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Earth magnetic field effects on the cosmic electron flux as background for Cherenkov Telescopes at low energies

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ABSTRACT

Cosmic ray electrons and positrons constitute an important component of the background for imaging atmospheric Cherenkov Telescope Systems with very low energy thresholds. As the primary energy of electrons and positrons decreases, their contribution to the background trigger rate dominates over protons, at least in terms of differential rates against actual energies. After event reconstruction, this contribution might become comparable to the proton background at energies of the order of few GeV. It is well known that the flux of low energy charged particles is suppressed by the Earth's magnetic field. This effect strongly depends on the geographical location, the direction of incidence of the charged particle and its mass. Therefore, the geomagnetic field can contribute to diminish the rate of the electrons and positrons detected by a given array of Cherenkov Telescopes.

In this work we study the propagation of low energy primary electrons in the Earth's magnetic field by using the backtracking technique. We use a more realistic geomagnetic field model than the one used in previous calculations. We consider some sites relevant for new generations of imaging atmospheric Cherenkov Telescopes. We also study in detail the case of 5@5, a proposed low energy Cherenkov Telescope array.

1. Introduction

The great success achieved by current systems of Imaging Atmospheric Cherenkov Telescopes (IACTs) has led ground-based gamma-ray astronomy to enter a period of great development, with the next generation of instruments being designed to reach unprecedented sensitivities and angular resolution in a more extended energy range, particularly with lower energy thresholds (E_{th}). One of the main motivations for the construction of IACTs with low E_{th} is the study of distant extragalactic sources. Gamma-rays from such sources are attenuated by their interactions with the background radiation present in the intergalactic medium. Due to this effect, the spectrum is severely suppressed, e.g. the energy cutoff for an extragalactic object with redshift $z = 1$ can be as low as $\sim$50 GeV [1]. For a general discussion of the physical motivations to lower the energy threshold of IACTs see, e.g. [2].

Current systems of IACTs like HESS, MAGIC and VERITAS have energy thresholds of $\sim$100 GeV with very large collection area. For a customized trigger system, the energy threshold of MAGIC can be as low as $\sim$25 GeV. At these energies gamma-rays can also be detected by instruments on satellites. The Fermi LAT gamma-ray detector is able to detect photons in the energy range from $\sim$20 MeV up to more than $\sim$300 GeV [3]. Its large field of view makes it a very efficient detector for the discovery of new sources. However, the collection area in satellites is very limited so the sensitivity worsens very rapidly above tens of GeV. Thus, although the energy range of Fermi overlaps with ground-based IACTs, the sensitivity at energies of few GeV is low for both detectors.

The most advanced project considering a low E_{th} is the Cherenkov Telescope Array (CTA), the largest international effort for the next generation of IACTs with an order of magnitude better sensitivity than current systems [4]. In particular, E_{th} for CTA was planned to be $\sim$10 GeV, although a more realistic value for the present design is $\sim$20 GeV. There are also specific proposals whose main technical objective is to lower the energy threshold, like STEREO ARRAY [5], ECO-1000 [6] and 5@5 [7]. For the 5@5 array it is shown that an E_{th} in the range 3–5 GeV 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 [8].

Cosmic ray protons and electrons are the most important background sources for the discrimination of gamma-ray showers developed in the Earth's atmosphere. Electron initiated showers are practically indistinguishable from those initiated by gamma-rays and thus their importance for gamma-ray astronomy. For energies below $\sim$20 GeV, it is predicted that electrons could be

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differentiated from gamma-ray initiated showers [9]. Protons are almost two orders of magnitude more numerous than cosmic electrons at energies below ~10 GeV, increasing toward higher energies as the electron spectrum is steeper than the one corresponding to protons [10,11]. However, protons need quite a bit more energy to produce the same amount of Cherenkov light, specially at the lowest energies, going from a factor ~5 (at ~1 TeV) to ~60 (at few GeV) [7,12]. Additionally, the trigger system of IACTs discriminate against protons, although this is less effective at the lowest energies due to fluctuations in the shower development and a drop in image intensity. In the end, for the lowest energies, electrons become the dominant component of the differential trigger rate for a low-energy-threshold IACT system [7,5,13]. All proton events passing the analysis cuts are considered as gamma-rays, and thus their reconstructed energy will be lower than the true energy. This causes the electron dominance to diminish, making the reconstructed flux of both electrons and protons comparable at the lowest energies [5].

Cosmic ray electrons and positrons[1] constitute ~1% of the total cosmic ray flux arriving at Earth in the GeV–TeV energy range. It is believed that the high energy component of the electron flux is directly produced by galactic sources such as supernova remnants and pulsars [14]. Electrons can also be produced by interactions of cosmic ray protons or light nuclei with the interstellar medium gas. Electrons undergo energy losses during their propagation in the interstellar medium. The main processes are: synchrotron radiation in the galactic magnetic field, inverse Compton scattering with photons from stars and the cosmic microwave background, bremsstrahlung with interstellar matter, and ionization. For energies grater than ~10 GeV, the electron flux is dominated by the local environment because the attenuation length is reduced to the kpc scale [14].

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 for IACTs. A first study of the geomagnetic field effects on the cosmic electron rate was performed by Cortina and González [15], in the context of the MAGIC telescopes, for several geographical positions around the world by using the dipolar approximation of the magnetic field of the Earth. A better description of the geomagnetic field is provided by the International Geomagnetic Reference Field (IGRF) [16], which is given as a multipole expansion up to 10th or 13th order, depending on the version under consideration. In this case, the problem cannot be solved analytically, and thus numerical methods are used. In particular, the backtracking technique is used to find the allowed and forbidden trajectories [17].

The shielding of charged particles is not the only effect caused by the magnetic field of the Earth at a given location. Extensive air showers develop in the atmosphere generating negatively and positively charged particles, particularly electrons and positrons being the most important for IACTs. These particles are deflected in opposite directions by the component of the geomagnetic field normal to the shower axis. This spread causes an additional dispersion in Cherenkov images recorded by IACTs and, consequently, diminishing the background separation efficiency. There are extensive studies in the literature about this effect (e.g. [18]), which depends not only on the location on Earth but also on the telescope pointing direction. While this and other effects might be of more importance than the shielding effect, they are not considered in this paper.

In this work we study the suppression of the cosmic electron flux due to geomagnetic field effects for locations in the Southern hemisphere. Moderate to high altitude sites with clear skies are available only in South Africa and South America. Thus, we consider here three candidate sites in the southern hemisphere (which are being considered for the installation of CTA): El Leoncito (31:47 S, 69:28 W), San Antonio de los Cobres (SAC, (23:50 S, 66:16 W)), both in Argentina [19], and the HESS site in Namibia [20]. We also study in detail the case of 5@5, for which we consider the sites Llano de Chajnantor in the Atacama desert, northern Chile [7], and SAC which is very close to the latter (less than 200 km southwest).

2. The cosmic electron flux

The electron flux has been measured by several experiments (see [10] for a compilation of experimental data). The most recent measurements with better statistics are from Fermi LAT [21] and PAMELA [10]. Fermi LAT covers the energy range from 7 GeV to 1 TeV, whereas the corresponding PAMELA range is from 1 GeV to 0.625 TeV. Although above ~10 GeV the PAMELA spectrum seems to be softer than Fermi LAT's, they are consistent within uncertainties. For energies below 10 GeV the data from older experiments fall within the range of the PAMELA and HEAT [22] results. The latter can be taken as the extreme minimum case for the measured electron flux arriving at Earth. For energies below ~10 GeV, the discrepancies on the electron flux measured by different experiments can be explained, in part, by solar modulation effects suffered by incident electrons.

In this work, the flux measurements from Fermi LAT, PAMELA and the low energy part ($E \leqslant 10$ GeV) of HEAT are considered. Fig. 1 shows the experimental data, where the error bars indicate statistical plus systematic uncertainties. For the numerical calculation an analytical expression of the electron and positron flux ($J = J_{ele} + J_{pos}$) is used, which is obtained by fitting the data shown in Fig. 1 with the following function,

$$J(E) = \begin{cases} a + \frac{b}{E} + \frac{c}{E^2} + \frac{d}{E^3} & E \leqslant 7\ \text{GeV}, \\ \phi_0\ E^{-\gamma} & E > 7\ \text{GeV}, \end{cases} \tag{1}$$

where E is in GeV, J is in m^{-2} s^{-1} sr^{-1} GeV^{-1}, and both $\{a, b, c, d\}$ and $\{\phi_0, \gamma\}$ sets of parameters are not independent, but related by the conditions that make the flux and its derivative continuous at $E = 7$ GeV.

Fig. 1 shows both fits considered here as the maximum and minimum cosmic electron fluxes: the first corresponding to the combination of PAMELA and Fermi LAT data (J_{PFL}: solid line), and the second to the combination of Fermi LAT and the low energy part of HEAT data (J_{HFL}: dashed line). Table 1 summarizes all parameters resulting from the fits, as specified in Eq. (1). It is considered that any other measured flux falls in between these two fits so that all possibilities are covered within uncertainties. The relevance of the goodness of these fits is discussed in next section. Nevertheless, to evaluate the geomagnetic field effects at a given site, the fit J_{PFL} is finally chosen as it is the more recent and better measured electron flux available at present.

Although at energies of the order of a few GeV the flux is dominated by the electron component, the positrons can contribute in a non negligible way to the IACTs background. Fig. 2 shows the positron fraction, $\delta(E) = J_{pos}(E)/(J_{pos}(E) + J_{ele}(E))$ as a function of primary energy, obtained by PAMELA [23] and Fermi LAT [24]. Also shown is a fit of the PAMELA data with the function,

$$\log \delta(E) = p_0 + p_1 \log E + p_2 \log^2 E, \tag{2}$$

where E is in GeV, $p_0 = -1.078,\ p_1 = -0.542$ and $p_2 = 0.352$. Note that the fit is consistent with the Fermi LAT data and, therefore, it is reliable up to 200 GeV, the maximum energy reached by Fermi LAT.

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[1] Hereafter, electrons will refer to both electrons and positrons. Any particular case will be specified explicitly.