Geomagnetic field effects on background primary electrons for low energy Cherenkov Telescopes

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Abstract: Extensive air showers produced by primary electrons constitute an important component of the background signal for imaging atmospheric Cherenkov Telescopes with low energy thresholds. When the threshold for gamma-ray detection is very low, down to 3-5 GeV as suggested for large telescopes at high altitude, the geomagnetic field effect becomes important.

In this work we study the propagation of low energy primary electrons in the Earth's magnetic field by using the backtracking technique. Recently measured electron spectra are used as the cosmic ray component under study. We consider some sites around the world, relevant for new generations of low energy imaging atmospheric Cherenkov Telescopes.

Keywords: Cosmic electrons; Cherenkov telescopes

1 Introduction

Thanks to the great success achieved by the present generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), ground-based gamma-ray astronomy is entering a period of very fast development towards the next generation of telescope systems. Many galactic and extragalactic gamma-ray sources have been discovered and studied in detail by HESS, MAGIC and VERITAS.

One purpose of the next generation of ground-based Cherenkov systems is to increase the flux sensitivity and angular resolution. The Cherenkov Telescope Array (CTA), the largest international effort for the next generation of detectors, is being designed with an increased angular resolution and one order of magnitude better sensitivity than current systems [1].

Due to the interaction of gamma-rays with extragalactic background light, it is desired for new IACT systems to have as low energy thresholds (E_{th}) as possible to see more distant sources. In particular, the energy threshold of CTA will be $\sim$ 10 GeV. There are also proposals specifically designed to lower the energy threshold, like the 5@5 array with E_{th} in the range $3-5$ GeV [2]. It is shown in [2] that such a low energy threshold can be achieved by 5 IACTs placed at 5 km of altitude. To test the feasibility of measurements at high altitudes, the OMEGA project is also under consideration [3]

Cosmic ray protons and electrons are the most important sources of background for the discrimination of gamma-ray showers developed in the Earth's atmosphere. At the lowest energies, electrons become the dominant component of background events detected by IACTs because of a combination of several effects [2], e.g. the energy spectrum of electrons is steeper than that corresponding to protons and the Cherenkov light produced by electrons is larger than protons with the same energy. Moreover, electron initiated showers are practically indistinguishable from those initiated by gammas-rays and thus, are difficult to eliminate by the standard methods used to reject hadrons.

Depending on the location on Earth, the geomagnetic field can act as a shield for charged particles, suppressing the flux of low energy electrons and, in this way, diminishing their contribution to the background. This effect was studied in detail by Störmer, who found the existence of a rigidity (momentum over charge, pc/Ze) cutoff, R_c, for the dipole representation of the Earth's magnetic field [4]. This cutoff depends on the geographical position of the impact point and the incidence direction of the charged particle. Therefore, particles with rigidity larger than R_c can reach the Earth's surface whereas particles with rigidity smaller than R_c do not. Note that based on the Störmer formulation an analytical expression for R_c can be obtained.

A study of the cosmic electron rate was performed, in the context of the MAGIC telescopes, for several geographical positions around the world by using the dipolar approximation of the geomagnetic field [9]. If the site under consideration is close to the South Atlantic Anomaly, the dipolar approximation is not enough to properly describe the geomagnetic field so a better description is required [5]. A good description is obtained by using a multipolar expansion up to order 10. In this case, the problem cannot be solved analytically, then numerical methods are used. In particular, the backtracking technique is used to find the allowed and forbidden trajectories [6].

In this work we study the suppression of the cosmic electron flux due to geomagnetic field effects for locations in the Southern hemisphere, where galactic astronomy is more important. For sites with clear skies and moderate to hight altitudes, only regions in southern South America and southern Africa are suitable. Thus, we consider here three candidate sites in the southern hemisphere (which are being proposed for CTA): El Leoncito, San Antonio de los Cobres (SAC), both in Argentina [7], and the HESS site in Namibia [8]. Note that SAC is very close (less than 200 km) to the site proposed for the installation of 5@5.

2 Numerical Analysis

The cosmic ray electron flux has been recently measured by Fermi-LAT and PAMELA experiments. The electron energy flux measured by Fermi-LAT covers the energy range 7 GeV to 1 TeV [10], whereas the corresponding to PAMELA [11] ranges from 1 GeV to 0.625 TeV. In figure 1 we show the electron flux obtained by these two experiments, which is considered in this work, and where error bars indicate statistical plus systematic uncertainties.

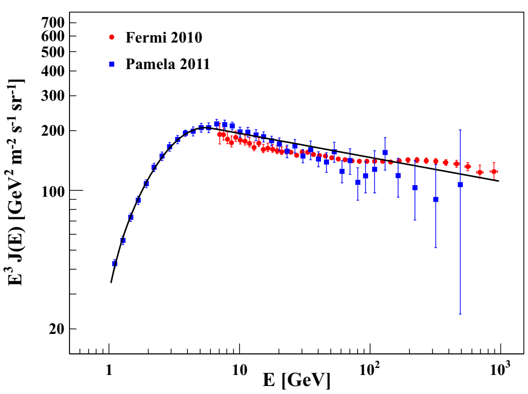

Figure 1: Electron flux multiplied by E^3 obtained by Fermi-LAT and PAMELA experiments. Error bars include statistical and systematic uncertainties. The solid line corresponds to the fit of the data with the function of Eq. (1).

To estimate the primary cosmic electron spectrum we combined the measured flux of both experiments, with the following fitting function,

$$J_{e^-}(E) = \begin{cases} a + \frac{b}{E} + \frac{c}{E^2} + \frac{d}{E^3} & E \leq 7 \text{ GeV} \\ \phi_0 E^{-\gamma} & E > 7 \text{ GeV} \end{cases} . \quad (1)$$

Here the sets of parameters $\{a, b, c, d\}$ and $\{\phi_0, \gamma\}$ are not independent, but related by the conditions that make the flux and its derivative continuous at $E = 7$ GeV. Figure 1 shows the result of the fit.

The propagation of cosmic electrons in the magnetic field of the Earth is performed by using the program *TJI95* [12] written by D.F. Smart and M.A. Shea, which uses a multipolar expansion up to $10th$ order. Given a location on the Earth's surface, the arrival probability of an incident cosmic ray electron strongly depends on the energy and arrival direction. As an example, in figure 2 we show the arrival probability as a function of energy, for electrons falling vertically at El Leoncito. The figure clearly shows the penumbra region which is centered at about 11 GeV and has a width of about 0.8 GeV.

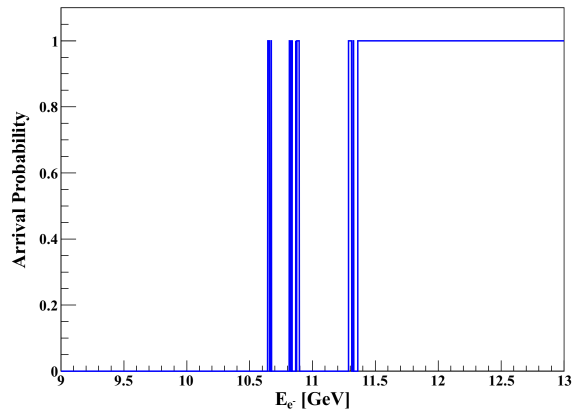

Figure 2: Arrival probability as a function of energy for vertical electrons falling at El Leoncito.

The penumbra region is delimited by two energy values, E_L (low) and E_H (high), such that, bellow E_L the arrival probability is zero and above E_H is 1. Figure 3 shows, in Aitoff projection, contour plots of E_H as a function of the azimuth (ϕ) and zenith (θ) angles, for all sites under consideration. The maximum zenith angle is 60°, above this value or even smaller, the data taken by IACTs need special treatment. The azimuth angle is measured clockwise from the North. The figure shows the well known East-West effect, i.e. for negatively charged particles arriving with the same zenith angle, the cutoff (or in this case E_H) is smaller for the East direction.

For El Leoncito E_H ranges from $\sim$ 8 GeV to $\sim$ 25 GeV, for SAC from $\sim$ 8.5 GeV to $\sim$ 26.8 GeV and for Namibia from $\sim$ 5.2 GeV to $\sim$ 11 GeV. Therefore, the largest values of E_H correspond to SAC. However, the difference with El Leoncito is small. On average, E_H for Namibia is about a factor two (or even more) smaller than the corresponding to the other two sites.

Including the geomagnetic field effects and for low enough energy thresholds, the expected electron rate for a given site strongly depends on the arrival direction of the incoming electrons. In order to quantify this effect, the following parameter is introduced,

$$F_{e^-}(E_{th}, \theta, \phi) = \frac{\int_{E_{th}}^{\infty} dE \; P_a(E, \theta, \phi) J_{e^-}(E)}{\int_{E_{th}}^{\infty} dE \; J_{e^-}(E)}, \quad (2)$$

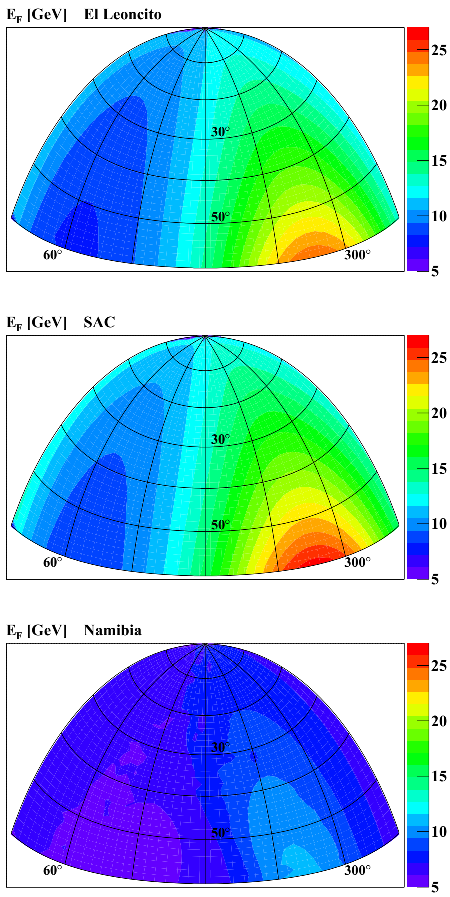

Figure 3: Contour plots of E_H as a function of azimuth and zenith angles. The azimuth angle is measured clockwise from the North.

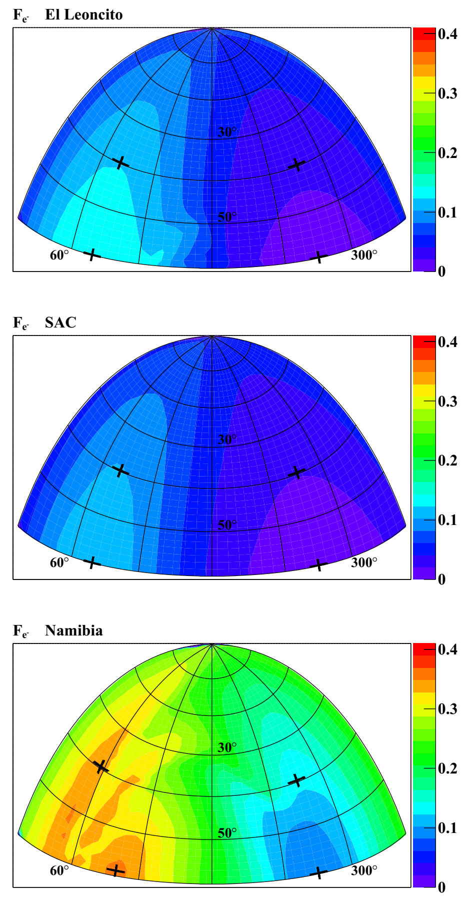

Figure 4: Contour plots of F_{e^-} as a function of azimuth and zenith angles for $E_{th} = 3$ GeV. Black crosses indicate the directions of incidence for the maximum and minimum values of F_{e^-}, obtained for $\theta_{max} = 40°$ and for $\theta_{max} = 60°$.

which is the ratio between the electron rate with and without including the geomagnetic field effects, for an ideal detector with detection area $A(E) = A_0\Theta(E - E_{th})$, where A_0 is a constant and $\Theta(x)$ is the Heaviside function. Here $P_a(E, \theta, \phi)$ is the arrival probability as a function of electron energy, zenith angle θ, and azimuth angle ϕ, for a given location.

Figure 4 shows, in Aitoff projection, contour plots of F_{e^-} as a function of azimuth and zenith angles for an energy threshold $E_{th} = 3$ GeV. As expected, smaller values of F_{e^-} are obtained for El Leoncito and SAC. This is due to the larger values of E_H obtained for these two sites, in comparison with Namibia. Although the differences between F_{e^-} for the first two sites are small, on average, F_{e^-} is smaller for SAC.

For $E_{th} = 3$ GeV the reduction on the electron rate due to geomagnetic effects can be quite large. For El Leoncito F_{e^-} ranges from ~ 0.012 to ~ 0.14, for SAC from ~ 0.011 to ~ 0.12, and for Namibia from ~ 0.09 to ~ 0.36.

The dependence of F_{e^-} with the energy threshold was also studied but only for arrival directions corresponding to the maximum and minimum of F_{e^-}, obtained for $E_{th} = 3$ GeV. As mentioned above, the IACT technique needs a special treatment for large values of the zenith angle. Therefore, two cases are considered, $\theta \leq 40°$ and $\theta \leq 60°$ in order to obtain the maximum and minimum values for each site. These points are indicated, by crosses, in the plots of figure 4, for both values of θ_{max} considered.

Figure 5 shows F_{e^-} as a function of energy threshold for the arrival directions under consideration. Solid lines correspond to $\theta_{max} = 40°$ and dashed lines to $\theta_{max} = 60°$. Note that, the curves corresponding to any other arrival direction would fall between the blue and red solid lines for $\theta_{max} = 40°$ and between the blue and red dashed lines for $\theta_{max} = 60°$.

From figure 5 it can be seen that, if the energy threshold of a given detector is larger than ~ 27 GeV and $\theta_{max} = 60°$, $F_{e^-} = 1$ for all sites, i.e. the geomagnetic field do not help suppressing the electron background for any of the three sites. For arrays with energy threshold smaller than

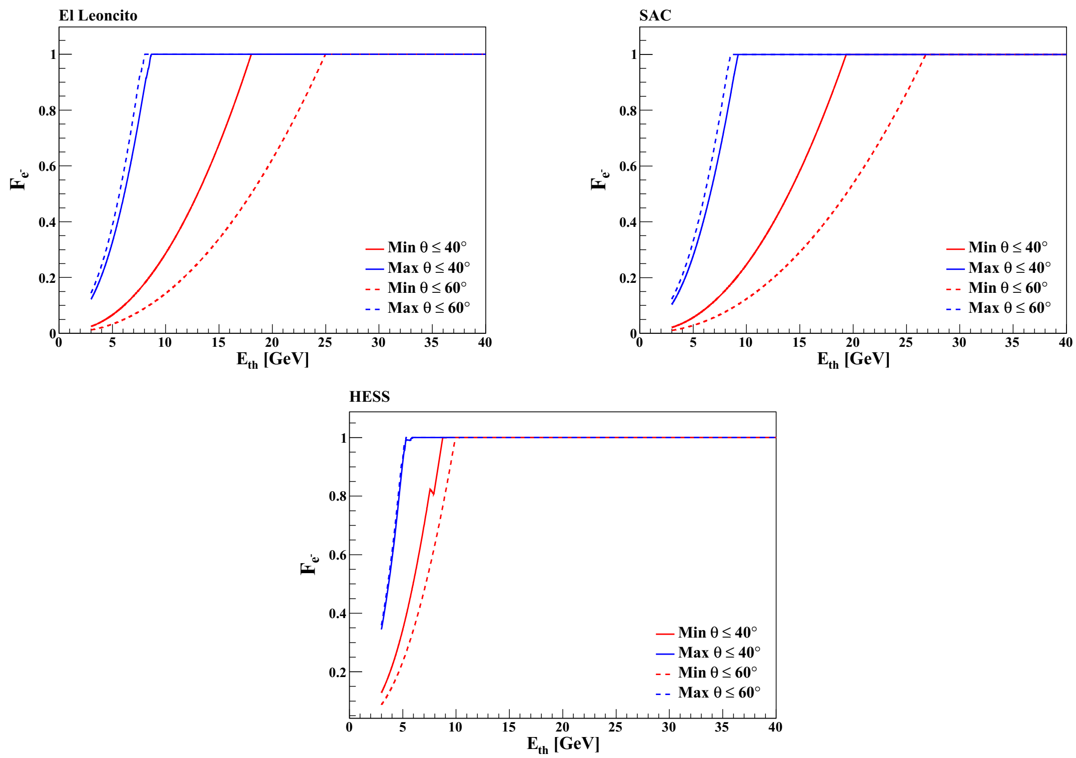

Figure 5: F_{e^-} as a function of E_{th}, for the three sites under consideration and for the arrival directions corresponding to the maximum and minimum of F_{e^-}, for $E_{th} = 3$. Solid lines correspond to $\theta_{max} = 40°$ and dashed lines corresponds to $\theta_{max} = 60°$.

$\sim$ 27 GeV and $\theta_{max} = 60°$, the best site (concerning just the suppression of the electron background) is SAC. If $\theta_{max} = 40°$ the three sites are equivalent for energy thresholds above ~ 18 GeV and SAC is the best option for energy thresholds bellow ~ 18 GeV. Again, the results obtained for El Leoncito are quite close to those obtained for SAC. For the Namibia site, the suppression of the electron flux due to the geomagnetic field starts to be important for energy thresholds smaller than ~ 9 GeV, depending on the value of θ_{max}.

3 Conclusions

In this work we have studied the suppression of the cosmic electron flux, due to the effect of the geomagnetic field, which is relevant to estimate the background for the next generation of ground-based gamma-ray detectors. We have considered three sites in the southern hemisphere, two in Argentina and one in Namibia, which are suitable for the installation of these type of instruments. To perform these studies we have used numerical methods based on the back-tracking technique and a multipolar representation of the Earth's magnetic field expanded up to order 10.

We have found that the largest values of the electron energy, bellow which the flux is dramatically suppressed, correspond to the location of SAC. The values obtained for El Leoncito are, on average, slighly larger than those of SAC. We have also found that for the Namibia site such values of energy are smaller by a factor two, or even more, depending on the arrival direction of the cosmic electron.

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