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Azimuthal effect on extensive air showers of cosmic rays

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Abstract

The azimuthal anisotropy of cosmic rays was revealed in 1930's as the east-west asymmetry. Here we present the first observation of geomagnetic effect on extensive air showers (EAS) using the long-term data of the Yakutsk array. More than 2.5×10^5 showers detected at $E > 10^{17}$ eV demonstrate the azimuthal modulation of the event rate for fixed θ, ρ_{600} at the significance level below 10^{-11} in zenith angle range $20^0<\theta<70^0$. The first harmonic of the measured north-south asymmetry increases with zenith angle but is almost independent of the primary energy. Consequences for the EAS data handling are discussed.

1 Introduction:

Since the first measurement of the azimuthal asymmetry of cosmic radiation (Johnson, 1933) there were azimuthal distribution observations with other cosmic ray (CR) components. The most recent results are: observation of the east-west anisotropy of the atmospheric neutrino flux with Super-Kamiokande (Futagami et al., 1999), an image distortion in Čerenkov telescope operating in Narrabri (Chadwick et al., 1999) and measurement of the north-south asymmetry of extensive air showers with the Yakutsk array (Ivanov et al., 1999). All these phenomena are caused by the charged particles trajectories curved in the geomagnetic field. Here we discuss in detail the features of the geomagnetic effect on EAS parameters using the data of the Yakutsk array and infer consequences concerning the data handling.

The density distribution of charged particles in extensive air showers is distorted in the Earth's magnetic field. This effect is appreciable in inclined showers with zenith angles $\theta > 20^0$ (Dyakonov et al., 1991). Due to the distribution of particles broadened along the Lorentz force in a plane perpendicular to the shower axis, the average density alters. Detecting showers with the fixed zenith angle and ρ_{600} - the particle density at r=600 m from the core, one can measure the azimuthal modulation of EAS event rate. Indeed, the observational data of the Yakutsk array have revealed the geomagnetic effect on the reliable statistical basis.

2 The array and data set:

The Yakutsk array is situated at 61.7^0 N, 129.4^0 E, 100 m. above sea level (1020 g/cm^2), where the Earth's magnetic field is H=0.6 G with a dip angle $\alpha=14^0$. The array consists of 58 ground-based and 6 underground scintillation detectors of charged particles (electrons and muons), 50 detectors of the atmospheric Čerenkov light - photomultiplier tubes. The total area covered by detectors with 500 m separation is ~12 km^2 (~18 km^2 before 1990). In the central part of the array there is a denser domain with lesser (100–250 m) detector separation. The array has been in operation since 1970; approximately 10^6 showers of the primary energy above about 3×10^{16} eV are detected. The highest energy event, E = $(1\div2)\times10^{20}$ eV, has been detected 7.05.1989 with an axis within the array area, but with zenith angle $\theta=59^0$.

The inclined showers like this event ought to be analyzed taking into account a geomagnetic field effect on the lateral distribution of charged particles. A common algorithm based on the axially symmetric function, for instance, results in the primary energy overestimated up to 28%. The difficulty is in the number of detectors running in a particular shower insufficient to draw out the individual lateral distribution function for an event. Only in the rare case of an inclined highest energy event one can make an estimation of the effect on a shower. The extensive air shower detected 7.05.1989 at $\theta=59^0$ is the case.

We have estimated a particle density correction factor for this event. There are 55 scintillator and 5 muon detector readings for this shower in a core distance range from 220 to 2270 m. They were used to evaluate the average ratio ξ of the largest core distance to the least one corresponding to the fixed particle density on an equidensity oval of the lateral distribution: $\xi \approx 1+\Delta\rho_{600}/\rho_{600} \approx 1.2$. This value is consistent with a correction factor given in our previous paper (Ivanov et al. 1999). The detected density ρ_{600} and a primary energy for this event should be corrected by 20% taking into account the geomagnetic effect.

3 Geomagnetic effect on EAS parameters:

3.1 Energy and zenith angle dependence: An azimuthal effect is analyzed here using the data of the Yakutsk array detected in the period 1974-1995 having energies above 10^{17} eV. The event rate distribution of 252996 showers, with the fixed zenith angle and ρ_{600}, with respect to the arrival direction azimuth demonstrates a modulation due to geomagnetic effect at the significance level shown in Table 1. An amplitude of the first harmonic as a function of zenith angle is shown in Figure1. The phase is in the vicinity of the magnetic meridian at Yakutsk (azimuth -20^0). The first harmonic of the measured north-south asymmetry is almost independent of the primary energy.

Table 1. The significance of the azimuthal effect (*P*), and the primary energy variation (*dE*/*E*).

θ, deg.	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
P, %	66.1	5.1	10^{-11}	10^{-23}	10^{-36}	10^{-27}	10^{-23}	0.16
dE/*E*, %	0.1	0.4	1.9	2.7	4.3	5.9	9.9	-

In order to account for the energy and zenith angle dependence of the geomagnetic effect it is convenient to consider a charged particle displacement in a field. Inclined showers with zenith angles $\theta>50^0$ consist of muons in the main. An average muon deviation in the geomagnetic field is $d\approx 0.5\times h^2\times B\times \sin\chi/E_\mu$, where h is a trajectory length of muon in the atmosphere; χ is an angle between the magnetic field B and a shower axis; E_μ is the mean energy of muons. A difference in the muon displacement for showers arriving from the north and south is $\Delta d\approx 0.5\times h^2\times B\times \sin\alpha\times\cos\theta/E_\mu$. The average particle density in the shower and EAS event rate are both connected to Δd. That is why the amplitude A_1 is almost independent of the primary energy due to the weak dependence of the muon trajectory length on this parameter. On the contrary, a zenith angle dependence is considerable. The electron-photon component dominated showers at $\theta<50^0$ have similar behaviour, as it is seen from Figure 1.

3.2 The primary energy correction: The average number of detectors, N_{det}, fired in an event can be used to estimate a shower area where the particle density is greater than the detector threshold and/or an array acceptance area. We have used the distribution of N_{det} in azimuth (for fixed θ, ρ_{600}) in order to evaluate the first harmonic amplitude of N_{det} which is given in Figure 1. Using the amplitude $A_1(n)=(n_S-n_N)/(n_N+n_S)$, where $n_N(n_S)$ is the shower number from the north (south); and $A_1(S)=(N_{det}^S-N_{det}^N)/(N_{det}^N+N_{det}^S)$, where $N_{det}^N(N_{det}^S)$ is the average detector number fired in a shower from the north (south); we can now estimate a primary energy variation: $dE/E = 2\times(A_1(n)-A_1(S))/\gamma$, where $\gamma = 3$ is the primary energy spectrum index. Observation time and the array acceptance in a solid angle can be omitted because of the same value for all azimuths. The calculation results are given in Table 1. Actually, the resultant value is a relative difference in the primary energy of showers with fixed θ and ρ_{600}, arriving from the north and south. Comparing it to the correction factor for a highest energy event one can conclude that the primary energy should be revised approximately by $3\times dE/E$ in order to discount off the geomagnetic effect.

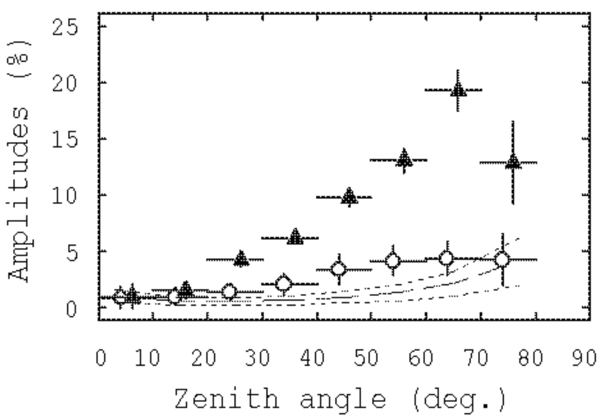

Figure 1: The first harmonic of the event rate (triangles) and N_{det} distributions (circles) in azimuth as a function of zenith angle. Statistical errors are shown by the vertical bars, horizontal bars show the angular bins. The expected harmonic amplitude for the uniform distribution in azimuth is given by a dashed curve. The standard deviation of expected amplitude is shown by the dotted curve.

3.3 Consequences for EAS arrival directions: An observed distribution of arrival directions in a horizontal system is distorted due to azimuthal event rate modulation in the geomagnetic field. The right ascension distribution isn't affected because of diurnal spreading. On the other hand, the declination distribution should be corrected.

We have used two distributions in azimuth: the uniform one and the observed spread of the Yakutsk array data in order to simulate the ratio of distorted to isotropic arrival directions. From the experimental data set zenith and azimuth angles were extracted of showers in the energy ranges $E > 10^{17}$ eV and $E > 2\times10^{18}$ eV; then the uniform sidereal time distribution was added to convert arrival directions to equatorial and galactic co-ordinates. In the case of isotropic spread a uniform distribution in azimuth was used instead of experimental one. The resultant ratios of observed to isotropic shower numbers as a function of declination and galactic co-ordinates are shown in Figures 2 to 4.

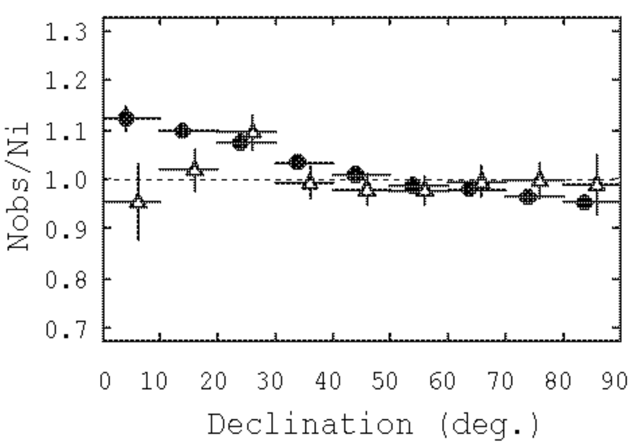

Figure 2: The observed-to-isotropic ratio of the declination spread. N_{obs} is the shower number observed and N_i is expected for isotropy at $E>10^{17}$ eV (circles) and $E>2\times10^{18}$ eV (triangles).

There exists an obvious systematic disfiguration of the initial isotropic distribution of a magnitude up to 10%. In the energy range $E > 10^{17}$ eV we have the event number sufficient to distinguish the geomagnetic effect on arrival directions. At higher energies (i.e. $E > 2\times10^{18}$ eV, a total of ~7000 events) the statistical errors of the Yakutsk array data are yet comparable to the deviation of N_{obs}/N_i so the effect is invisible.

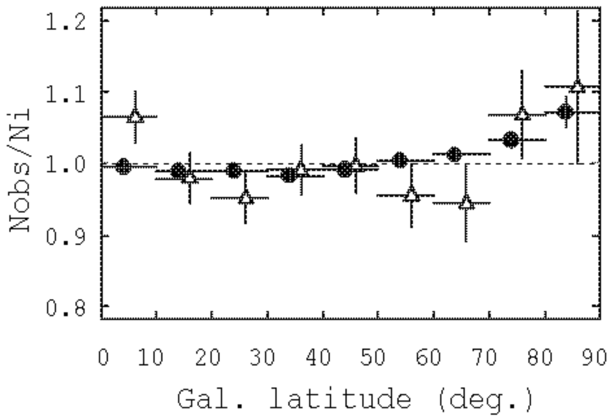

Figure 3: The observed-to-isotropic ratio of the galactic latitude distribution. The notation is the same as in Figure 2.

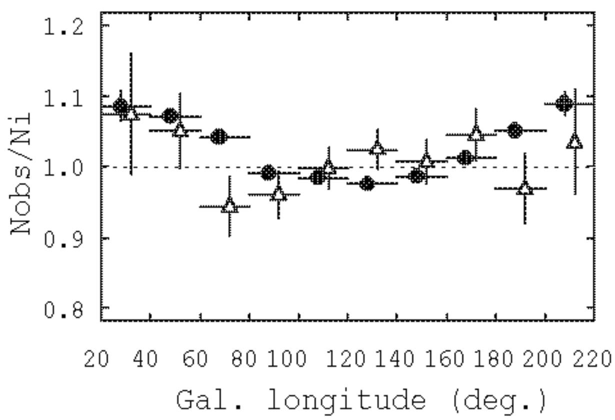

Figure 4: The observed-to-isotropic ratio of the galactic longitude distribution. The notation is the same as in Figure 2.

4 Conclusions:

We have demonstrated the azimuthal effect on EAS event rate caused by the geomagnetic field using a bulk of the Yakutsk array data at $E > 10^{17}$ eV. The value of the effect is approximately the same in the whole energy range. The primary energy and arrival directions of showers appear to be modified due to geomagnetic distortion of the EAS particle density with a magnitude up to 10-20%, relative to the case when a field is switched off.

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