Anisotropy of the high energy cosmic ray flux measured by means of muon bundles in the Experimental complex NEVOD

Z T Izhbulyakova, M B Amelchakov, V S Vorobyev, A A Kovlyaeva,

R P Kokoulin, S S Khohlov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409, Russia

E-mail: Izhbulyakovazarina@yandex.ru

Abstract. The work is devoted to the study of the anisotropy of the high energy cosmic ray flux by means of muon bundles registered during 2012-2018 with the coordinate-tracking detector DECOR, which is a part of the Unique Scientific Facility «Experimental complex NEVOD». We have analyzed data for two event samples corresponding to $E > 10^{15}$ eV and $E > 10^{16}$ eV energy ranges of primary particles. The method of data processing is described and estimates of the dipole anisotropy parameters (the amplitude and the phase) are presented.

1. Introduction

Study of the primary cosmic ray (CR) flux is one of the fundamental tasks of the modern science. The information about the spatial distribution of the cosmic ray flux would help to solve many of cosmological and nuclear-physical problems such as the character of the relativistic charged particles motion in space, distribution of their probable sources and understanding of the nature of the “knee” in the cosmic ray spectrum, and so on. Due to the rapidly decreasing power-type cosmic ray energy spectrum, direct primary particles measurements with energies above $10^{15}$ eV on satellites in space or on balloons in the atmosphere become ineffective. Therefore, the study of the ultrahigh energy cosmic rays is carried out by recording secondary particles which represent various components of extensive air showers (EAS).

The presence of magnetic fields in the Galaxy changes charged particle directions and prevents them escape it. The primary particles with relatively low energy are entangled in the magnetic fields and their flux becomes quasiisotropic. On the average, according to the existing estimates [1], the strength of the magnetic field in our Galaxy is approximately 3 $\mu$G. In these conditions, we are able to observe the primary particle sources at the distance not more than Larmor radius. For protons with energy of $10^{15}$ eV the Larmor radius is about 1 pc. More distant sources will not be visible. For higher energy the visible space is increasing, and $10^{18}$ eV protons get opportunity to leave the Galaxy since their Larmor radius becomes comparable with the thickness of the galactic disk ~ 1 kpc [2].
2. Theoretical assumptions

Taking into account the peculiarities of the structure of the Galaxy, at present it is assumed that the diffusion of primary CR from the center of the Galaxy and the Compton-Getting effect \[3, 4\] may be the reasons of the anisotropy.

The density of the matter decreases with the distance from the center of the Milky Way. This aspect is used in the diffuse model of cosmic ray propagation. According to it, there is a constant CR flux from the central regions of the Galaxy to its periphery. In the papers describing the diffusion model \[5, 6\], the formula is given for calculating the amplitude of the dipole anisotropy:

\[
A = \frac{3D(E) \frac{1}{c} \frac{dN}{dr}}{N_z}, \tag{1}
\]

where \(D(E)\) is the diffusion coefficient of CR, \(c\) is the speed of light, \(r\) is the distance to the center of the Galaxy, and \(N_z\) is the concentration of the nuclei with the charge \(z\) in the cosmic radiation.

The particles emerge isotropically and their intensity is independent of time in the framework of the model of the stationary source located in the center of the Galaxy. In this case, formula (1) can be simplified to the form:

\[
A = \frac{3D(E)}{cr}. \tag{2}
\]

Substituting the known parameters in (2) with energy \(E \sim 10^{15}\) eV, the expected anisotropy amplitude for the primary CR would be about \(10^{-2}\).

The anisotropy associated with the motion of the solar system relative to cosmic rays - the Compton-Getting effect is determined by the formula \[4\]:

\[
A = (\gamma + 2) \frac{w}{v}, \tag{3}
\]

where \(\gamma\) is the module of the exponent of the differential energy spectrum of cosmic rays, \(w\) is the velocity of the Sun motion relative to the cosmic ray flux, and \(v\) is the particle velocity. Solar system moves at a speed of 22-25 km/s with respect to the interstellar gas \[7\] in the direction of the Ophiuchus constellation (\(\alpha = 258^\circ, \delta = 17^\circ\)) \[8\]. The anisotropy amplitude expected from the Compton-Getting effect is \(\sim 3 \times 10^{-4}\).

The orbital Earth motion can also be a source of the anisotropy. The Earth velocity permanently changes its direction in the Solar system, and the anisotropy effect can be compensated if the measurements are carried out for an integer number of years. Therefore, despite of the fact that the orbital velocity of the Earth's motion is comparable with the speed of the solar system with respect to the interstellar gas, the averaging significantly reduces the influence of this factor on the measured CR anisotropy.

An evident anisotropy of the CR flux can appear also as a result of uneven distribution of the setup "live" operating time during the sidereal day. Therefore, the distribution of the live observation sidereal time has to be taken into account in the analysis of the anisotropy.

3. Experimental data

Muon bundles are the events caused by the simultaneous passage through the detector of genetically related muons. The main mechanism for the generation of bundles is the decay of pions and kaons produced in the development of the nuclear cascade process in the atmosphere. Bundles are a convenient tool for studying the anisotropy of cosmic rays, since the direction of their arrival with a high accuracy coincides with the direction of primary particles.
Figure 1. An example of muon bundle registered in the DECOR detector.

The coordinate-tracking detector DECOR [9] is a part of the Experimental complex NEVOD (MEPhI, Moscow). Eight DECOR supermodules (SMs) are arranged around the Cherenkov water detector (CWD) [10] as shown Figure 1 on the left in. The sensitive area of each SM is 8.4 m². The supermodules consist of eight vertical planes of plastic streamer tubes. The spatial and angular accuracy of muon track localization is better than 1 cm and 0.8°, respectively. The coordinate-tracking detector DECOR was specially designed for investigations of multi-particle events at large zenith angles. An example of a recorded event with the muon bundle is shown in Figure 1. The arrival direction of the muon bundles is determined in the local coordinate system of the experimental complex NEVOD. The time of the event is recorded in UTC.

The analysis of the dipole anisotropy has been performed for two samples of events. The first sample includes events with three tracks of muons registered in at least three DECOR supermodules. For such events the primary cosmic rays have the energies more than \(10^{15}\) eV according to [11]. About 8.7 million of such events were registered during the period from 03.05.2012 to 27.02.2018. "Live" time of the measurements was ~ 1513 days.

The second sample includes events with five quasiparallel tracks of muons registered in at least three DECOR supermodules screened by the water volume of the CWD with zenith angles greater than 55°. For such conditions, the characteristic values of the energy of the primary particles exceed \(10^{16}\) eV [11]. These events were recorded during the period from 03.05.2012 to 15.02.2018. The total number of the second event sample is about 60 thousand, and "live" time is ~ 1477 days.

The 2nd Equatorial Coordinate System (Figure 2) is used to represent the obtained results.

Figure 2. Visualization of the celestial sphere in the 2nd Equatorial Coordinate System in Hummer-Aitoff [12] projection.
The equatorial plane of the Earth is the main plane in this system. The point position in space is determined by two coordinates. The beam declination (δ) is the angle of the inclination of the beam from the system center to the point to the plane of the Earth's equator. The right ascension (α) is determined along the line of the equator from the beam direction to the point of the vernal equinox. Besides real CR anisotropy effects, the measured intensity of muon bundles is affected by meteorological conditions [13] which create an additional noise in the anisotropy search. Therefore, in calculating live time distribution we introduced a correction that compensates the intensity variations caused by atmospheric changes. This correction is small, but still important if we search for effects on the level of 10^{-3} or less. The calculation of the "live" operating time of the setup with atmospheric correction was carried out within every minute of the sidereal time. The obtained distribution of the "live" time in every minute of the sidereal day is shown in Figure 3.

![Figure 3](image.png)

**Figure 3.** The distribution of live time in each minute of the sidereal day with the atmosphere effect correction for two samples of events.

4. **Determination of the expected number of particles**

The muon track directions in the DECOR are determined in the local coordinate system. The horizontal axes of this system are rotated by 34.7° from the South to the East with respect to the Earth’s meridian. The distributions of zenith and azimuth angles for the arrival directions of the registered muon bundles for the two samples are given in Figure 4 and Figure 5.

![Figure 4](image.png)

**Figure 4.** Zenith (left) and azimuth (right) angle distributions for the first sample of events in the local coordinate system.
In the distribution of the azimuthal angles, the intensity of the recorded events varies due to the features of the detector design and the conditions of the event selection. For the first sample, there are four preferred directions in the local system with azimuth angles of $45^\circ$, $135^\circ$, $225^\circ$, and $315^\circ$. Additional selection conditions that are used for the second sample reduce the aperture of the detector, as shown in Figure 5. Most of events for the second sample have zenith angles in the range from $55^\circ$ to $65^\circ$. There are only two preferred directions in the local system with azimuth angles of about $150^\circ$ and $210^\circ$.

To obtain the expected number of particles from a given arrival direction in the coordinates of the 2nd Equatorial Coordinate System, the celestial sphere is divided into cells with equal solid angles of observation. The solid angle in the equatorial system is given by the formula:

$$\Delta\Omega = \Delta(\sin\delta)\Delta\alpha;$$

in this case each cell is assigned to the mean values of the right ascension and declination ($\alpha, \delta$).

The distribution of recorded events $N(\vartheta, \varphi)$ in the local coordinate system contains information about the aperture of the setup. Angular distributions of events in the 2nd Equatorial Coordinate System for a fixed sidereal time are shown in Figure 6.

The Earth's rotation axis coincides with the axis of the 2nd Equatorial Coordinate System; therefore, the declination values are independent of the moment of registration. This aspect is used to obtain the expected number of particles for the celestial sphere in the 2nd Equatorial Coordinate System.
System. To calculate the distribution of the expected events \( N_{\text{exp}}(\alpha, \delta) \), it is necessary to integrate \( N(\alpha, \delta) \) over the right ascension (Figure 7):

\[
I(\delta) = \int_0^{2\pi} N(\alpha, \delta) \, d\alpha.
\]  

(5)

Figure 7. Distribution for the sine of declination for the first (left) sample and the second (right) sample of events in the 2nd Equatorial Coordinate System.

As a result, the matrix of the expected number of events can be calculated as follows:

\[
N_{\text{exp}}(\alpha, \delta) = I(\delta) \cdot \tau(\alpha) / T_{\text{total}},
\]

(6)

where \( T_{\text{total}} \) is total "live" time, \( \tau(\alpha) \) – "live" time, corresponding to the cell of the matrix with the right ascension \( \alpha \).

The final distribution of the expected number of events is shown in Figure 8. Due to the DECOR location, we can observe only the northern part of the celestial sphere. Regions have poor statistics with the declination of \( \delta < -8^\circ \) for the first sample and \( \delta < 14^\circ \) and \( \delta > 72^\circ \) for the second sample.

Figure 8. Distribution of the expected number of events in the 2nd Equatorial Coordinate System for the first (left) and the second (right) event samples in Hammer-Aitoff projection.

5. Search for dipole anisotropy

The anisotropy is determined as a relative deviation of the measured number of muon bundles \( N_{\text{mes}} \) from the expected one \( N_{\text{exp}} \) in a chosen angular range of arrivals of primary CR over a long time period of measurement:

\[
A = \frac{N_{\text{mes}} - N_{\text{exp}}}{N_{\text{exp}}}.
\]  

(7)
Using (7), we have obtained the relative deviation for each cell of the celestial sphere. As a result, two colored matrices for both event samples are presented in Figure 9. The regions with poor statistics (see section 4) in these matrices are deleted. Visually, one can notice the presence of the dipole anisotropy for the first sample of events.

![Figure 9. Anisotropy for the first (left) and the second (right) event samples.](image)

The distribution data were projected onto the axis of the right ascension (Figure 10). Approximation of the data by the function \( f(\alpha) = \text{const} \) corresponds to the hypothesis of an isotropic flux. The value \( \chi^2 / \text{d.o.f.} \) for the first sample is 25/17 and for the second sample 9/17. The parameters of the dipole anisotropy can be obtained by approximating the data in Figure 10 with a function

\[
f(\alpha) = B \cdot \cos(\alpha - \varphi),
\]

where \( B \) is the anisotropy amplitude and \( \varphi \) is the phase. The red lines in Figure 10 represent the amplitude dependence over the phases which are equal to the values of the right ascension (\( \alpha \)) in the picture. The grey regions correspond to \( \pm 2\sigma \) deviation of found amplitudes. For the first sample, the maximum amplitude of the dipole anisotropy was found to be \((13.7 \pm 4.8) \times 10^{-4}\) with the phase of \(249^\circ \pm 10^\circ\) and \( \chi^2 / \text{d.o.f.} = 17/15 \), and for the second sample: \( B = (8.8 \pm 5.8) \times 10^{-3} \) with the phase of \( \sim 175^\circ \) and \( \chi^2 / \text{d.o.f.} = 7/15 \).

![Figure 10. Relative deviation as a function of the right ascension for the first (left) and the second (right) event samples.](image)

From the point of view of Pearson criterion for the 10% significance level, \( \chi^2 / \text{d.o.f.} = 25/17 \) is approximately equal to the critical value. Consequently, it is preferable to adopt the hypothesis of a dipole anisotropy, for which \( \chi^2 / \text{d.o.f.} = 17/15 \). For the second sample, the Pearson criterion practically does not change its value.
Thus, we suppose that the dipole anisotropy is seen in the first event sample. The anisotropy has not been detected yet for the second event sample, but we are able to set the upper limit for the amplitude of \(2.0 \times 10^2\) with a 95\% confidence level.

A comparison of the measurement results of the dipole anisotropy parameters obtained with the detector DECOR and other setups in a close energy range is presented in the Table 1. There is a good agreement for data of Tibet Air Shower Array [14], IceCube [15] and DECOR. Together all the setups observe the entire celestial sphere.

Table 1. The parameters of the dipole anisotropy obtained with different setups.

| Setup     | Energy, PeV | Declination | Amplitude | Phase     |
|-----------|-------------|-------------|-----------|-----------|
| IceCube   | ~1.4        | -90°;-25°   | \(6.0 \pm 1.5\)\times10^4 | 260° ± 10° |
| Tibet ASγ | ~1.0        | -30°;+90°   | \(13.0 \pm 3.0\)\times10^4 | 287° ± 13° |
| DECOR     | >1          | -8°;+90°   | \(13.7 \pm 4.8\)\times10^4 | 249° ± 10° |

6. Conclusion

As a result of the data analysis for the period 2012-2018, the estimates of large-scale dipole anisotropy parameters were obtained for two samples of events corresponding to energy ranges \(E > 10^{15}\) eV and \(E > 10^{16}\) eV.

For an energy \(E > 10^{15}\) eV, the phase of the dipole anisotropy with the amplitude of \(\sim 10^{-3}\) corresponds to the direction to the center of the Galaxy. An upper limit of the amplitude of the dipole anisotropy was obtained for the range \(E > 10^{16}\) eV.

The DECOR results are in a good agreement with the data of other setups for close energy ranges.

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