Azimuthal distribution of Cherenkov photons and corresponding electron-positron asymmetry in EASs of different primaries

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We study the azimuthal distributions of Cherenkov photons in Extensive Air Showers (EASs) initiated by γ-ray, proton and iron primaries of different energies at various zenith angles over a high altitude observation level. The azimuthal distributions of electrons and positrons along with their asymmetric behaviour have also been studied here to understand the feature of azimuthal distributions of Cherenkov photons in EASs.

The main motivation behind this study is to see whether the azimuthal distribution of Cherenkov photons can provide any means to distinguish the γ-ray initiated showers from that of hadron initiated showers in the ground based γ-ray astronomy experiment. Apart from this, such study is also important to understand the natures of γ-ray and hadronic showers in general. We have used the CORSIKA 6.990 simulation package for generating the showers. The study shows the double peak nature of the azimuthal distribution of Cherenkov photons which is due to the separation of electron and positrons in the azimuthal plane. The pattern of distribution is more sensitive for the energy of the primary particle than its angle of incidence. There is no significant difference between distributions for γ-ray and hadron initiated showers.

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I. INTRODUCTION

The earth’s atmosphere is opaque to γ-rays coming from astrophysical sources. So for the ground based detection of VHE γ-rays from such celestial sources in the energy range of few hundred GeV to few TeV, an indirect detection method known as the ‘Atmospheric Cherenkov Technique (ACT)’ is used most extensively. This technique is based on detection of Cherenkov photons which are emitted in the atmosphere by the charged particles of Extensive Air Showers (EASs) produced by the incoming γ-rays during the interactions with the earth’s atmospheric particles. However, there is an inherent problem with the ACT that the sources which emit γ-rays also produces Cosmic Rays (CRs). CRs also produce EASs in the earth’s atmosphere and hence the Cherenkov photons captured with the ground based detectors contains contributions from both the γ-rays and CRs. Unlike γ-rays, CRs are charged particles and so they are deflected by the intragalactic magnetic fields. As a result of which, the CRs when reach the earth, loses their direction of origin. Whereas γ-rays being electrically neutral retains its direction of origin. Therefore the detection of γ-rays can provide the information about the direction of their origin. Therefore, for proper estimation of different parameters of the incident γ-rays, the huge background of CRs has to be removed from the observed data. Thus the development of effective γ-hadron separation technique is an important issue in the ground based γ-ray astronomy experiments, where ACT is being used. In this regard the detailed study of lateral, temporal and angular distributions of Cherenkov photons in EASs of different primaries using Monte Carlo simulation is essential for proper disentangle of the γ-ray showers from the hadronic ones.

In our earlier works [1,2] we have already made some detail investigations on parameters, viz., density, arrival time and angular distributions of Cherenkov photons in EASs of different primaries to distinguish γ-ray initiated showers from that of hadron initiated showers. Some very interesting works related to the azimuthal and other angular distributions of Cherenkov photons in EASs and corresponding electron positron asymmetry has already been carried out using available detailed simulation techniques [3,4]. However, not many studies have been found which focus on for distinguishing the γ and hadron initiated showers, specially over high altitude observation levels. Hence, in this work we study the azimuthal distribution of Cherenkov photons in EASs of different primaries incident over a high altitude observation level for exploring the possibility of providing additional inputs to the effective γ-hadron separation techniques.

We have generated EASs for γ-rays, proton and iron nuclei with different energies and angle of inclination with the zenith. The simulation has been done by using CORSIKA 6.990 package [9]. CORSIKA is a detailed Monte Carlo simulation code to study the evolution and properties of EASs in the atmosphere. Using CORSIKA one can simulate interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to energies of some 10^{20} eV [10]. The availability of seven high energy hadronic interaction models and three low energy hadronic interaction models makes the CORSIKA suitable for simulation study of variety of hadronic interactions. It uses EGS4 code [11] for the simulation of electromagnetic component of the air shower [10]. This paper has been organized as follows. The details about the simulation process is discussed in the next section. In the section III we discuss about the analysis of the simulated data and the results. The summary and conclusion of the work are made in the section IV.

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II. SIMULATION OF THE EXTENSIVE AIR SHOWER

In this simulation work we have used the QGSJETII.3 high energy hadronic interaction model and the FLUKA low energy hadronic interaction models out of the available options in the CORSIKA 6.990 package. In our earlier works [1, 2] we have already compared the other available high and low energy hadronic interaction models available in CORSIKA and found that almost all the combinations of high energy and low energy models produces very identical results with one another. Thereby revealing almost model independent nature of our study, specially for the input parameters used during the simulation. We have generated EASs for γ-ray, proton and iron primaries incident vertically as well as inclined at zenith angle 10°, 20°, 30° and 40°. The numbers of showers generated at different energies and zenith angles for the three primaries are given in Table I.

| Primary particle | Energy  | Number of Showers |
|------------------|---------|-------------------|
| γ-ray            | 100 GeV | 10000             |
|                  | 250 GeV | 7000              |
|                  | 500 GeV | 5000              |
|                  | 1 TeV   | 2000              |
|                  | 2 TeV   | 1000              |
|                  | 5 TeV   | 400               |
| Proton           | 250 GeV | 10000             |
|                  | 500 GeV | 8000              |
|                  | 1 TeV   | 5000              |
|                  | 2 TeV   | 2000              |
|                  | 5 TeV   | 800               |
| Iron             | 5 TeV   | 5000              |
|                  | 10 TeV  | 2000              |
|                  | 50 TeV  | 500               |
|                  | 100 TeV | 100               |

The range of energies of the primaries used for the work corresponds to the typical ACT based observational energies in terms of their equivalent Cherenkov photon yields. Using the HAGAR Experiment [12] at Hanle as the reference, we have taken the observational height as 4270 m with the longitude: 78° 57′ 51″ E, the latitude: 32° 46′ 46″ N, and the magnetic field: H = 32.94 µT, Z = 38.29 µT. We have considered a flat horizontal detector array having 25 telescopes in the East-West direction with 25 m separation between two consecutive detectors, and 25 telescopes in the North-South direction with 20 m separation between two consecutive detectors. This dimension of detector array is considered by taking into account the range of energies and zenith angles at which showers were generated as shown Table I. The shower core is assumed to coincide with the centre of the detector array. The individual detectors have an effective collection area of 9 m² for minimization of background noise and at the same time for collecting sufficient number of Cherenkov photons by detectors. The variable bunch size option of Cherenkov photon is set to ’5′ which is optimized for reduction of data size without losing the useful information. The parameter STEPFC is set at 0.1 and the energy cut-offs of kinetic energy for hadrons, muons, electrons and photons are chosen as 3.0 GeV, 3.0 GeV, 0.003 GeV and 0.003 GeV respectively, which are reasonable values for not to eliminate those parent particles which might decay to secondaries under investigation. The Linsley’s parametrized US standard atmospheric model [13] has been used here among the different atmospheric models available in CORSIKA, as we have not observed any significant impact of the different Atmospheric models on the distribution of Cherenkov photons from one of our earlier studies [2].

III. ANALYSIS OF THE SIMULATION AND RESULTS

To obtain the azimuthal distribution of the Cherenkov photons we have divided the detector array into four quadrants: with (+x,+y) coordinates as the first quadrant in the anticlockwise direction, (-x,+y) as the second quadrant, (-x,-y) as the third quadrant and (+x,-y) as the fourth quadrant. The detectors in the first quadrant collect the photons emitted within 0 to 90 degree, detectors in the second quadrant within 90 to 180 degree, detectors in the third quadrant within 180 to 270 degree and the detectors in the fourth quadrant within 270 to 360 degree in the azimuthal plane. The Cherenkov photons detected by all the detectors within a certain azimuthal angle bin are added to get the total Cherenkov photons per shower within that azimuthal angle bin. Repeating the same for all the showers we finally obtain the average value of Cherenkov photons per shower for a given azimuthal angle bin. These data are then represented as histograms of suitable azimuthal angle bins. To understand the pattern of distribution of Cherenkov photons in the azimuthal plane, we also collected the number of electrons and positrons for the same azimuthal angle bin following the same procedure as stated above. Moreover, the electron and positron asymmetry...
\( A_S \) has been calculated by using the formula given as \[14\]

\[ A_S = \frac{N_e - N_p}{N_e + N_p}, \]

where \( N_e \) and \( N_p \) are the photon counts corresponding to the electron peak and the positron peak respectively of the Cherenkov photon’s distribution histogram. The analysis has been carried out on the root platform \[15\] by using C++ programs. The results of this works are discussed in the following sub sections:

A. Azimuthal distribution of Cherenkov photons

![Fig. 1: Smoothed histograms of Cherenkov photons with respect to azimuthal angle for \( \gamma \)-ray, proton and iron primaries for different energies and at a fixed angle of incidence.](image)

Fig.1 shows the smoothed histograms of Cherenkov photon counts as a function of the azimuthal angle initiated by the \( \gamma \)-ray, proton and iron primaries for different combinations of energies at a particular angle of incidence. In all the cases we can see the double peak distribution pattern with the first peak occurring in between 70° and 90°, whereas the second peak occurring in between 270° and 290°. The left peak occurs due to the Cherenkov photons produced by the electrons in EAS, whereas the right peak occurs because of the positrons. Actually, the separation of electrons and positrons in EAS takes place over the azimuthal plane due to the opposite effect of earth’s magnetic field on their charges. Thus the double peak distribution of Cherenkov photons in EAS over the azimuthal plane is a signature effect of the electron-positron separation over the azimuthal plane due to the effect of earth’s magnetic field on them. Fig.2 shows the similar azimuthal distribution patterns of Cherenkov photons initiated by the three primaries but for a fixed energy and variable angle of incidence. The distribution patterns do not show any major differences between the \( \gamma \)-ray and hadron initiated showers. However, there is a small difference in the overlapping zone near about 180° for the iron initiated showers. The prominence of this difference increases with increasing energy and...
FIG. 2: Smoothed histograms of Cherenkov photons with respect to azimuthal angle for γ-ray, proton and iron primaries for different angle of incidence and at a fixed energy of the primary.

angle of incidence of the iron primary. Moreover, except for the proton primaries the pattern of distributions appears to almost independent of energy and angle of incidence. But the difference in distributions with respect to energy is more sensitive than that with respect to angle of incidence, specially for the proton primary.

FIG. 3: Azimuthal distributions of electrons and positrons initiated by vertically incident 1 TeV γ-rays.

FIG. 4: Smoothed histograms of Cherenkov photons with respect to azimuthal angle for γ-ray, proton and iron primaries for same energy and same angle of incidence.

To justify our explanation that two peaks of the azimuthal distribution of Cherenkov photons in EAS are due to separation of electrons and positrons over the azimuthal plane as a consequence of geomagnetic effect as mentioned earlier, in the Fig.5 we have shown the azimuthal distributions of electrons and positrons initiated by the 1 TeV γ-rays, as an example. This figure clearly shows that the left peak of azimuthal distribution of Cherenkov photons is due to electrons while right hand side peak is due to the contributions from positrons. The separation between electron peak and the positron peak is due to the geomagnetic effect or effect of the earth’s magnetic field [3]. The geomagnetic field deflects the electrons and positrons in opposite directions due to the opposite nature of their charge. Since the observational site in our study has a strong geomagnetic field (see the section II), the separation is quite prominent.

In the Fig.4 we have shown the comparison of the three primaries for a primary energy of 5 TeV at three different angles of inclination. From the figure it can be seen that the azimuthal distributions of Cherenkov photons due to the three primaries of same energy are not much different, but they are looked very much similar. However, to see the difference between these
FIG. 5: Percentage relative difference ($\Delta N$) between the histograms of Cherenkov photons for $\gamma$-ray, proton and iron primaries.

Histograms clearly, we have calculated the percentage relative difference of the proton initiated and iron initiated histograms from that of $\gamma$-ray initiated histogram for the combination of energy and angle of incidence as shown in the Fig.4. The percentage relative difference has been obtained by using the following formula:

$$\Delta N = \frac{N_x - N_\gamma}{N_\gamma} \times 100\%,$$

where $\Delta N$ is the percentage relative difference, $N_x$ and $N_\gamma$ are the number Cherenkov photons per shower at a given azimuthal angle bin corresponding to the given primary and to the $\gamma$-ray primary respectively. From the Fig.5 it can be seen that the percentage relative difference of the azimuthal distributions of Cherenkov photons initiated by the proton and iron primaries to that with initiated by the $\gamma$-ray is mostly limited to 5%. More differences are basically noticeable for smaller azimuthal angles. However, with higher angle of incidence such noticeable differences persist for over all range of azimuthal angles.

B. Electron-positron asymmetry

As already mentioned that due to the earth’s magnetic field the Cherenkov photons produced by electrons and the Cherenkov photons produced by positrons are separated in the azimuthal plane which is manifested as two peaks in the azimuthal distribution profile of Cherenkov photons. In Fig.6 and Fig.7, we have shown the electron-positron asymmetry as a function of energy for the $\gamma$-ray, proton and iron initiated showers. In all the cases we have seen positive asymmetry indicating the higher numbers of electrons in comparison to positrons. However, with the increase in energy, for all the primary particle and angle of incidence, we can see an increasing tendency towards symmetry. This is expected as higher energy particles are less affected by the earth’s magnetic field. In the Fig.6, we can see certain difference in the variation of asymmetry with energy for the iron primaries then in comparison to $\gamma$-ray and proton primaries. For iron primaries, the magnitude of asymmetry is less in comparison to $\gamma$-ray and...
proton primaries. Also for the γ-ray and proton primaries we can observe a near linear decrease in the asymmetry whereas for iron it is not that smoothly varying (see Fig[7]). This is due to the complex nature of iron initiated showers than that initiated by other primaries.

IV. SUMMARY AND CONCLUSION

The objective behind this work was to study the distribution pattern of Cherenkov photons in the azimuthal plane to see whether the information about the azimuthal distribution can be used for γ-hadron separation along with the study of electron-positron asymmetry due to earth’s magnetic field. The study has showed the double peak distribution of Cherenkov photons in the azimuthal plane. Also we have seen that the variations of the distribution is more sensitive to the parameter energy of the primary than the angle of incidence. This is expected, as with the energy of the incident particle the effect of earth’s magnetic field also changes. Further, for the range of energy and angle of incidence combinations, that we have used in our study, azimuthal distributions of photons do not show any significant differences between the three primaries except at certain azimuthal angles. However, the variation of electron and positron asymmetry with energy shows certain differences in the three primaries- specially for the iron primaries. This could be due to the simple fact that since iron is comparatively much heavier hadron primary, so its EAS is much complex than that of other primaries [1, 2]. Hence, we can conclude that though the study reveals some interesting behaviours of Cherenkov photon distributions in the azimuthal plane, a more elaborate study covering a wider range of energy of the primaries and also inclusion of few more sensitive parameters may give a more insight in the γ-hadron separation possibility from such study. In future we plan to report the same.

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