Study of lateral density distributions of Cherenkov photons in extensive air showers at primary energy 50 GeV and above

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Abstract. An EAS (extensive air shower) refers to the cascade of secondary particles created from the interactions of high energy primary cosmic ray particles with the air nuclei and subsequent decay of the particles produced. Ultra-relativistic secondary charged particles in the atmosphere produce Cherenkov radiation, which may be detected by ground based detector array. Such an array, HAGAR (High Altitude GAmma Ray) experiment is operating at Hanle, Ladakh, at an energy threshold of about 100 GeV, which will be lowered to 50 GeV using MACE telescope. We have studied the simulations of the distribution patterns of lateral density of Cherenkov photons generated in EAS for different primary particles $\gamma$, $p$, $\pi^+$ incident with the fixed primary energy 50 GeV and these are compared with those of 100 GeV showers using the standard CORSIKA code. From our study it has been found that, for all primary particles, the variation of lateral density distribution of Cherenkov photons almost obey the functional relation, $\rho_{ch}(r) = \rho_0 e^{-\beta r}$. The steepness of the lateral distribution function is found to depend on the primary mass composition. Further a prominent hump is observed in the lateral distribution for gamma shower only.

1. Introduction

When very high energy cosmic rays enter the earth’s atmosphere, they produce electromagnetic showers, which can be well detected by ground based detector array [1,2]. The ultra-relativistic charged particles also produce Cherenkov light in the atmosphere and measuring atmospheric Cherenkov radiation is presently the most effective way to detect the sources of cosmic rays. The atmospheric Cherenkov technique (ACT) is used to detect the gamma-rays emitted by celestial sources using an array of ground-based telescopes within the energy range of some hundred GeV to few TeV [3,4]. In this technique, gamma rays are detected against the abundant background of hadronic showers. Background rejection methods are based on image shape parameters from imaging telescopes. However, non-imaging Cherenkov telescopes use methods based on the differences in the intrinsic properties of the Cherenkov radiation from pure electromagnetic and hadronic cascades. The lateral distribution of Cherenkov light at ground level records important information on the longitudinal development of the air shower which is important for the primary particle identification. Very brief and bright flashes of gamma rays are also produced in violent stellar explosions, called GRB (Gamma Ray Burst) [5]. The energy flux peaks at a few hundred KeV and in many bursts there is a long high energy tail extending up to 50 GeV or beyond [6]. Cherenkov light produced by such a gamma ray may be detected by ACT at a high altitude observatory. HAGAR (High Altitude GAmma Ray) experiment at Hanle, Ladakh,
India (longitude: 78°57′51″E, latitude: 32°46′46″N, altitude: 4270 m) is detecting atmospheric Cherenkov photons using ACT to detect celestial sources and operating at an energy threshold of about 100 GeV. An Imaging Atmospheric Cerenkov telescope (IACT) called major atmospheric Cerenkov experiment telescope (MACE) is being established at Hanle. It is the highest (in altitude) Cerenkov telescope in the world. With upcoming MACE telescope with HAGAR, it is expected to lower the threshold for gamma shower to 50 GeV, opening a possibility to observe a high energy GRB. ACT is an indirect method, and a detailed Monte Carlo simulation study of atmospheric Cherenkov photons is necessary to estimate the nature and the energy of incident gamma-rays.

In this paper, air shower is simulated using CORSIKA [COsmic Ray SImulations for KAscade] code, with Cherenkov option [7], for a horizontal flat detector array used in HAGAR telescope. Possibility of detection of lower energy shower of 50 GeV as compared to threshold energy of 100 GeV and gamma hadron separation based on lateral distribution parameters are studied.

2. Cherenkov Radiation

When a charged particle moves in a dielectric medium, polarization occurs. Cherenkov light is emitted if the velocity of the charged particle exceeds the phase velocity of light in that medium, i.e, \( v > c/n \)

![Figure 1. Cherenkov radiation](image)

where \( v \) is the velocity of charged particles, \( c/n \) is the phase velocity of light and \( n \) is the refractive index of the medium. Light is emitted at an angle \( \theta \) with respect to the direction of motion of the particle,

\[
\cos\theta = \frac{n}{\beta c t}
\]

where \( \beta = \frac{1}{n} \) can only emit Cherenkov radiation, thus setting a threshold energy.

3. Simulation and methodology

CORSIKA (COsmic Ray SImulations for KAscade) is a detailed Monte Carlo simulation code to study the evolution and properties of EAS in the atmosphere. CORSIKA program has the ability to simulate interactions and decays of different types of nuclei, hadrons, muons, electrons and photons in the atmosphere up to \( 10^{20}\)eV of energy. It provides multiple informations like the type, energy, location,
direction and arrival times of all secondary particles which are generated in an air shower passing through a selected observation level.

The simulation of Cherenkov lateral distribution is performed using the CORSIKA 6.990 package. We have used two hadronic interaction models QGSJET (Quark Gluon String model with JET01) for high energy and GHEISA (Gamma Hadron Electron Interaction Shower code) for low energy.

The altitude of HAGAR experiment at Hanle is taken as the observational level in our simulation work. HAGAR experiment is based on wavefront sampling technique. From Monte Carlo simulation, it is found that the Cherenkov photon density increases by a factor of 4-5 near shower core compared to that at sea level. Also, atmospheric attenuation of Cherenkov photons is about 14% at Hanle compared to 50% attenuation at sea level. Higher altitude experiment is basically used to decrease energy threshold of the Cherenkov experiment. Attempts are going on to decrease energy threshold below 100 GeV. Lower energy threshold experiments can detect larger number of AGN and also it is helpful for detection of GRBs. Currently in India, a Cherenkov imaging telescope namely, Major Atmospheric Cherenkov Experiment Telescope (MACE) is developed which will trigger the HAGAR array to bring down the threshold energy [8,9]. We have done simulation to study the lateral density distributions of Cherenkov photons associated with EAS of primary γ and p of energy 50 GeV and above.

The configuration of the detectors in our study is a horizontal flat detector array. With a separation of 25 m, 17 telescopes are placed in the E–W direction, while 21 telescopes are kept in the N–S direction separated from each other by 20 m[10]. The mirror area of each telescope is 9 $m^2$. For our analysis, we have simulated 10000 showers for each primary particle (gamma, proton) at energy 50 GeV and for comparative analysis we have carried out same simulations at 100 GeV also. Cherenkov option for rectangular detector grid has been chosen for our simulation.

4. Results and Discussions
The Cherenkov lateral density as a function of core distance is given by the equation

$$\rho_{ch}(r) = \rho_0 e^{-\beta r}$$

where $\rho_{ch}(r)$ represents Cherenkov photon density as a function of position, $r$ is the shower core distance, $\rho_0$ is the Cherenkov photon density at the core of the shower and $\beta$ is the slope parameter. Values of $\rho_0$ and $\beta$ are different for different primaries.
Figures (2-5) show the variation of average density of Cherenkov photons as a function of the distance from shower core of gamma-ray and proton primary for the QGSJET-GHEISA model combination. It is evident from the figures that the average density of Cherenkov photons goes on decreasing exponentially as the core distance increases. It can be viewed from figure (2) and figure (3) that for gamma ray primary, a hump is present around 100 m from the core for both the primary energies studied.
However, no hump is seen for proton primary (figure 4 and figure 5). The existence of hump characteristic in the lateral distribution of Cherenkov photons can be used as a gamma-hadron separation technique for rejecting hadronic background in gamma ray astronomy [11]. To study this feature, we have fitted separately the data set before and after the hump for gamma shower, while for proton shower, single fitting is found to work. The two portions of the gamma shower are fitted with the same function (1) but with different set of parameters. Values of the intercept parameter \( \rho_0 \) and slope parameter \( \beta \) are obtained by using Least square iteration method. The parameters for proton primary are compared with those of gamma initiated showers as shown in table 1 and table 2.

Table 1. Values of fitted parameters for gamma ray primary

| Primary energy (GeV) | Before hump |          | After hump |          |
|----------------------|-------------|----------|------------|----------|
|                      | \( \rho_0 \) | \( \beta \) | \( \rho_0 \) | \( \beta \) |
| 50                   | 27.392 +/-0.3264 | 0.0037 +/-0.0002 | 53.1022 +/-3.82401 | 0.011015 +/-0.0005 |
| 100                  | 78.738 +/-1.509  | 0.0058 +/-0.000323 | 137.81 +/-9.16       | 0.0121 +/-0.00046   |

Table 2. Values of fitted parameters for proton primary

| Primary energy (GeV) | \( \rho_0 \) |          | \( \beta \) |          |
|----------------------|-------------|----------|------------|----------|
| 50                   | 0.66642 +/-0.00923 |          | 0.001913 +/-8.69935e-05 |
| 100                  | 7.80453 +/-0.118054 |          | 0.006253 +/-0.00012595 |

5. Conclusion
From our analysis it can be concluded that gamma and proton primaries show exponential shape of Cherenkov lateral distributions. The negative exponential function well fits all the distributions. We get a much steeper lateral density distribution for gamma ray initiated shower compared to proton initiated shower for both the primary energies considered. The steepness for both the primaries increases with an increase of primary energy. For gamma shower, the steepness parameter increases after crossing the hump for both 50 GeV and 100 GeV primary energy. Formation of hump for gamma shower for both the energies considered, is a distinguishing feature, which may be exploited for gamma hadron separation at lower threshold energies.
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