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A possible high altitude high energy gamma ray observatory in India

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Abstract. Recently an Indian Astronomical Observatory has been set up at Hanle (32° 46′ 46″ N, 78° 57′ 51″ E, 4515m amsl) situated in the high altitude cold desert in the Himalayas. The Observatory has 2-m aperture optical-infrared telescope, recently built by the Indian Institute of Astrophysics.

We have carried out systematic simulations for this observation level to study the nature of Čerenkov light pool generated by gamma ray and proton primaries incident vertically at the top of the atmosphere. The differences in the shape of the lateral distributions of Čerenkov light with respect to that at lower altitudes is striking. This arises primarily due to the proximity of the shower maximum to the observation site. The limited lateral spread of the Čerenkov light pool and near 90% atmospheric transmission at this high altitude location makes it an ideal site for a gamma ray observatory. This results in a decrease in the gamma ray energy threshold by a factor of 2.9 compared to that at sea-level. Several parameters based on density and timing information of Čerenkov photons, including local and medium range photon density fluctuations as well as photon arrival time jitter could be efficiently used to discriminate gamma rays from more abundant cosmic rays at tens of GeV energies.

1 Introduction

Atmospheric Čerenkov technique is a well established technique for study of VHE gamma ray emission from astronomical sources. This technique has been successfully exploited by several experiments such as Whipple, CAT, CANGAROO, HEGRA, TACTIC etc based on imaging technique as well as by CELESTE, STACEE, SOLAR-2, GRAAL, PACT etc based on wavefront sampling technique (Ong, 1998). Next generation experiments including large imaging telescope, like MAGIC, as well as arrays of imaging telescopes such as VERITAS and HESS are under construction. These experiments as well as wavefront sampling experiments with large collection area such as CELESTE, SATCEE etc are expected to achieve low energy threshold of the order of few tens of GeV. Alternatively, it is possible to decrease energy threshold by conducting an experiment at higher observation altitudes. All the existing experiments are being carried out at altitudes of upto 2.5 km. Here we investigate the feasibility of an experiment based on wavefront sampling technique at a location called Hanle situated in the cold desert in the Himalayas at an altitude of about 4.5 km, based on simulation studies.

Mt. Saraswati in Hanle is an exceptionally fine astronomical site offering about 260 spectroscopic nights per year, with uniform coverage of all right ascensions, low precipitable water vapour ($\sim\ 1\ mm\ cm^{-2}$), low aerosol content and extinction ($\sim\ 0.1^m\ in\ V\ band$), low sky brightness $21^m.5(V)\ arcsec^{-2}$ and median seeing $< 1''$. Moreover it is situated right in the middle of the gap between Woomera (137° E) in Australia and La Palma (20° W).

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2 Lateral distributions of Čerenkov photons

We have simulated a large number of air showers generated by $\gamma-$rays and protons of various primary energies using CORSIKA (Heck et al., 1998). The Čerenkov radiation produced by the secondary charged particles in the shower within the bandwidth of 300-650 nm is propagated to the observation level. Location and altitude appropriate for Hanle are used in simulations. An array of 357 telescopes, each consisting of seven mirrors with a total area of 4.45 m^2 per telescope, spread over an area of 400 m × 400 m is considered. All the showers are vertically incident at the top of the atmosphere, with shower core chosen to be at the centre of the array. Typically 100 showers were simulated for higher energy $\gamma-$rays (50 and 500 GeV) and protons of energies 150 GeV and 1 TeV. For lower energy primaries, i.e., $\gamma-$rays of energy 1 and 10 GeV and for protons of energy 15 and 50 GeV, 500 showers were simulated. Energies of primaries are chosen so that $\gamma-$ray and proton showers have comparable

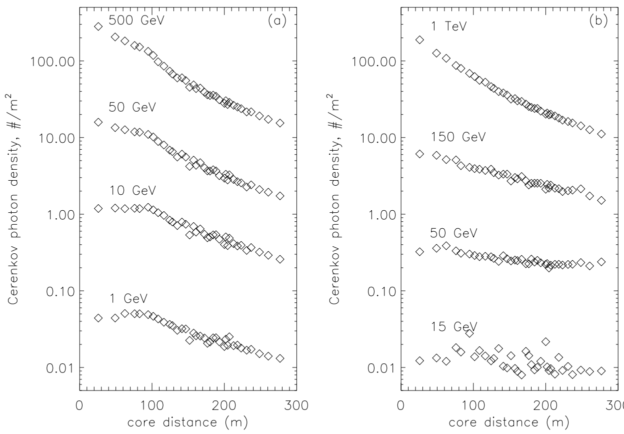

Fig. 1. Average Čerenkov photon density at Hanle as a function of core distance for showers initiated by (a) $\gamma-$rays of energies 1, 10, 50 and 500 GeV and (b) protons of energies 15, 50, 150 GeV and 1 TeV. Distributions are averaged over 500 showers for lower energy primaries and over 100 showers for higher energy ones.

Čerenkov yields.

Figure 1 shows the average Čerenkov photon density as a function of core distance for showers initiated by $\gamma-$rays and protons of various energies. Lateral distributions from $\gamma-$ray primaries indicate presence of proverbial hump at a core distance of about 90 m, due to effective focusing of Čerenkov photons from a range of altitudes. However, this hump is somewhat less prominent compared to that seen at lower altitudes, for example, the one seen at observation altitude of 1 km (Chitnis and Bhat, 1998). 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 an expected feature (Rao and Sinha, 1988). Also the comparison of lateral distributions show that the Čerenkov photon density near the shower core at Hanle is higher by a factor of about 5-6 compared to that at sea-level, for a given primary energy. Wavelength dependent atmospheric attenuation of Čerenkov photons is not taken into consideration here. 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.

3 Gamma-hadron separation

All atmospheric Čerenkov experiments have to deal with a substantial background from air showers generated by cosmic rays emulating those initiated by $\gamma-$ray primaries. It is necessary to incorporate the methods for effective rejection of this background for improving signal to noise ratio. In imaging experiments background rejection is based on differences in shapes and orientations of images produced by these two species (Fegan, 1997). Whereas in experiments based on wavefront sampling technique parameters based on arrival time of Čerenkov shower front and Čerenkov photon density at various locations in Čerenkov pool can be used for discrimination. The usefulness of these techniques at lower observation altitudes has already demonstrated (Chitnis and Bhat, 2001; Bhat and Chitnis, 2001). Here we study the effectiveness of these parameters at Hanle altitude.

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

$$Q_f = \frac{N_a^\gamma}{N_T^\gamma}\left(\frac{N_a^{pr}}{N_T^{pr}}\right)^{-\frac{1}{2}} \tag{1}$$

where N_a^γ is the number of $\gamma-$rays accepted (i.e. below threshold), N_T^γ is the total number of $\gamma-$rays, N_a^{pr} is the number of protons accepted and N_T^{pr} is the total number of protons.

3.1 GHS based on timing information

We have examined the applicability of three types of parameters based on Čerenkov photon arrival times at various locations in Čerenkov pool, *viz*, 1. the curvature of shower front, 2. shape of Čerenkov pulse at the telescopes and 3. relative arrival time jitter. For details of these parameters see Chitnis and Bhat (2001). For a given shower, mean arrival times of shower front at various core locations are fitted with a spherical front. Radius of curvature of this shower front is found to be roughly equal to the height of the shower maximum from the observation level. It also provides moderate discrimination against cosmic ray showers. This is mainly because of the interaction length of hadrons in the atmosphere being around twice the radiation length. Hence the hadron initiated showers reach shower maximum deeper in the atmosphere compared to a $\gamma-$ray initiated showers. Optimum quality factor, derived using radius of curvature as a parameter is given in Table 1 which is self explanatory. Distributions of fitted radii for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons are shown in Figure 2. Threshold radius for optimum quality factor is indicated by dashed line.

Second parameter investigated is related to pulse shape. As in the case of lower observation altitudes, the Čerenkov 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 Čerenkov photon density for lower energy $\gamma-$ray primaries remains almost constant until a core distance of $\sim$ 110 m. Hence quality factors have been calculated using telescopes within a core distance of 110 m. Quality factor using decay time of Čerenkov pulse is listed in Table 1. Based on decay time alone it is possible to reject about 76% of proton showers, retaining about 68% of $\gamma-$ray showers. Distributions of decay times for both the primaries are shown in Figure 2 along-with the threshold corresponding to optimum quality factor.

Third parameter is the relative timing jitter. This is the ratio of RMS of average arrival times of Čerenkov photons

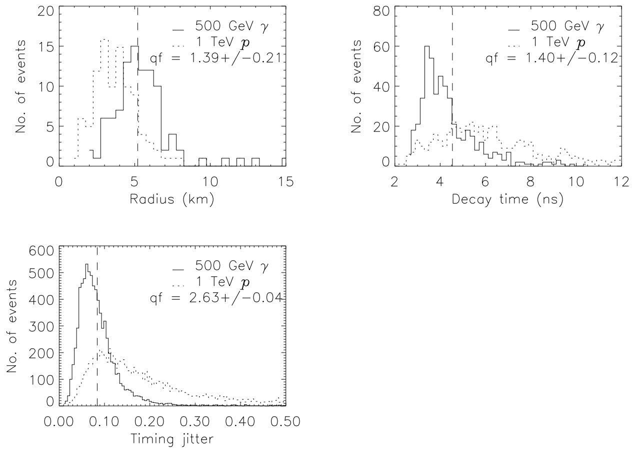

Fig. 2. Distributions of three primary species sensitive parameters based on Čerenkov photon timing information *viz.* radius of curvature of the shower front, pulse decay time and relative arrival time jitter. The derived quality factors and the primary energies considered here are indicated.

Table 1. Gamma-hadron separation for showers initiated by 500 GeV $\gamma-$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

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 $\gamma-$ray showers. Also relative jitter is found to be roughly independent of core distance. Quality factor based on timing jitter for the showers generated by 500 GeV $\gamma-$rays and 1 TeV protons for telescopes within a core distance of 110 m are listed in Table 1. Distributions of relative timing jitter for both the species are shown in Figure 2. Threshold value of jitter for optimum quality factor is also indicated. Based on the arrival time jitter, it is possible to reject about 97% of proton showers retaining about 49% of $\gamma-$ray showers.

3.2 GHS based on Čerenkov photon density

There are certain kinematical differences in air showers initiated by cosmic rays and $\gamma-$rays. These differences originate from those in first interaction of primary, presence of hadronic secondaries and muons in cosmic ray showers. As a result, cosmic ray showers are expected to show larger density fluctuations compared to $\gamma-$ray showers. We have parameterized density fluctuations and examined their efficacy for gamma hadron separation. Three types of parameters have been already studied for lower observation altitudes (Bhat and Chitnis, 2001). First parameter considered is the local density fluctuations (LDF) or density jitter. Each telescope consists of seven mirrors and LDF is the ratio of RMS of Čerenkov photon densities at these mirrors to the mean density. As in the case of lower altitudes, we find that for Hanle altitude also LDF is larger for proton showers compared to $\gamma-$ray showers at all the core distances. Quality factor based on LDF for core distance within 110 m is given in Table 1. Based on LDF it is possible to reject about 72% of proton showers retaining about 80% of $\gamma-$ray showers.

Secondly, we consider medium range density fluctuations (MDF). As in the case of PACT or Pachmarhi Array of Čerenkov telescopes (Bhat et al., 2001), we assume that the proposed array to be divided into the sectors consisting of six telescopes in each sector. Then 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. Quality factor based on MDF for core distances within 110 m is listed in Table 1. It is possible to reject about 90% of proton showers retaining about 39% of $\gamma-$ray showers using MDF as discriminating parameter.

Third parameter investigated is the well-known flatness parameter. Lateral distributions from $\gamma-$ray showers are roughly flat within hump region. Also the lateral distributions from $\gamma-$ray showers are smooth compared to proton showers. These differences in lateral distributions can be parameterized using flatness parameter α, which 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 triggered in sector, ρ_i : photon density measured by individual telescopes of a sector and ρ_0 : average density.

Lateral distributions from $\gamma-$ray showers are expected to have a smaller value of α compared to that from proton generated showers, on the average. At lower altitudes we have seen that proton showers have larger value of flatness parameter compared to $\gamma-$ray showers at all distances away from hump (Bhat and Chitnis, 2001). Hence flatness parameter serves as a good discriminant at core distances away from hump. However, at Hanle altitude flatness parameter is not a useful discriminant as reflected in smaller quality factor listed in Table 1. This is primarily due to the reduction in differences between the lateral distributions of Čerenkov photons generated by the two species at higher altitudes. LDF and MDF, on the other hand, provide comparable background rejection at all the observation altitudes.

4 Discussion and conclusions

4.1 Čerenkov photon lateral distribution

It is generally said that the lateral distributions of Čerenkov 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 (Rao & Sinha, 1988). However the situation changes as the observation altitude increases, since the shower maximum for a given primary energy comes 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 grammage is $\sim 598\ gcm^{-2}$, the radius of curvature (or the height γ-ray shower maximum from observation level) is around $5\ km$. The Čerenkov 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 1. 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 Čerenkov photon lateral distributions 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 γ-rays. As a result, at lower primary energies, the use of a focal point mask provides a simple discrimination against hadrons.

In addition, the atmospheric attenuation of Čerenkov photons at Hanle altitude is $\sim 14\%$ as compared to $\sim 50\%$ at sea-level. The ratio of Čerenkov yield for high energy γ-rays to that of protons of same energy increases exponentially with decreasing energy (Ong, 1998). Combined with increased photon density due to reduced lateral spread of the pool makes a high altitude observatory like Hanle an ideal site for GeV γ-ray astronomy. The above two considerations are expected to reduce the $\gamma-$ray energy threshold by a factor of $\sim$ 2.9 compared to that at sea level.

4.2 Gamma - hadron separation

Because of the proximity of the shower maximum at higher observation altitudes, radius of curvature is more sensitive to primary species as compared to lower observation levels. However certain parameters like the pulse decay 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. Third parameter, $viz.$ the relative timing jitter is comparable to that at lower levels. Combining the second and the third parameter in tandem makes γ-hadron separation more efficient at higher observation altitude. 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.

Similarly, among the density based parameters, α is less sensitive at higher energies because of the similarity between the lateral distributions of γ-rays and protons. However efficiencies of LDF and MDF as discriminants are not very sensitive to the observation altitudes. Background rejection can be improved further by applying various parameters in tandem. MDF and flatness parameter are very similar in definition, both calculated using Čerenkov photons densities at each telescope in the sector. Hence these parameters are not strictly independent. LDF, on the other hand, is density jitter in the telescope itself and hence independent of MDF or flatness parameter. As can be seen from the table 1, if one uses these two parameters in tandem then it is possible to reject about 95% of proton showers retaining about 34% of $\gamma-$ray showers.

By exploiting the advantages of the high observation altitude and low energy characteristics of Čerenkov emission in the atmosphere, it is possible to achieve very low energy threshold as well as an excellent gamma-hadron discrimination without using bulky and expensive hardware.

References

Bhat et al., 2001, *Wavefront Sampling Technique: VHE $\gamma-$ray Experiments in India*, Proc. of *Int. Symp. on Gamma-ray Astrophys. through Multi-wavelength Expts*: GAME-2001, March 8-10, 2001, Mt. Abu, India (Ed. R. K. Kaul and C. L. Kaul)

Bhat, P. N. and Chitnis, V. R., 2001., *Gamma-hadron Separation Using Čerenkov Photon Density Fluctuations , ibid*

Chitnis, V. R. and Bhat, P. N., Astropart. Phys., 9, 45, 1998.

Chitnis, V. R. and Bhat, P. N., Astropart. Phys., 15, 29, 2001.

Fegan, D. J., *J. Phys. G: Nucl. Particle Phys.*, 23, 1013, 1997.

Heck, D. *et al.*, Forschungszentrum Karlsruhe Report, FZKA 6019, 1998.

Ong, R., *Phys. Rep.*, 305, 93, 1998.

Rao M. V. S., and Sinha, S., J. Phys. G, 14, 811, 1988.