LMR-ultraflex-400 and RG 213 with total length of about 85m. Data acquisition and recording is done through CAMAC based instrumentation which is interrupt driven. There are two types of interrupts: Event interrupt which arises on event trigger and monitor interrupt which arrives at the frequency of 1 Hz. Pulses from 7 phototubes of each telescope are added linearly to form a telescope pulse. Event trigger is generated on coincidence of at least 4 out of 7 telescope pulses in narrow coincidence window. Data recorded on event interrupt consists of (a) relative arrival time of Cherenkov shower front at each mirror accurate to 0.25 ns as given by TDCs, (b) Cherenkov photon density or pulse height at each mirror given by 12 bit ADC and (c) absolute arrival time of event accurate to μs as given by Real Time Clock (RTC) module synchronised with GPS. Various count rates including individual phototube rates, telescope rates etc are recorded on monitor trigger.

2.3 Pointing Model

It is necessary to attain good pointing accuracy of mean direction of 7 mirrors in each telescope as well as low spread in pointing directions of mirrors about this mean. The mirrors are initially co-aligned roughly with a guiding telescope provided with each telescope, by sighting a distant stationary light source. Initially the pointing models for guiding telescopes are worked out sighting large no. of stars. CCD camera(ST-4) is used to obtain the pointing data for this purpose. Afterwards several RA-DEC scans are performed pointing telescopes to isolated bright stars. In these scans, telescopes are offset from the star in RA and DEC in the steps of 0.5 deg and count rates are recorded for each mirror. Count rate vs offset profile is generated for each mirror and centroid of this profile gives offset of the mirror. Based on these offsets, mirror alignment is fine tuned and improvement is verified conducting RA-DEC scans again. RA-DEC scans also provide mean of the pointing directions of seven mirrors as a function of altitude and azimuth of the stars. This data is used for fine tuning pointing models of all the telescopes.

Azimuth and altitude corrections in pointing models are given by following expressions:

$$\Delta A = -AN \times \sin A \times \tan E - AW \times \cos A \times \tan E + NP$$

$$AE \times \tan E + IA + ACEC \times \cos A + ACES \times \sin A \quad (1)$$

and

$$\Delta E = AN \times \cos A - AW \times \sin A + IE + CTC \times \sin E + CTT \times \tan E \quad (2)$$

where A = Azimuth angle of the star, E = Elevation angle of the star, AN, AW, NPAE, IA, IE, ACEC and ACES are coefficients corresponding to real physical misalignments and other mechanical distortions in the telescope (Wallace, 2010), CTC and CTT are empirically found coefficients.

The distribution of offsets of stars relative to axis of the guiding telescope after application of pointing model is shown in Fig. 4. Similarly, the distribution of the pointing errors of 7 mirrors in a telescope after fine tuning of mechanical alignment and after refinement of the pointing model is shown in Fig. 5. The overall pointing accuracy of HAGAR telescope mirrors achieved by this method is 0.2±0.12 deg.

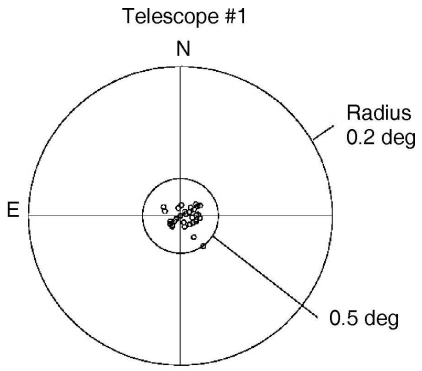

Fig. 4: A typical pointing error distribution of a guiding telescope after applying pointing model

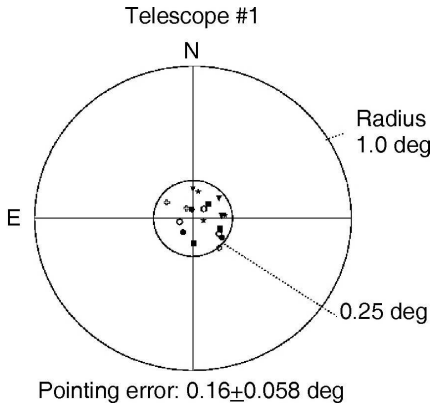

Fig. 5: Pointing error distribution of 7 mirrors in a typical telescope

3. Performance Parameters of HAGAR

Experiments like HAGAR, which are based on atmospheric Cherenkov technique, detect gamma rays with energies from few hundreds of GeV to few tens of TeV indirectly. It is not possible to directly calibrate these experiments using calibration beams of known energies. In absence of direct calibrations, performance of these experiments can be understood only through detailed simulations. These simulations consist of two parts. First part is simulation of extensive air showers initiated by gamma rays and Cherenkov emission caused by these showers. Second part is simulation of detector response which takes into account design parameters of the experiment.

We have used a package called CORSIKA (COsmic Ray SImulation for KASCADE) version 6.019 for simulations of extensive air showers for HAGAR (Heck *et al.,* 1998). This package was originally developed by a German group at Karlsruhe to perform simulations for KASCADE (KArlsruhe Shower Core and Array DEtector) experiment. This is one of the packages used widely for simulations of atmospheric Cherenkov experiments. We have simulated showers initiated by gamma rays as well as those initiated by cosmic rays, which form background against which gamma ray signal is to be detected. Amongst the cosmic rays, we have simulated showers initiated by by protons, alpha particles and electrons since these form bulk of the triggers for HAGAR. In CORSIKA we have selected package GHEISHA for lower energy hadronic interactions and VENUS for higher energy hadronic interactions.

Gamma rays are simulated over the energy range of 20-5000 GeV following spectral slope of -2.49 in accordance with spectrum of Crab nebula as measured by Whipple experiment. These showers are assumed to be incident along the vertical direction. Showers initiated by protons and alpha particles are initiated following spectral slope of –2.7 over the energy ranges of 50 GeV-5 TeV and 100 GeV-10 TeV respectively. Showers initiated by cosmic electrons

were also simulated following steeper spectrum with index of -3.3 over the energy range of 50 GeV - 5 TeV. Gamma rays originate from particular sources, so these showers were generated assuming vertical incidence. Cosmic ray initiated showers were simulated within 3^o cone around vertical following isotropic distribution. Impact parameter of shower axis relative to centre of HAGAR was varied over 0-200 m. Geomagnetic field appropriate for Hanle location was used. Altitude of observation level was set to Hanle altitude i.e 4.3 kms. US standard atmosphere profile was assumed. Information regarding Cherenkov photons reaching HAGAR array, with wavelengths within the range of 270-650 nm was recorded. This information includes arrival position, arrival angle, arrival time since first interaction and production height of each Cherenkov photon.

Cherenkov photon distribution given by CORSIKA is then passed through the detector simulation program which simulates processing of Cherenkov pulse in HAGAR experiment. This package is developed in-house and takes into account various instrumental and site related details. These include night sky background at Hanle (1.5×10^8 ph/cm^2/s/sr), mirror reflectivity (80%), phototube quantum efficiency (peak value of 24% at 400 nm), phototube pulse shape (Gaussian with 2 ns rise time and 3.3 ns width), phototube gain of 2.2×10^6, attenuation of Cherenkov pulse in coaxial cables, amplification of pulse (by factor of 10) by amplifier module, discriminator threshold for telescope pulse (~180 mV) etc. Finally this program applies trigger criteria of at least four telescope pulses out of seven, crossing discriminator threshold in narrow coincidence window of about 150 ns and writes down Cherenkov photon pulse information for triggering showers.

Total trigger rate obtained from simulations, which is sum of trigger rates from protons, alpha particles and electrons, is 13.7 Hz. This is consistent with the observed trigger rate of about 14 Hz near vertical. Energy threshold of the experiment is one important performance parameter and is conventionally given as a peak of the differential rate curve for gamma ray initiated showers. Energy threshold of HAGAR is about 185 GeV for vertically incident showers, as shown in the Fig. 6. Expected trigger rate from Crab like source is about 9.6 counts/minute. Collection area of the experiment is estimated to be about 4×10^4 m^2 for vertically inclined showers. Both, energy threshold and collection area will increase for showers incident at an angle relative to vertical. 5σ sensitivity of HAGAR for 50 hours of observations is estimated to be about 1.68×10^{-10} erg/cm^2/s.

Efforts are on to reduce energy threshold of HAGAR. At present phototubes are operated at somewhat lower gain. In order to have idea about variation of trigger rate and energy threshold with phototube gains, simulations were performed for various values of gains between 1×10^6 to 5×10^6 . Energy thresholds and trigger rates for these various conditions are shown in the Fig. 7. For the phototube gain of 5×10^6 , energy threshold is 60 GeV.

Sensitivity of atmospheric Cherenkov experiment is the ability of the experiment to detect gamma ray signal in presence of cosmic ray background. Sensitivity of HAGAR is estimated under various conditions and given in Fig. 8. This figure shows observation duration required to detect gamma ray signal at 5σ significance level as a function of source flux in Crab units. At present raw sensitivity of HAGAR, i.e. sensitivity without cuts

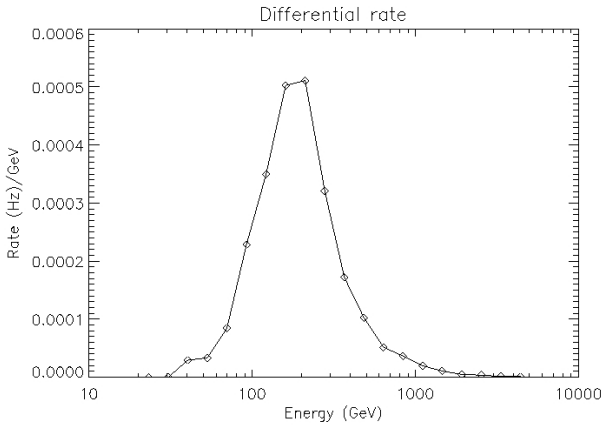

Fig. 6: Expected differential gamma ray count rate spectrum from Crab nebula with peak around 185 GeV

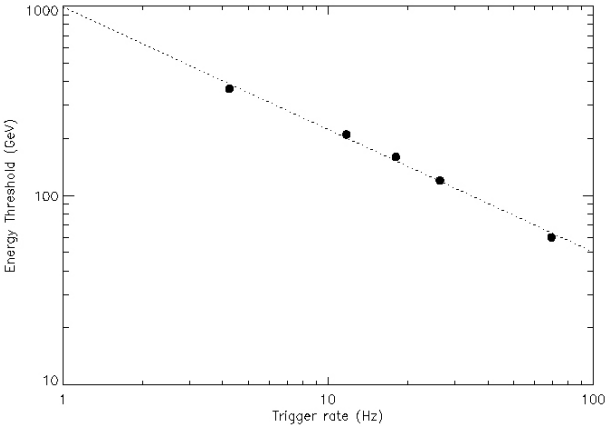

Fig. 7: Trigger rate vs energy threshold for phototube gains of 1, 2, 2.5, 3 and 5 × 10^6. Energy threshold decreases and trigger rate increases with increase in phototube gain

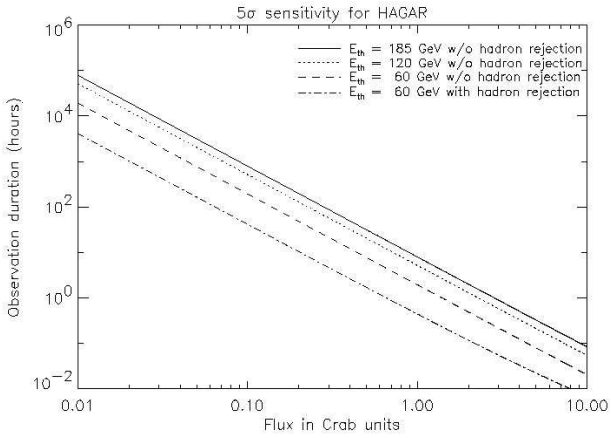

Fig. 8: 5σ sensitivity of HAGAR array under various conditions

to reject cosmic ray generated showers, is 1.8σ/√hour (shown by solid line in the figure). It means that we can detect Crab like source at 5σ significance level in about 7 hours of observation duration. This sensitivity is rather poor. It is due to the fact that gamma ray signal is quite weak compared to cosmic ray background. Ratio of no. of gamma ray triggers to cosmic ray triggers is almost 1:100, as is evident from trigger rates of 9.6 counts/minute and 13.7 Hz for gamma rays and cosmic rays respectively. Only way to improve this sensitivity is by rejecting large fraction of cosmic ray triggers, at the same time retaining most of the gamma ray events, while analysing the data. There are two possibilities for effective rejection of cosmic ray showers. Firstly, cosmic rays are isotropic in nature, whereas gamma rays originate from specific sources. So if experiments have good angular resolution, it is possible to detect large fraction of cosmic ray showers. Secondly, even though there are many similarities in showers initiated by gamma rays there are certain differences due to difference in kinematics of these two types of showers. For example, at lower observation altitudes gamma ray showers show distinct hump in lateral distribution at distance of about 120-140 m from core. This is due to artificial focusing of Cherenkov photons from range of altitudes for which product of Cherenkov angle and altitude remains roughly constant (Rao and Sinha, 1998). Such hump is not seen in the case of cosmic ray showers (Chitnis and Bhat, 1998). Also cosmic ray showers show larger fluctuations in Cherenkov photon density as well as higher jitter in arrival times of Cherenkov photons, compared to showers initiated by gamma rays (Chitnis and Bhat, 2002; Chitnis and Bhat, 2001). Also there are differences in Cherenkov pulse shapes produced by gamma ray and cosmic ray initiated showers (Chitnis and Bhat, 1999 and Chitnis and Bhat, 2001). These type of differences can be studied and parameterised through simulations and applied to experimental data. These are gamma-hadron separation parameters. Using these, one can reject cosmic ray showers. Work on these parameters and study of their efficacy for HAGAR is underway. We have estimated sensitivity of HAGAR under various conditions as shown in Fig. 8. Sensitivity is estimated for higher phototube gains. For highest phototube gain considered here, sensitivity will be 3.6σ/√hour (shown by dashed line in the figure). For the highest phototube gain, we have estimated sensitivity assuming 98% rejection of cosmic ray showers (which we hope to achieve using off-axis rejection and through usage of GHS parameters), and 35% acceptance for gamma ray showers sensitivity of HAGAR is estimated to be 7.6σ/√hour (shown by dash-dotted line in figure). This is the best possible sensitivity we can hope for HAGAR and corresponds to detection of Crab at significance level of 5σ in just about 26 minutes.

The Fig. 9 shows sensitivity of HAGAR alongwith other experiments. Sensitivity of GLAST

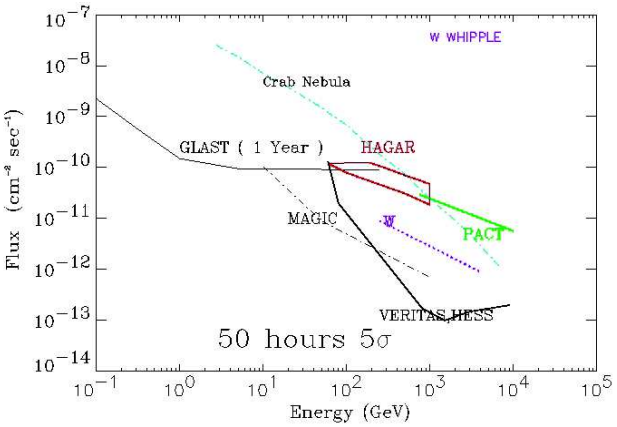

Fig. 9: Sensitivity of various satellite based and atmospheric Cherenkov experiments given as gamma ray flux that can be detected at significance level of 5σ in 50 hours of observation duration

i.e. Fermi telescope is shown for duration of one year. Sensitivity of other experiments, which are atmospheric Cherenkov experiments, is given as gamma ray flux that can detected at 5σ significance level in 50 hours of observation. The figure shows sensitivity of Whipple which pioneered imaging technique. Sensitivities of present generation big telescopes, i.e. VERITAS, HESS and MAGIC are also shown. Green line indicates sensitivity of Pachmarhi Array of Cherenkov Telescopes (PACT). This experiment is similar to HAGAR, but larger in size and located at altitude of 1 km at Pachmarhi in Madhya Pradesh. Energy threshold of PACT is 750 GeV, whereas that of HAGAR is 185 GeV at present. By going to high altitude, we have already achieved reduction in energy threshold by factor of 4. Sensitivity of HAGAR is shown as band corresponding to various conditions in Fig. 8.

4. Results from HAGAR

Since October 2008, regular observation of celestial objects using HAGAR were started. The signal extraction procedure relies heavily on the estimation of arrival direction of the shower. The arrival direction is obtained by fitting the time of arrival of spherical Cherenkov wavefront at the telescopes, using plane front approximation as the radius of curvature is large (5 km). Cosmic ray background could be reduced considerably by limiting the field of view of the reconstructed showers close to telescope axis (i.e by rejecting the off-axis events). This approach is suited for point source searches as cosmic rays arrive isotropically whereas γ-ray events arrive from the direction of source. To extract the signal in the presence of cosmic ray background, source observations were carried out in ON-OFF mode, i.e. observing Source and Off-source regions in succession, at the same local coordinates on the sky so as to have the same overburden of air mass. A pair of observations typically last for about an hour. The Source region is compared with the Off-source region and an estimate of γ-ray signal from Source is made. However the atmospheric observing conditions do change even though On-source and Off-source data were collected over the same zenith angle region as the ON-OFF pair is off-set in real time (On-source and Off-source data were not collected simultaneously). Thus, normalization of events from both ON and OFF source data is necessary and done by comparing the distribution of arrival direction of showers at large space angles (defined as the angle between the telescope axis and the reconstructed shower direction) where, γ-ray events from a point source are not expected. An important step in the validation of data analysis method is to analyse data

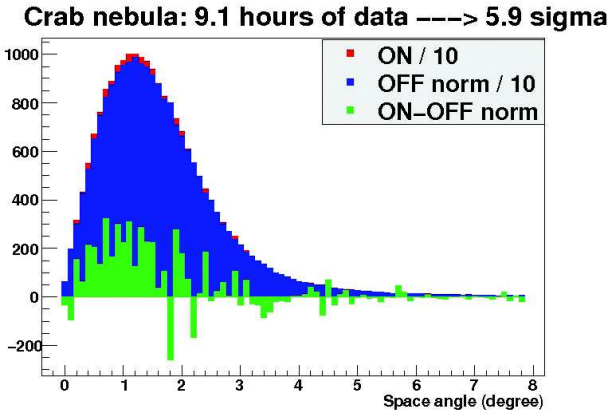

Fig. 10: Distribution of space angle of events from Crab (On-source), background region (normalised Off-source) and signal (background subtracted On-source). For readability ON and OFF distributions were scaled down by a factor of 10

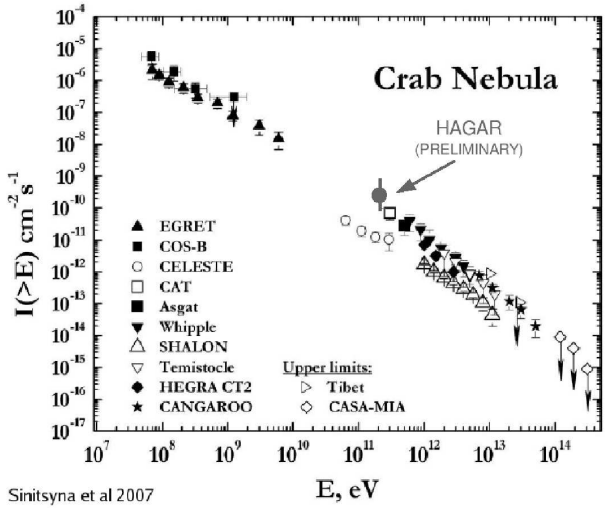

Fig. 11: Integral energy spectrum of γ-rays from Crab nebula as measured by different groups. The preliminary flux estimation from HAGAR is also shown

from fake sources (dark regions not having any sources). We do not expect to see the γ-ray signal from these sources. The same method is later applied to the standard candle source Crab Nebula. As an example, the space angle distribution of events from Crab nebula, normalised off-source data and the background subtracted On-source events were shown in Fig. 10. An estimate of flux of gamma rays from Crab nebula from HAGAR experiment is shown and compared with other results in Fig. 11 (Britto *et al.*, 2009).

5. Conclusions

HAGAR has been operating since October 2008. Routine observations on AGNs, pulsars and supernova remnants are being carried out. The data acquisition system is upgraded recently with the addition of 8 channel, 1 GHz sampling pulse digitizers. This additional system besides aiding tools for Gamma-hadron separation also serve as parallel data acquisition system. Further, MACE, 21 m diameter imaging telescope, will be commissioned by the BARC group at the same site in the near future (Koul *et al*., 2005) . Both MACE and HAGAR will then be integrated to have greater ability to reject cosmic ray background.

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