High Altitude Gamma Ray Observatory at Hanle (HAGAR)

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Abstract

Taking advantage of the high altitude of nearly 4.5 km above the mean sea level of Hanle (situated in the cold desert in the Himalayas) we have proposed to set up a pilot experiment to detect celestial γ-rays of energy $\geq 20\ GeV$ using the atmospheric Cerenkov Technique at this site. In this experiment, we plan to deploy 7 telescopes, similar to the ones used in PACT at pachmarhi, in the form of a hexagonal mini-array and use the wave-front sampling technique for rejection of cosmic ray background. The chief advantage of this experiment is the low energy threshold that may be achieved, which overlaps with the energy range of future satellite-based detectors. The limited lateral spread of the Cerenkov light pool, near 90% atmospheric transmission of Cerenkov light and low sky brightness makes this high altitude site an ideal place to set up a ground-based γ-ray observatory.

Introduction

Atmospheric Cerenkov technique is a well established ground-based technique for the study of VHE γ-ray emission from celestial sources. This technique has been successfully exploited by several experiments using imaging or wavefront sampling technique for the rejection of cosmic ray background (?). The next generation of experiments using very large imaging telescopes (MAGIC and the like) or an array of imaging telescopes (HESS, CANGAROO-III and VERITAS) or large collection area arrays that use wave-front sampling technique (CELESTE, SATCEE, etc.) are expected to achieve low energy threshold of the order of few tens of GeV.

Alternatively it is possible to lower the energy threshold by conducting experiments at higher observation altitudes. All the existing experiments are being carried out at altitudes of upto 2.5 km. Here we describe an experiment [5] based on wavefront sampling technique to be carried out at a location called Hanle at an altitude of about 4.5 km. A panaromic view of the proposed site is shown in Figure 1. The Indian Astronomical Observatory has been set up recently at Hanle (32° 46' 46" N, 78° 57' 51$\prime\prime$ E, 4515m amsl), situated in the high altitude cold desert in the Himalayas. The observatory has 2-m aperture optical-infrared telescope, installed by the Indian Institute of Astrophysics, Bangalore, India. The high altitude of this site offer certain advantages for the ground-based γ-ray astronomy. The limited lateral spread of the Cerenkov light pool, and near 90% atmospheric transmission at this location makes it an ideal site for a γ-ray observatory. These could result in a very low gamma ray energy threshold $\sim 20\ GeV$ for a modest set-up at this altitude.

Figure 1. Panaromic view of the proposed site of HAGAR at Hanle

Lateral distribution of Čerenkov photons

We have carried out Monte Carlo simulation studies using CORSIKA package [6] for this observation altitude to study the nature of Cerenkov light pool generated by γ-ray and proton primaries incident vertically at the top of the atmosphere. Air showers generated by γ-rays and protons of various primary energies were simulated. The Cerenkov radiation, produced by the secondary charged particles in the shower, within the bandwidth of 300-650 nm is propagated to the observation level (The wavelength dependent atmospheric attenuation of Cerenkov photons is not taken into consideration in this calculation). Location and altitude appropriate for Hanle are used in the simulations. For low energy primaries (γ-rays of energy 1 and 10 GeV, and protons of energy 15 and 50 GeV) 500 showers were simulated while 100 showers were simulated for higher energy γ-ray (50 and 500 GeV) and proton (150 GeV and 1 TeV) primaries. The energies of γ-ray and proton primaries are chosen such that their showers have comparable Cerenkov photon yields at the observation level. The average Cerenkov photon density as a function of core distance for showers initiated by γ-rays and protons of various energies are shown in figure 2.

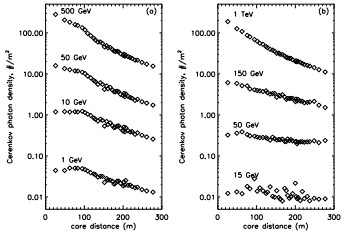

Figure 2. Average Cerenkov photon density at Hanle as a function of core distance for showers initiated by (a) γ-rays of energies 1, 10, 50 and 500 GeV and (b) protons of energies 15, 50, 150 GeV and 1 TeV.

The lateral distributions from γ-ray primaries indicate presence of proverbial hump at a core distnace of about 90 m, due to effective focussing of Cerenkov photons from a range of altitudes. However, this hump is somewhat less prominent compared to that seen at lower altitudes [2]. Also the density distribution within hump is not as flat as in the case of lower observation altitudes. Dilution of the hump at higher primary energies as well as at higher altitudes is expected [8]. Also the comparison of lateral distributions due to a primary of given energy show that the Cerenkov photon density near the shower core at Hanle is higher by a factor of about 5-6 compared to that at sea-level. This higher photon density as well as the smaller distance to hump from shower axis at Hanle is due to the compactness of shower at higher altitudes. This will reduce the energy threshold of the experiment appreciably compared to same array at lower altitudes.

Gamma-hadron separation

All atmospheric Cerenkov experiments have to deal with a substantial background from air showers generated by cosmic rays emulating those initiated by γ-ray primaries. It is necessary to incorporate the methods for effective rejection of this background for improving signal to noise ratio. In experiments based on wavefront sampling technique, such as the present one, parameters based on arrival time of Cerenkov shower front and Cerenkov photon density at various locations within the Cerenkov pool could be used for discrimination. The usefulness of these techniques at lower observation altitudes was demonstrated by Chitnis and Bhat [3,4]. We have studied the effectiveness of these parameters at Hanle altitude. A fictitious array of 6 telescopes, each consiting of seven mirrors with a total reflector area of 4.45 m^2 per telescope, spread over an area of 20 m × 50 m is considered.

We use quality factor as a figure of merit to distinguish between γ-ray and proton initiated showers. If is defined as

$$Q_f = \frac{N_\gamma^a}{N_p^a}\left(\frac{N_p^{gr}}{N_\gamma^{gr}}\right)^{-1} \qquad (1)$$

where N_γ^a is the number of γ-ray events accepted, N_γ^{gr} is the total number of γ-ray events, N_a^{gr} is the number of proton events accepted and N_p^{gr} is the total number of proton events in the data sample. The optimum quality factors, derived using various parameters is given in Table 1.

Table 1. Gamma-hadron separation for showers initiated by 500 GeV γ-rays and 1 TeV protons at Hanle

Parameter	Threshold value	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
Shower front curvature	5.2 km	1.39 ± 0.21	0.577	0.173
Decay time of pulse	4.54 ns	1.40 ± 0.12	0.682	0.236
Timing jitter	0.084	2.63 ± 0.02	0.487	0.034
Decay time and jitter	4.54 ns, 0.084	2.25 ± 0.05	0.349	0.024
LDF	0.127	1.53 ± 0.03	0.803	0.276
MDF	0.164	1.24 ± 0.09	0.386	0.097
Flatness parameter	34.8	1.01 ± 0.05	0.963	0.902
LDF and MDF	0.127, 0.164	1.60 ± 0.15	0.338	0.045

We have examined the applicability of six parameters, 3 each based on Cerenkov photon arrival times at the telescopes (the curvature of spherical shower front, Shape of Cerenkov pulse and Relative arrival time jitter) and Cerenkov photon density (local density fluctuations (LDF), medium range density fluctuations (MDF)and flatness of lateral distribution of photon density).

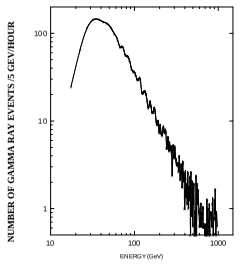

Figure 3. Gamma-ray count rate differential spectrum for Hanle altitude using wave-front sampling technique.

The radius of curvature of shower front is found to be roughly equal to the height of the shower maximum from the observation level. This parameter provides moderate discrimination against cosmic ray showers. This is mainly because of the interaction length of hadrons in the atmosphere being about twice the radiation length. Hence the hadron initiated showers reach shower maximum deeper in the atmosphere compared to a γ-ray initiated showers. As in the case of lower observation altitudes, The Cerenkov pulse decay time gives reasonably good discrimination, whereas rise time and pulse width are not much effective. Discrimination is best in the vicinity of hump region at all altitudes. Quality of discrimination is somewhat inferior at Hanle altitude compared to lower altitudes due to the dilution of hump at this observation level. The timing jitter parameter is defined as the ratio of RMS of average arrival times of Cerenkov photons at seven mirrors of the telescope to the mean of seven averages. Due to the differences in kinematics, cosmic ray showers are expected to have higher timing jitter compared to γ-ray showers. Also relative jitter is found to be roughly independent of core distance.

We have parameterized Cerenkov photon density fluctuations and examnied their efficacy for gamma hadron separation. Three types of parameters as suggested by Chitnis and Bhat [4] for lower observation altitudes have been studied. The local density fluctuations (LDF) or density jitter, defined as the ratio of RMS of Cerenkov photon densities at 7 mirrors of a telescope to the mean density. We find that LDF is larger for proton showers compared to γ-ray showers at all the core distances as in the case of lower altitudes. The medium range density fluctuations, MDF, is defined as the ratio of RMS of photon densities recorded at six telescopes to the mean density. As in the case of lower altitudes, MDF is larger for proton showers at all core distances. The Lateral distribution of Cerenkov photons in γ-ray showers are roughly flat within hump region. Also it is smooth compared to proton showers. These differences in lateral distributions can be parameterized using a parameter α, called flatness parameter. It is defined as

$$\alpha = \frac{1}{N}\left[\sum_{i=1}^{N}\frac{(\rho_i - \rho_0)^2}{\rho_0}\right] \qquad (2)$$

where N : no. of telescopes triggred, ρ_i : photon density measured by individual telescopes and ρ_0 : average density.

The γ-ray initiated showers are expected to have a smaller value of α compared to that due to protons, on the average. At lower altitudes proton showers have larger value of flatness parameter compared to γ-ray showers at all distances away from hump [4]. Hence this parameter serves as a good discriminant at core distances away from hump. However, at Hanle altitude this is not a useful parameter. This is primarily due to the reduction in differences between the lateral distributions of Cerenkov photons generated by the two species at higher altitudes. The LDF and MDF, on the other hand, provide comparable background rejections at all the observation altitudes.

Conclusions

It is generally said that the lateral distributions of Cerenkov radiation from γ-ray and proton generated showers are distinctly different in the sense that in the former case it is flat up to about $\sim 140\ m$ at sea level and characterized by a hump at that distance while in the latter case it is steeper and smoother with practically no hump [8]. However the situation changes as the observation altitude increases, since the position of shower maximum for a given primary energy becomes closer to the observation level. This situation is similar to the case of increasing primary energy at a given observation altitude. Thus the prominence of hump decreases with increasing altitude. For the same reason the core distance at which the hump appears also decreases with increasing observation level. At an observation altitude of 4500 m, where the atmospheric over burden is $\sim 598\ gcm^{-2}$, the radius of curvature (or the height of shower maximum from observation level) is around 5 km. The Cerenkov angle at shower maximum is around 1° and the expected position of hump is $\sim 90\ m$ purely from geometric considerations which agrees well with figure 2. The proximity of the shower maximum to the observation level becomes more sever for higher energy γ-ray primaries and the hump almost disappears. Here the contribution from higher energy electrons closer to the observation level becomes appreciable at near core distances because of which at higher observation altitudes the hump is seen in the case of lower energy primaries only.

Another feature of the lateral distribution of Cerenkov photons is that they become increasingly flatter with decreasing primary energy. The flattening is far more significant for proton primaries as compared to γ-ray primaries. As a result the pool size increases with lowering primary energy which is a consequence of significantly larger number of photons arriving at larger angles. When the lateral distribution curves are generated with a finite focal point mask, the density as well as the total number of photons detected reduces significantly for proton primaries. For example, the fractions of photons detected when a 5° mask is in use are 64.3% and 33.2% respectively for 50 GeV & 15 GeV protons. Similar fractions for γ-ray primaries are 90.1% and 96.4% respectively for 10 & 1 GeV energy. As a result, at lower primary energies, the use of a focal point mask provides a simple discrimination against hadrons.

Several parameters based on density and timing information of Cerenkov photons, including local and medium range photon density fluctuations as well as photon arrival time jitter could be efficiently used to discriminate γ-rays from more abundant cosmic rays at tens of GeV energies. Because of the proximity of the shower maximum at higher observation altitudes, the parameters like radius of curvature is more sensitive to primary species as compared to lower observation levels. As can be seen from table 1, using these parameters in tandem it is possible to reject about 98% of proton showers retaining about 35% of $\gamma-$ray showers.

In addition, the atmospheric attenuation of Cerenkov photons at Hanle altitude is $\sim 14\%$ as compared to $\sim 50\%$ at sea-level. The ratio of Cerenkov yield for high energy γ-rays to that of protons of same energy increases exponentially with decreasing energy [7]. Combined with increased photon density due to reduced lateral spread of the pool makes a high altitude observaotory like Hanle an ideal site for GeV γ-ray astronomy.

Based on the Monte Carlo studies we plan to set up a pilot experiment at Hanle to detect celestial γ-rays of energy $> 20\ GeV$ using the atmospheric Cerenkov Technique. In this experiment, we plan to deploy 7 telescopes, similar to the ones used in PACT at Pachmarhi [1], in the form of a hexagonal mini-array. The figure 3 shows a preliminary estimate of the expected differential γ-ray count rate spectrum from Crab nebula for such an array at Hanle altitude. The chief advantage of this experiment is the considerably lower energy threshold, almost overlapping with the energy range of future satellite based detectors, that may be achieved. The high slew speeds ($\sim 30°/min.$) of these telescopes would be ideal to orient quickly to a possible Gamma Ray Burst (GRB) location for searching any GeV γ-ray counter parts of GRB after-glows.

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