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. Additionally we show that measurements of sub-TeV γ-rays from the Crab nebula are affected even for a low GF strength of $|\vec{B}_\perp| \approx 33\,\mu$T.

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 more visible than for 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 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.
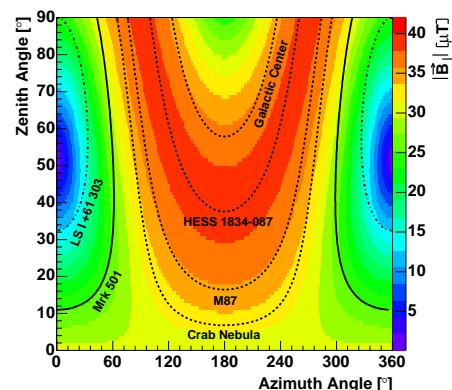

Figure 1: The absolute value of the vertical component of the GF strength at the Roque de los Muchachos observatory on La Palma.
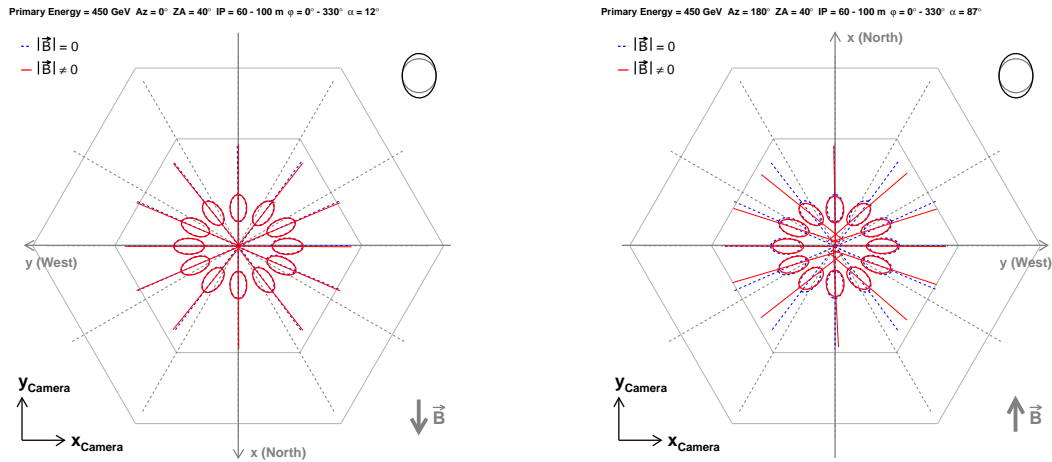
Figure 2: Hillas ellipses in different regions of the camera for primary γ-rays of 450 GeV energy, impact parameters 60 m - 100 m, ZA $40°$, azimuth angle $0°$ (left), $180°$ (right). Red lines with, blue without GF.

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 ZA $= (90° - I) \approx 51°$, 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 ZA $= I \approx 39°$, 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.

Monte Carlo Simulations & Analysis

To study the GF effects, dedicated MC data 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 ray-tracing of the Cherenkov photons.

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

In contrast 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 calibration and the image parameter calculation (Hillas analysis [10]) was done using the MAGIC Analysis and Reconstruction Software (MARS) [11].

In addition to the MC data 50 min of low-ZA ($7°$ - $10°$) Crab nebula data from February 2007 were analyzed considering GF effects.
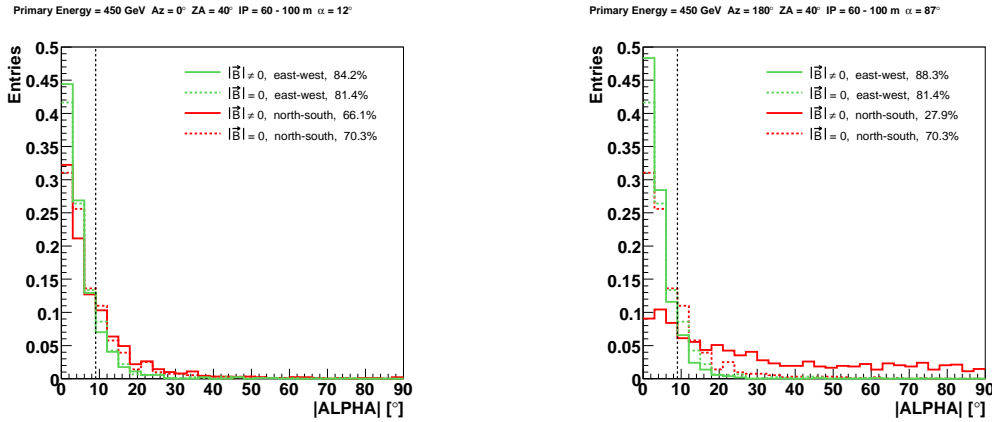
Figure 3: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters 60 m - 100 m, ZA $40°$, azimuth angle $0°$ (left), $180°$ (right).

Results & Discussion

Only few selected results can be discussed here and a more detailed 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. The azimuth angle was set to $0°$ (small effect expected, figure 2, left image) and $180°$ (strong effect expected, figure 2, right image). The red ellipses (solid lines) were obtained for enabled GF in the MC simulation and the blue ones (dashed lines) for disabled GF. The average orientation 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. 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 and the same input parameters as above. Again, the azimuth angle was set to $0°$ (small effect expected, figure 3, left image) and $180°$ (strong effect expected, figure 3, right image). The ALPHA distributions drawn as red and green 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 green 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 green dotted lines, respectively. The gray dotted line indicates the region considered as the signal region. The MC simulations show that for some arrangements the ALPHA distribution (red) is significantly degraded even if the images are not rotated. However, the ALPHA distribution (green) 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 requires the knowledge of the image parameter.

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

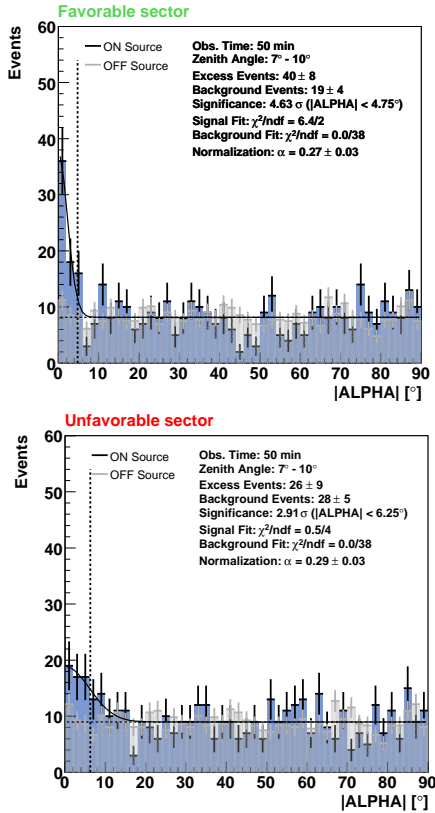γ candidates from real data will be systematically underestimated by up to 20 %.

Figure 4: ALPHA distributions for the low-ZA Crab nebula dataset for γ-ray energies above $\sim$ 120 GeV, considering GF effects.

This is not only the case for low energies but also at higher energies of at least 1 TeV. The Cherenkov light distributionon on ground from showers close to the threshold energy can be thinned out such that most of the events do not survive the trigger level, i.e. the detection efficiency for γ-rays can vary by up to 25 % [12].

Figure 4 shows the ALPHA distributions for the small low-ZA Crab nebula dataset for γ-ray energies above $\sim$ 120 GeV, considering GF effects. The upper distribution corresponds to events oriented at the most favorable camera sector and the lower figure to events oriented at the most unfavorable directions with regard to the influence of the GF, i.e. images are oriented either vertically or parallel with respect to the direction of the GF.

Conclusions

The results 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 $\lesssim 100$ GeV but also for the reconstruction of VHE γ-rays of at least 1 TeV [12]. The analysis of low-ZA Crab nebula data taken with the MAGIC telescope proofs that the instrument is sensitive enough to demonstrate the influence of the GF even for a very low vertical component of the GF ($|\vec{B}_\perp| \approx 33 \, \mu$T).

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