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Geomagnetic Field Effects on the Imaging Air Shower Cherenkov Technique

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Abstract: Imaging Air Cherenkov Telescopes (IACTs) detect the Cherenkov light flashes of Extended Air Showers (EAS) triggered by very high energy (VHE) γ-rays impinging on the Earth's atmosphere. Due to the overwhelming background from hadron induced EAS, the discrimination of the rare γ-like events is rather difficult, in particular at energies below 100 GeV. The influence of the Geomagnetic Field (GF) on the EAS development can further complicate this discrimination and, in addition, also systematically affect the γ efficiency and energy resolution of an IACT. Here we present the results from dedicated Monte Carlo (MC) simulations for the MAGIC telescope site, show the GF effects on real data as well as possible corrections for these effects.

Introduction

The influence of the GF on EAS was already qualitatively discussed in 1953 [1] and later in [2, 3].

Charged secondary particles in EAS are deflected by the GF which causes a broadening of the EAS. The east-west separation of electrons and positrons in EAS due to the Lorentz force can be non negligible compared to the displacement due to Coulomb scattering.

The effect on γ-ray induced EAS is expected to be bigger than on hadron induced EAS, as their shape is initially more regular and the scattering angles occurring in nuclear interactions are typically larger than that produced by the deflection of secondary charged particles due to the influence of the GF. The Cherenkov images on ground can be affected in a way that the threshold energy of an IACT increases [4] as well as its γ/hadron separation capability is expected to be deteriorated. The goal of the MC studies carried out in this work was to find out about the impact of the GF on the extraction of the γ-ray signal from a VHE γ-ray source. Figure 1 shows the vertical component $|\vec{B}_\perp|$ of the GF strength at the site of the MAGIC telescope [5] on the Roque de los Muchachos observatory on

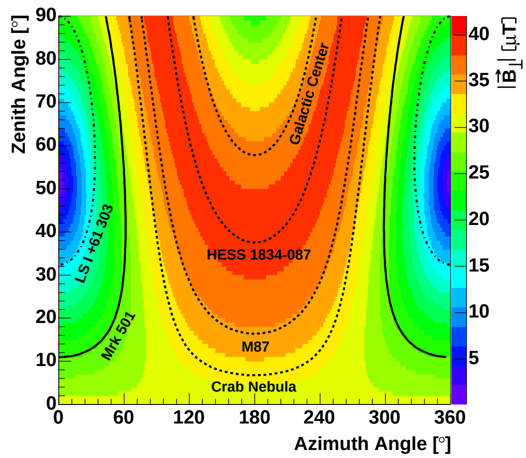

Figure 1: The absolute value of the vertical component of the GF strength at the Roque de los Muchachos observatory on La Palma, together with the trajectories of some sources.

La Palma (28.8° N,17.9° W) for 10 km a.s.l., calculated for November 2006 for the epoch 2005 International Geomagnetic Reference Field (IGRF) model [6], together with the trajectories of some established and potential VHE γ-ray sources. For all sources, the field strength changes very little along the source trajectory. For La Palma, the minimum influence of the GF is expected to occur in direction of the magnetic north at zenith angle $\mathrm{ZA} = (90^\circ - I) \approx 51^\circ$, where the angle between the shower axis and the GF lines becomes smallest. I denotes the angle under which the GF lines dip into the Earth's surface. Hence, the maximum influence is expected to occur for $\mathrm{ZA} = I \approx 39^\circ$, i.e. for EAS oriented perpendicular to the direction of the GF lines. It was shown elsewhere [7] that IACT measurements of TeV γ-rays from the Crab nebula were not significantly affected when the GF strength was below $35\,\mu$T. However, the sensitivity of an instrument to the influence of the GF depends on the imaging performance, i.e. point spread function (PSF) and pixel resolution. IACTs currently in operation as well as future instruments will be more sensitive to GF effects.

Monte Carlo Simulations & Analysis

The MC data used for the GF studies were produced following the standard MC production of the MAGIC telescope, doing three steps [8]:

1) The CORSIKA program (version 6.019) [9] is used to simulate the delevopment of γ-ray as well as hadron induced extensive air showers (EAS) for a given set of input parameters, like the primary γ-ray energy, the magnitude and direction of the GF, etc. The GF components were set to the values for La Palma (28.8° N,17.9° W) according to the IGRF model [6]. As a reference, MC data were also produced without GF.

2) The output of CORSIKA, containing information on the location and wavelength of each Cherenkov photon on ground, is processed with a dedicated Reflector program, which does the raytracing of the Cherenkov photons. The Reflector program also accounts for the absorption and scattering of Cherenkov photons through the atmosphere.

3) Finally, the output of the Reflector program is processed by the Camera program simulating the entire readout chain, i.e. photomultiplier response, trigger and FADC system including electronic noise.

In constrast to the production of standard MC data, where the EAS core location is randomly placed somewhere in a circle on the plane perpendicular to the direction of the EAS (to estimate the effective collection area), the EAS for this study were simulated for fixed impact positions with respect to the telescope location. This approach allows to investigate the influence of the GF on the shower images in greater detail. The energy of the primary γ-ray was varied between 30 GeV and 5 TeV, the ZA between 0° and 60° in steps of 20° and the azimuth angle between 0° and 180° in steps of 30°. The impact parameter was varied between 20 m and 200 m in steps of 20 m. About 10^5 MC events were generated per impact position and γ-ray energy. The calibration and the image parameter calculation (Hillas analysis [10]) was done using the MAGIC Analysis and Reconstruction Software (MARS) [11].

Results & Discussion

Only few selected results can be discussed here; more detailled analysis can be found in [12].

Figure 2 shows the Hillas ellipses for MC simulated γ-rays of 450 GeV energy, 40° ZA and impact parameters between 60 m and 100 m in different regions of the telescope. The azimuth angle was set to 0° (figure 2a) and 180° (figure 2b). For the former orientation, the GF effects are expected to be rather small (figure 2a) compared to the latter one (figure 2b), where the EAS evolves nearly vertically to the direction of the GF lines.

The red ellipses (solid lines) were obtained for enabled GF in the MC simulation and the blue ones (dashed lines) for disabled GF.

As can be seen from the Hillas ellipses in figure 2b, the average pointing of the major axis of the ellipses is preserved for images oriented either parallel or vertically with respect to the direction of the GF. Images oriented at intermediate angles are rotated away from the direction of the GF, i.e. the major image axes do not point any more towards the camera center as expected for γ-rays coming from a point-like source pointed at by the telescope.

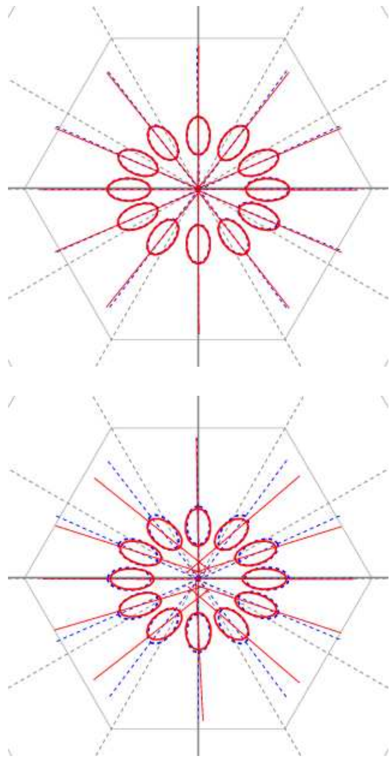

Figure 2: Hillas ellipses in different regions of the camera for primary γ-rays of 450 GeV energy, impact parameters 60 m – 100 m, zenith angle 40°, azimuth 0° (top), 180° (bottom). Red lines with, blue without geomagnetic field.

The influence of the GF on EAS can significantly alter the pointing of MC simulated γ-ray shower images. Therefore, the γ/hadron separation based on the orientation of the shower images is expected to be degraded. The extent of the rotation depends on various parameters, like the γ-ray energy, the impact parameter, and the position of the EAS with respect to the telescope.

Figure 3 shows the normalized distributions of the image parameter ALPHA for MC simulated γ-rays of 450 GeV energy, 40° ZA and impact parameters between 60 m and 100 m. The azimuth angle was set to 0° (figure 3a) and 180° (figure 3b). The latter orientation of the EAS with respect to the direction of the GF is rather unfavorable and results in a strong influence of the GF. The ALPHA distributions drawn as red and blue solid lines were obtained for two different directions of the EAS with respect to the telescope position. However, both distributions correspond to the shower images that are not rotated (shower images situated on the x-axis and y-axis of the CORSIKA coordinate system, figure 2). The red distributions correspond to an arrangement where the connecting line between shower axis and telescope optical axis is parallel to the north-south direction, whereas the blue distributions correspond to an arrangement where the connecting line between shower axis and telescope optical axis is parallel to the east-west direction. The ALPHA distributions obtained for disabled GF in the MC are drawn as red and blue dotted lines, respectively. The black dotted lines indicates the region considered as the signal region.

From figure 3 it can be seen that for some arrangements the ALPHA distribution (red) is significantly degraded even if the images are not rotated. However, the ALPHA distribution (blue) can be slightly enhanced (stronger peaked at low values) due to the influence of the GF. The remaining possible arrangements lead always to ALPHA distributions that are degraded due to the rotation of the shower images.

The de-rotation of rotated shower images does not help to recover the pointing entirely. At most 10 % of the events can be recovered by de-rotation of the shower images. Furthermore, the de-rotation procedure requires the knowledge of the image parameter. Thus, for unfavorable orientations of the γ-ray initiated EAS with regard to the influence of the GF, a simple procedure could be to remove those regions in the camera which are expected to be affected strongest.

It is remarkable that not only low-energy γ-ray showers at ~ 100 GeV are affected but also high-energy γ-ray showers at ~ 5 TeV energy.

The MC simulations performed for this work show also that the GF significantly affects the energy reconstruction and the γ efficiency. For unfavorable orientations of the EAS with regard to the influence of the GF the reconstructed shower image intensity can be significantly reduced. Therefore, if the GF effects are not taken into account the energy of γ candidates from real data will be systematically underestimated by up to 20 %. This is not only the case for low energies but also at higher energies of at least up to 5 TeV.

In case of low-energy showers close to the trigger threshold and unfavorable orientations of EAS with regard to the influence of the GF, the Cherenkov light distribution can be thinned out in a way that a significant fraction of the events do not survive the trigger level. As a result the γ efficiency decreases by up to 25 %. If this effect is not taken into account, the flux from a γ-ray source will be wrongly reconstructed.

Conclusions

The result from the MC studies suggest that the influence of the GF can significantly reduce the γ/hadron separation capability, the energy estimation as well as the γ efficiency of an IACT. Altogether, the GF is expected to affect the γ-ray sensitivity of an IACT and the determination of both the differential γ-ray flux and the absolute flux level of a γ-ray source candidate. Furthermore, the MC studies on the GF effect indicate that appropriate MC datasets are not only required for the analysis of low-energy data < 100 GeV but also for the reconstruction of VHE γ-rays of at least 5 TeV.

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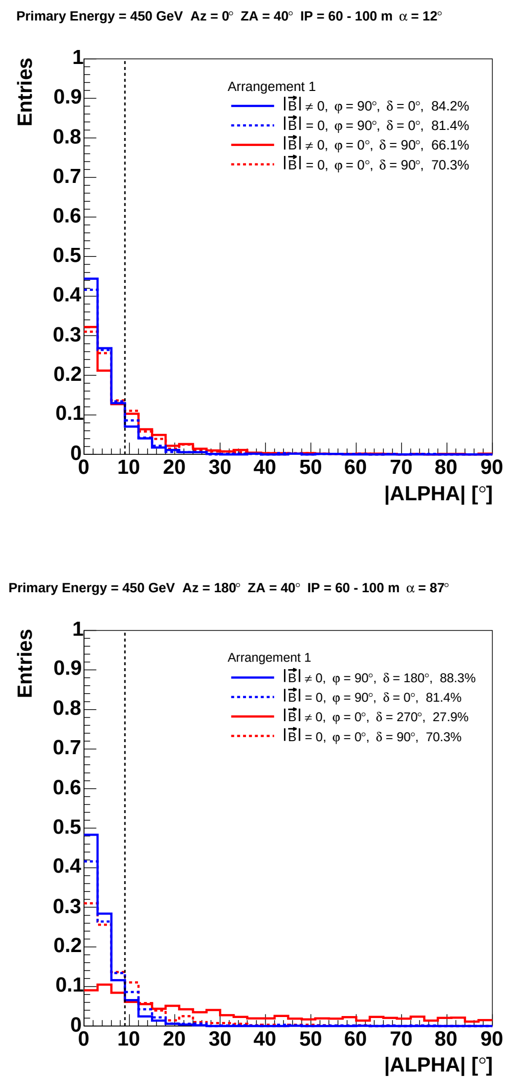

Figure 3: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters 60 m – 100 m, zenith angle $40°$, azimuth angle $0°$ (top), $180°$ (bottom).

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