Evidence of geomagnetic effect on the azimuthal distribution of extensive air showers

Paolo Bernardini and Simona N. Sbano
on behalf of the ARGO-YBJ Collaboration

Dipartimento di Matematica e Fisica "Ennio De Giorgi", Università del Salento, Lecce, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Lecce, Lecce, Italy
E-mail: paolo.bernardini@le.infn.it, simona.sbano@le.infn.it

Abstract. The geomagnetic field causes not only the East-West effect on the primary cosmic rays but also affects the trajectories of the secondary charged particles in the shower, causing their lateral distribution to be stretched. Thus both the density of the secondaries near the shower axis and the trigger efficiency of detector arrays decrease. The effect depends on the direction of the showers, thus involving the measured azimuthal distribution. The non-uniformity of the azimuthal distribution of the events collected by the ARGO-YBJ detector is deeply investigated for different zenith angles in the light of this effect.

1. Introduction
The effect of geomagnetic field (GMF) on primary cosmic rays (CR’s) is well known. The GMF acts also on the charged particles of the extensive air showers (EAS) during their path in the atmosphere. Cocconi [1] suggested that the lateral displacement induced by the Earth magnetic field is not negligible with respect to the Coulomb scattering when the shower is young. Therefore the effect could increase for high altitude measurements. The shower extension is enlarged by the GMF as a function of the azimuth angle and the different density of charged particles introduces an azimuthal modulation due to the different trigger efficiency of EAS detectors. This modulation was observed at the Yakutsk array for EAS with energy above 50 PeV [2] and at the Alborz observatory for energy above 100 TeV [3]. The effect has been also observed in radio-experiments [4] and studied to improve the EAS simulation [5], to correct the pointing of Čerenkov telescopes [6] and to discriminate the primary mass [7]. The importance of the azimuthal modulation has been pointed out also in studies on CR large-scale anisotropy [8].

ARGO-YBJ [9] is a full-coverage array located in Tibet (P.R. of China) at 4300 m above sea level (90°31’50”E, 30°06’38”N). The trigger threshold is ~ 1 TeV for primary CR, well beyond the rigidity cutoff. The GMF effect on the ARGO-YBJ data was studied and simulated [10, 11]. Here those studies are updated and compared with a very large data sample.

2. Simple model of the GMF effect
EAS charged particles are affected by the Lorentz force in the plane (bending plane) perpendicular to the magnetic field $\vec{B}$. Along the GMF direction the force is null and the velocity is constant. Therefore the main result of the GMF action is a shift of the particles in
the bending plane. On the shower front this shift results

\[ d = \frac{q}{2p} \left( \frac{h}{\cos \theta} \right)^2 B \sin \xi \]  

where \( q \) is the electric charge, \( p \) the particle momentum, \( h \) the vertical height of the particle path, \( \theta \) the zenith angle and \( \xi \) is the angle between \( \vec{B} \) and \( \vec{p} \).

The equation (1) does not describe fully the GMF effect. Indeed the particle time of flight is modified by the shift in the bending plane, then also a shift in the GMF direction is foreseen. At last the model should take into account all the particles in the EAS, each one with its values of \( p \), \( \theta \) and \( h \). In short a Monte Carlo simulation is necessary and it will be presented in the next section. Anyway equation (1) indicates an enlargement of the shower footprint. Far from the core the shower density is enhanced by the GMF effect proportionally to \( d^2 \) and then to \( \sin^2 \xi \) [2, 8]. Close to the core a decrease is expected and consequently a reduction of the ARGO-YBJ trigger efficiency depending in some way on \( B \) and \( \xi \). The angle is given by the equation

\[ \sin \xi = \sqrt{A_0 + A_1 \cos(\phi - \phi_B) + A_2 \cos[2(\phi - \phi_B)]} \]  

where \( \phi \) is the EAS azimuth and \( \phi_B = 71.89^\circ \) the GMF azimuth in the ARGO-YBJ reference frame. The coefficients are

\[ A_0 = \sin^2 \theta + \sin^2 \theta_B \left( 1 - \frac{3}{2} \sin^2 \theta \right), \quad A_1 = -\frac{\sin 2\theta_B \sin 2\theta}{2}, \quad A_2 = -\frac{\sin^2 \theta_B \sin^2 \theta}{2} \]  

3. Simulation of CR beams

Beams of primary protons have been simulated in order to study the magnetic effect and to disentangle it from detector effects. All beams have the same primary energy (3 TeV), the same zenith angle (45°) and the same interaction height (19 km). Different azimuth angles (\( \phi = 71.5^\circ \), 115.5°, 161.5° and 251.5°) have been used in order to get different values of \( \sin \xi \) (0.02, 0.51, 0.87, 1). Three intensities of the magnetic field have been used: 0.0, 49.7 (actual GMF at the
Entries $3.473657 \times 10^8$

Mean $179.2$

RMS $104$

$\chi^2 / \text{ndf} = 641.9 / 67$

$N = 259 \pm 4.825 \times 10^6$

$g_1 = 0.00008 \pm 0.01507$

$\phi_1 = 0.29 \pm 72.75$

$g_2 = 0.000076 \pm 0.005458$

$\phi_2 = 0.4 \pm 87$

Figure 3. Real data: azimuthal distribution. The fit with function (4) is superimposed (only statistical errors).

Figure 4. Real data: coefficient $g_1$ versus zenith angle. The fit $g_1 = k_1 \sin 2\theta$ is superimposed (only statistical errors).

ARGO-YBJ site) and 99.4 $\mu$T (twice the actual GMF). The CORSIKA code [12] has been used to reproduce the shower development and a GEANT3-based code [13] to simulate the detector response. The primary trajectory has been projected on a $10 \times 10$ $m^2$ area at the center of the carpet. At first the detector acceptance has been studied by simulating the showers in absence of the GMF. The result is an azimuthal modulation of $\sim 0.3\%$ with phase $90^\circ$ and periodicity $180^\circ$ due to analysis cuts and trigger efficiency.

The magnetic effect has been studied looking separately at negative and positive EAS components. Eq. (1) is validated by the fact that the distance between positive and negative cores increases linearly with $\sin \xi$ and $B$ (Fig. 1). It has been also verified that the shower stretching does not affect the reconstruction of the direction, but acts on the trigger efficiency. Fig. 2 shows clearly that the trigger efficiency decreases as magnetic field or $\sin^2 \xi$ increase.

4. Data analysis

Data collected in 8 days (October 7-14, 2010) have been analyzed. The array has been carefully time-calibrated [14] because also small errors in the pointing angle introduce large systematic errors in the azimuthal distribution, especially for small zenith angles.

In order to get a reliable reconstruction of the shower direction, the following cuts have been applied: shower core reconstructed inside a square of $40 \times 40$ $m^2$ at the center of the carpet, EAS zenith angle lower than $60^\circ$. After these cuts more than 347 millions of events are selected.

The azimuthal distribution in Fig. 3 is fitted by a double harmonic function

$$\frac{dN}{d\phi} = N_0 \{ 1 + g_1 \cos (\phi - \phi_1) + g_2 \cos [2 (\phi - \phi_2)] \}$$  \hspace{1cm} (4)

The high value of $\chi^2 / \text{ndf}$ is mainly due to some inefficiencies at $\phi \sim n 90^\circ$ ($n = 0, 1, 2, 3, 4$) not discussed here. The fit improves adding negative terms to take into account these inefficiencies (the $\chi^2 / \text{ndf}$ value becomes 1.7).

According to the simple model and the simulations it is expected

$$\phi_1 = \phi_2 = \phi_B, \quad g_1 \propto -A_1 \propto \sin 2\theta, \quad g_2 \propto -A_2 \propto \sin^2 \theta.$$  \hspace{1cm} (5)

if the origin of the modulation is only geomagnetic. Indeed the measured phase $\phi_1$ is compatible with the GMF azimuth. Also the dependence of $g_1$ on $\sin 2\theta$ is verified (Fig. 4). This is not the
case for coefficient and phase of the second harmonic. The anomaly can be solved simply taking into account the detector effect observed in the simulation without magnetic field. Therefore the second harmonic can be split in two components: one (2B) is due to the GMF, the other one (2A) to the detector acceptance. Three different data sets have been selected on the basis of the zenith angle in order to disentangle these two effects. The φ-distributions of the subsamples have been fitted all together with a single function:

\[
\frac{dN}{d\phi} = N_i \left\{ 1 + k_1 (\sin 2\theta)_i \cos (\phi - \phi_1) + k_{2B} (\sin^2 \theta)_i \cos [2(\phi - \phi_1)] + g_{2A}^i \cos [2(\phi - \phi_{2A})] \right\}
\]

(6)

where the coefficients of the magnetic component are deduced from eq.s (5), the phase \(\phi_1\) is used for first and magnetic second harmonic and the index \(i = \alpha, \beta, \gamma\) indicates the subsamples. Then the fit parameters are \(k_1, k_{2B}, \phi_1, g_{2A}^\alpha, g_{2A}^\beta, g_{2A}^\gamma\) and \(\phi_{2A}\). The new fit works very well (\(\chi^2/\text{ndf} = 1043/209\) and it becomes lower and lower taking into account the inefficiencies at \(n 90^\circ\)) and the parameter values (see table 1) confirm that the azimuthal distribution depends on magnetic and detector effects. Again the phase \(\phi_1\) is almost equal to \(\phi_B\), the coefficients \(g_{2A}^i\) increase with \(\theta\) and \(\phi_{2A}\) is compatible with \(90^\circ\) as expected for a detector effect.

Table 1. Results of the fit with function (6) applied to azimuthal distributions of samples \(\alpha, \beta\) and \(\gamma\) selected in \(\theta\)-ranges \(0^\circ - 20^\circ, 20^\circ - 40^\circ\) and \(40^\circ - 60^\circ\). Only statistical errors are reported.

| \(k_1\) | \(k_{2B}\) | \(\phi_1\) |
|--------|--------|--------|
| 2.078\% ± 0.010\% | 0.68\% ± 0.20\% | 72.18° ± 0.28° |
| \(g_{2A}^\alpha\) | \(g_{2A}^\beta\) | \(g_{2A}^\gamma\) | \(\phi_{2A}\) |
| 0.139\% ± 0.015\% | 0.341\% ± 0.038\% | 1.236\% ± 0.083\% | 92.1° ± 1.8° |

5. Conclusion
The modulation of the azimuthal distribution of a large EAS sample has been analyzed. The origin and the features of this modulation are fully understood by means of a simple model, also confirmed by MonteCarlo simulations. The azimuthal modulation is well described by two harmonics, the first one of the order of 1.5\%, the second one of the order of 0.5\%. The first harmonic is due to the geomagnetic Lorentz force on the shower charged particles. The second harmonic is a mix of magnetic and detector effects. The measurement of the geomagnetic phase \((\phi_1 = 72.18° ± 0.28°)\) is fully compatible with the expected value \((\phi_B = 71.89°)\) and this result confirms the proper timing calibration of the array.

References
[1] Cocconi G 1954 Phys. Review 93 646-7, erratum 1954 Phys. Review 95 1705-6
[2] Ivanov A A et al 1999 JETP Letters 69 288-93
[3] Bahmanabadi M et al 2002 Experim. Astronomy 13 39-57
[4] Khakian Ghomi M et al 2007 Proc. of 30th Int. Cosmic Ray Conf. (Merida) 4 11-4
[5] Cillis A and Sciutto S J 2000 J. Phys. G: Nucl. Part. Physics 26 309-21
[6] Comminchau C et al 2008 Nuclear Instrum. Methods A 595 572-86
[7] Capdevielle J N et al 2000 Astropart. Physics 13 259-75
[8] Abreu P et al (Pierre Auger Collaboration) 2011 J. Cosmol. Astropart. Phys. JCAP11 022
[9] Aielli G et al (ARGO-YBJ Collaboration) 2012 Nuclear Instrum. Methods A 661 S50-5
[10] He H H et al 2009 Proc. of 29th Int. Cosmic Ray Conf. (Pune) 6 5-8
[11] P. Bernardini et al 2011 Proc. of 32nd Int. Cosmic Ray Conf. (Beijing) HE1.1 0755
[12] www-exo.fzk.de/corsika/
[13] www-asd.web.cern.ch/www-asd/geant/
[14] He H H et al 2007 Astropart. Physics 27 528-32
Aielli G et al (ARGO-YBJ Collaboration) 2009 Astropart. Physics 30 287-92