GEOMAGNETIC EFFECTS IN ELECTROMAGNETIC CASCADES

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Abstract

We have calculated the angular distribution of electrons and positrons in electromagnetic cascades in the atmosphere, including the effect of the Earth's magnetic field on the angular distributions. Results of the new calculations were fitted by simple analytical expressions.

1. Introduction

Optical detection of cosmic ray air showers has become an important technique in studies of ultra high energy Y-ray sources in the atmosphere. The angular dependence of the emitted Cherenkov light from these cascades can be obtained from detailed Monte Carlo calculations. Since Cherenkov emission in air is nearly straight forward along the charged particle's path, the main factor contributing to the angular spread of the Cherenkov emission is the angular distribution of the particles themselves. For showers at large zenith angles, the electromagnetic cascades develop at high altitude in low density air. Under these conditions the magnetic field of the earth or geomagnetic field(GMF) distorts the angular distributions, destroying azimuthal symmetry. Calculational results for such effects are given in Section 3 of this paper.

2. Methods

The Monte Carlo calculations were done using effects of importance electrons and positrons with energies above 20 MeV, since the threshold for Cherenkov emission in the atmosphere is above 20 MeV for all altitudes.

The particle production processes of pair creation, bremsstrahlung, and Compton scattering were simulated using the methods and cross sections given in References 1 and 2. The sampled differential cross sections were compared to those given by Rossi [Ref. 3] and were found to be in good agreement.

Except for geomagnetic effects, the angular distributions are determined mostly by Coulomb scattering. The calculation included multiple, plural and single scattering according to Ref. 4. Coulomb scattering was sampled at track length intervals ranging from 0.01 to 0.1 radiation lengths.

The rate of ionization energy transfers less than ,l MeV was taken from Hillas [Ref. 51. Other energy losses (Moller and Bhabha scattering, bremsstrahlung with low energy photon emission) were added to the Hillas formula.

Geomagnetic scattering was calculated at each step for which Coulomb scattering was evaluated. Coordinates were chosen such that the z-axis was in the direction of the shower (usually not the vertical direction). The x-axis was perpendicular to the shower direction, in a direction such that the GMF was 0. Thus, particle deflection for particles moving along the z-axis was in the ± x direction. The angle is measured between the direction of a particle and the z-axis. The azimuthal angle ϕ is measured between the projection of a particle's velocity in the x-y plane and the x-axis.

The U.S. Standard Atmosphere was used as the. model of the atmosphere. In evaluating the direction of the magnetic deflection, equal numbers of positrons and electrons were assumed. (For all particles above 20 MeV, the fraction of electrons is smaller than 55%, justifying this assumption.)

To cover the range of air densities of interest, angular distributions were calculated for threshold energies, E_T, of 20, 30, 40 and 50 MeV. Normalized angular distributions from calculations without the GMF were found as functions of a and E_T. With the GMF effect included, results are given in terms of E_T, θ, ϕ, and á. The parameter á is 10^{-3} B_1/ρ_m, where B_1 is the GMF component perpendicular to the particle's path. the air density at the cascade maximum is ρ_m. Usually, 100 GeV cascades initiated by photons were calculated. The normalized angular distributions were observed to be nearly energy independent for cascade energies greater than 100 GeV.

The formulas fitted to the calculation results are accurate within 10% for all fitted points. It is notable that the parameter a works very well in summarizing the effects of shower orientation and altitude on the angular distributions.

3. RESULTS

In this section, results of the calculations without the GMF will be given first and they will be compared to the results of others. The results for the angular distributions are given for all particles in the cascade. These results can be expected to be close to those obtained by looking at the cascade at age s = 1.0. Energy distributions of particles in the cascade have been evaluated at ages s = 0.4, 1.0, and 1.4 and they agree with those given by Hillas [Ref. 5] extremely well.

Without the GMF effects, the angular distributions have azimuthal symmetry. For energy thresholds from 20-50 MeV and for 9 < 30° and $dN/d\theta > 10^{-3}$ $dN/d\theta$ ($\theta = 0°$), the angular distributions are given by $\exp(-\theta / \theta_0) / \theta_{0,}$ with $\theta_0 = 0.77\ E_T^{-0.65}$ radians for E_T in MeV. In previous work by an independent Monte Carlo calculation, [Ref. 6], Stanev et al. found $\theta_0 = 0.83^{-0.67}$. By integrating the angular distributions from Hillas [Ref. 51 over energy above threshold values of 20, 30, 40, 50, 100 and 200 MeV, exponential distributions (maximum discrepancy < 10%) were obtained. The θ_0 dependence on E_T was fitted well by $\theta_0 = 0.85\ E_T^{-0.66}$. Thus the different results without the GMF agree quite well and are given by simple expressions.

When the GMF effects are included the angular distributions depend on azimuthal angle, air density, and the orientation of the shower with respect to the GMF. For 20 < E_T < 50 MeV, the 9 dependence can still be adequately represented by exponentials if the normalizations of the exponentials and the e0 values are allowed to become ϕ dependent.

Calling the ϕ-dependent value of the mean θ value θ_l,

$$\theta_{l} = \theta_0 + 1.92 \times 10^{-3}\text{á} + 6.81 \times 10^{-3}\text{á}^2\cos^2\phi \qquad (1)$$

where á = $10^{-3}\ B_1 / \rho_m$ Gauss $cm^3 g^{-1}$ and e = $0.77\ E_T^{\ -0.65}$ radians, E_T in MeV. Note that the E_T dependence^0 is contained in θ_0.

However, another factor is needed to give the dependence of the number of particles on ϕ. This distribution is F_1 (á, ϕ).

$$F_1 (\text{á}, \phi) = (1 + 0.98\ \text{á} \cos^4\phi)/(2\pi + 2.32\ \text{á}) \qquad (2)$$

where $F_1 = dN/d\phi$, ϕ in radians. A remarkable result of the calculations was that F_1 was almost completely independent of E_T in the range of 20-50 MeV. I Equations 1 and 2 give the normalized angular dependence of all electrons and positrons in the cascade.

$$F (E_T, \text{á}, \theta, \phi) = F_1 (\text{á}, \phi)\ \theta_1^{-1} \exp (-\theta/\theta_1) \qquad (3)$$

These equations were obtained for 0.2 < á < 2.4 kilogauss $g^{-1}cm^3$

4. Discussion

Equations 1 to 3 give an angular distribution which falls off exponentially with θ for all ϕ values but which has different normalizations and different mean θ values for different ϕ values. The Monte Carlo calculations did not show how the angular distribution behaves for $\theta \ll 1°$. The Cherenkov emission angular distribution near $\theta = 0$ is smoothed out by the conical Cherenkov light emission pattern.

The Cherenkov angular distribution is also affected by the fact that particles near the threshold energy do not radiate as effectively as much more energetic particles. Distributions given by Hillas [Ref. 5] were used to fold in the light emission efficiency to get the angular distribution of emitted light. For no GMF and s = 1.0, a roughly exponential dependence on θ was found. Without the efficiency factor θ_0 was $0.85\ E_T^{-0.66}$, with the efficiency folded in it was $\theta_0 = 0.77\ E_T^{-0.68}$.

5. Conclusions

For the case of no magnetic field, 3 independent calculations give exponential angular distributions for all shower particles. The mean deviations of the particles from the shower axis are given by $\theta_0 = a\ E_T^{-b}$,where the values of a and b agree quite well in the 3 Monte Carlo calculations. Equations given by Hillas [Ref. 51 allow the angular distributions to be calculated for arbitrary age values.

Calculations have also been done for the cascade angular distributions in the presence of the geomagnetic field. Simple expressions were found to describe geomagnetic effects, making it relatively easy to calculate Cherenkov light angular distributions from air showers at large zenith angles for which geomagnetic effects are large. The present work, of course, does not include the effects of Cherenkov emission by muons.

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