Observation of geomagnetic effects in EAS muon component

A.G. Bogdanov, R.P. Kokoulin, A.A. Petrukhin, O. Saavedra, V.V. Shutenko, I.I. Yashin

***Abstract*—The dependence of the intensity of muon bundles registered at the Earth surface by means of coordinate detector DECOR on the angle between muon arrival direction and geomagnetic field vector (pitch angle) has been analysed. It is found that muon bundle intensity decreases with the increase of the transverse component of the magnetic field in comparison with calculations performed under assumption of azimuthal uniformity of the flux, the effect being enhanced with the increase of zenith angle. Comparison with CORSIKA-based simulations shows that this effect is explained by changes in EAS muon lateral distribution functions caused by propagation of particles in the geomagnetic field. Another effect - appearance of a coplanar component in relative directions of EAS muons in a plane determined by the shower axis and Lorentz force vector - has been also observed.**

1. INTRODUCTION

The effects of the influence of the Earth magnetic field (EMF) on ground level muon flux characteristics are well-known. For example, the azimuth asymmetry of low energy muon intensity related with primary particles geomagnetic cut-off is observed [1]. The influence of the magnetic field on the trajectories of secondary particles (muons) changes the observed value of their charge ratio; the effect is the most significant for East-West direction at low geomagnetic latitudes near horizon [2]. Considerably less understood is the influence of EMF for multi-muon events. Experimental indications for destruction of the axial symmetry of muon lateral distribution function (LDF) were found in giant air showers at large zenith angles [3-4]. Though theoretically the EMF influence on EAS muon component was considered by several authors [5-6], the quantitative experimental data on these effects are practically absent.

In this paper, the results of the analysis of EMF influence on muon bundle characteristics measured by means of coordinate-tracking detector DECOR [7] are presented. The setup is located in Moscow. The absolute value of the EMF induction vector B_0 = 52 μT [8]; the declination is about 9° East; the inclination is equal to 71° (that is, the zenith angle of the EMF vector $\theta = 19°$).

2. ANGULAR DEPENDENCE OF MUON BUNDLE INTENSITY

As it was noticed earlier [6], in a small-angle approximation the displacement of muons in a plane orthogonal to the shower axis is proportional to the transverse component of the magnetic field, inversly proportional to particle momentum, and directly proportional to the squared geometrical path (that is, nearly proportional to the squared zenith angle secant). As a result, at large zenith angles low energy muons are swept out to shower periphery, the particles are separated in charge sign and momentum. Axial symmetry of the shower is destroyed, and muon LDF becomes "8-shaped" with the main axis parallel to the Lorentz force vector. Muon density in the central part of the shower considerably decreases.

When muon bundles are detected with a small-size setup (smaller than typical sizes of the shower), the event rate is determined primarily by muon density near the shower axis [9]. In this case, the EMF influence leads to the decrease of the bundle intensity, and, if the magnetic field vector is not vertical, for a fixed zenith angle the dependence of the event rate on the azimuth angle must appear.

In order to check this effect experimentally, we have used the data on muon bundles obtained by means of the coordinate-tracking detector DECOR in series of 2004-2005 measurements (about 4200 hours "live" registration time). The side part of DECOR [7] has a total area of 70 m^2 and consists of 8 supermodules; each of them includes 8 vertical planes of plastic streamer tube chambers. Charged particles are registered by means of external strip readout system in two orthogonal views, that allows reconstruct particle tracks in space. To ensure high statistics of the data, low multiplicity events with 3 muons detected in three different supermodules (the minimal number determined by trigger conditions) were selected. Total number of events in four zenith angle intervals (35°-45°, 45°-55°, 55°-65°, and 65°-75°) amounted to about 150 thousands.

The expected number of events for different zenith and azimuth angle bins was calculated taking into account the effective setup area, registration conditions and selection criteria. In calculations, a power dependence of the flux of incident events with local muon density D was assumed [9]:

$$dF/dD \sim D^{-(\beta+1)} \cos^{\alpha}\theta; \qquad (1)$$

A.G. Bogdanov, R.P. Kokoulin, A.A. Petrukhin, V.V. Shutenko and I.I. Yashin are with Moscow Engineering Physics Institute (State University), Moscow 115409, Russia (e-mail: VVShutenko@mephi.ru).

O. Saavedra is with Dipartimento di Fisica Generale dell' Universita di Torino, 10125 Torino, Italy.

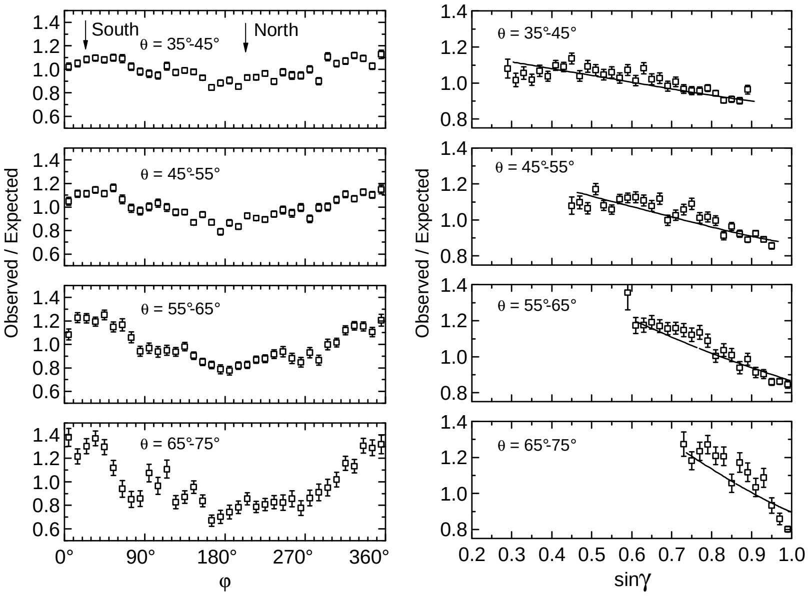

Figure 1: The ratio of the observed number of muon bundles to the expected one as a function of azimuth angle (left) and of the pitch angle sinus (right)

the parameters (α ~ 4.5, β ~ 1.95 - 2.10) were estimated from the experimental distributions of muon bundle characteristics. The expected event number was computed under assumption of azimuthal uniformity of the flux; then the total number of events was normalized to the observed one for every zenith angle interval.

In Fig.1 (left panel), the ratio of the measured and expected intensity of muon bundles is plotted as a function of arrival azimuth angle in the laboratory frame (direction to geomagnetic South corresponds to φ = 26°). As it is seen from the figure, this ratio is far not uniform. In the right panel, the same ratio is shown as a function of the sinus of angle between muon bundle direction and EMF vector (pitch angle). In this case, the dependence becomes regular and monotonous; the slope is increasing for larger zenith angles.

Solid curves in the right part of Fig.1 represent the results of calculations of the expected muon bundle intensity (also normalized to the total number of events for every zenith angle bin) for fixed zenith angles and different values of the pitch angle, obtained on the basis of muon LDF simulated by means of the CORSIKA code [10] (version 6.502). Comparison of the curves and the data exhibits a good qualitative (and a reasonable quantitative) agreement and confirms that the observed angular dependence of the event intensity is explained by the changes of EAS muon LDF under the influence of the geomagnetic field.

3. COPLANARITY OF TRACKS IN MUON BUNDLES

Apart from stochastic processes of the angular deflection of muon trajectory from the direction of the primary particle (transverse momenta in hadronic interactions, parent meson decay kinematics, multiple Coulomb scattering in air), there exists a regular component caused by the Earth magnetic field. An equivalent transverse momentum p_{EMF} may be estimated as

$$p_{\mathrm{EMF}} = 0.3\, B_0 \sin\gamma\, H_0 \sec\theta. \qquad (2)$$

Here H_0 is the effective muon production altitude; usual system of units (GeV/c, T, m) is used. A typical value of this momentum in conditions of the present experiment for 60° zenith angle is about 0.3 - 0.5 GeV/c which is comparable to transverse momentum for meson production; contribution of multiple scattering is several times less.

Muon bundles detected by a small-size setup contain muons initially emitted in different directions and slightly turned (differently, depending on the momentum and sign) by the magnetic field. Hence, in the directions of particles that hit the detector a kind of alignment (coplanarity) in a plane defined by the EAS axis and Lorentz force vector must appear. Let us note, that for EAS arrival directions close to the geomagnetic meridian (that means, for showers arriving from North or South) the Lorentz force vector is horizontal; for EAS arriving from East or West the regular component of transverse momenta must be inclined relative to horizon.

To search for this effect, we have selected muon bundle events with four (and only four) quasi-parallel particles detected in four different supermodules of DECOR from data collected in 2004-2007 (10102 hours “live” time). The last condition only one track in each supermodule was necessary for unambiguos spatial reconstruction of individual particle tracks. The events with zenith angles 55°-65° in four sectors of azimuth angle (nearly equivalent from the view-point of track registration and geometry reconstruction, but differently oriented relative to geomagnetic meridian) were analyzed.

For every muon bundle event, the average direction was determined, and then deviations of individual tracks from this average bundle vector in a horizontal plane (ΔX) and across it (ΔY) were calculated. In Fig.2, scatter diagrams of the track

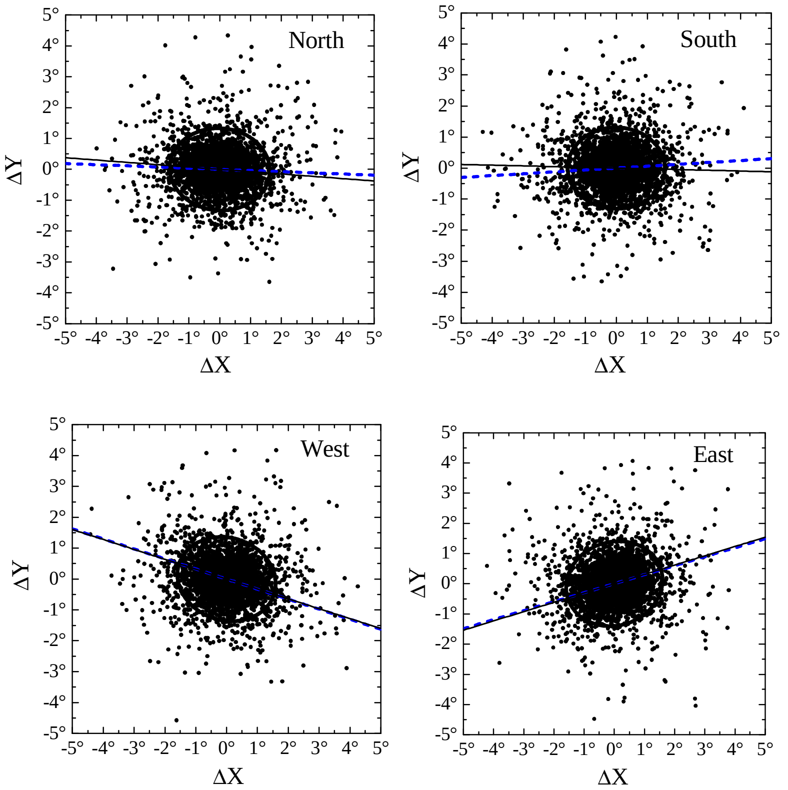

Figure 2: Scatter diagrams of relative track directions in muon bundles; θ = 55°- 65°; different azimuth angle intervals. Ellipses show 2σ-contours of 2D-Gaussian fits; solid lines: main axes of the ellipses; dotted lines: directions of Lorentz force vector

directions in (ΔX, ΔY) coordinates for muon bundles arriving from four different azimuth angle intervals are presented. Ellipses in the figures correspond to 2σ-contours of 2D-Gaussian fit of the distribution; solid lines indicate the main axes of the ellipses, dotted ones show the directions of Lorentz force (average for every data sample). As it is seen from the figure, at the background of measurement errors and random scattering factors, a regular component (with rms-value about 0.3°-0.4°) close to Lorentz force vector is really observed in muon track directions.

4. CONCLUSION

Analysis of muon bundles registered in coordinate-tracking detector DECOR has shown that the event intensity significantly decreases with the sinus of the angle between the muon bundle arrival direction and geomagnetic field vector; this effect is enhanced with the increase of zenith angle. Comparison with CORSIKA-based simulations shows that this phenomenon is explained by the distortion of muon lateral distribution functions resulting from propagation of EAS muons in the geomagnetic field. A reasonable agreement between calculations and data may be considered as a validation of CORSIKA treatment of EMF influence on EAS muon component. A new phenomenon - coplanarity of muon bundle tracks in a plane determined by the Lorentz force vector and EAS axis - has been found.

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REFERENCES

[1] Pham Ngoc Diep et al., “Measurement of the east-west asymmetry of the cosmic muon flux in Hanoi”, Nucl. Phys. B, 678 (2004), p. 3.
[2] O.C.Allkofer et al., “Cosmic-ray muon spectra at sea-level up to 10 TeV”, Nucl.Phys.B, 259 (1985), p. 1.
[3] A.M. Hillas et al., ”Calculations on the particle and energy-loss densities in extensive air showers at large axial distances”, Proc. 11th ICRC, Budapest, 3 (1969), p. 533.
[4] L. Nellen et al., ”Detection of Very Inclined Showers with the Auger Observatory”, Proc. 29th ICRC, Pune, 7 (2005), p. 183.
[5] L.G. Dedenko et al., ”Charged Particle Separation in EAS by the Geomagnetic Field”, Proc. 24th ICRC, Roma, 1 (1995), p. 309.
[6] M. Ave et al., ”Modeling horizontal airshowers induced by Cosmic Rays”, Astropart. Phys., 14 (2000), p. 91.
[7] M.B. Amelchakov et al., ”High-resolution large area coordinate detector for investigations of high energy cosmic ray phenomena at the ground level”, Proc. 27th ICRC, Hamburg, 3 (2001), p. 1267.
[8] http://www.ngdc.noaa.gov/ngdc.html
[9] N.S. Barbashina et al., ”Ultra-high energy cosmic ray investigations by means of EAS muon density measurements”, Nucl. Phys. B (Proc. Suppl.), 165 (2007), p. 317.
[10] D. Heck et al. http://www-ik.fzk.de/corsika