Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 613–616

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Direction and Magnitude of the Anisotropy of Cosmic Rays of TeV Energies

A.S. LIDVANSKY, YU.M. ANDREYEV, D.D. DZHAPPUEV, V.A. KOZYARIVSKY,
A.U. KUDZHAEV, T.I. TULUPOVA
Institute for Nuclear Research, Russian Academy of Sciences
lidvansk@sci.lebedev.ru

Abstract: We discuss the results of measuring the diurnal variations of cosmic ray intensity in the energy range 1-100 TeV. While the phase of the first harmonic of the sidereal daily wave directly determines the phase (right ascension) of the anisotropy vector, the amplitude and declination of the true anisotropy cannot be reconstructed from the first harmonic amplitude. However, they can be determined by taking into consideration the zero harmonic. It is demonstrated that some recent experiments pretending to measure the cosmic ray anisotropy with high resolution and precision interpret their experimental data erroneously.

Introduction

Galactic cosmic rays (GCR) have rather small anisotropy that is measurable in the energy range where the solar modulation of GCR stop acting (above 1 TeV), but the counting rate of detectors of reasonable dimensions is still high enough to ensure the necessary statistical accuracy (approximately up to 100 TeV). In this energy range the experiments are performed either under a heavy overburden of rock (water, ice) using large-area cosmic muon detectors or on the ground surface with arrays counting small-size air showers. Recently, two giant international collaborations representing muon underground detectors (Super-Kamiokande in Japan) and surface air shower arrays (Tibet AS in China) published their data on the anisotropy of GCR [1, 2]. They claim to measure the magnitude and direction of the anisotropy with higher accuracy and resolution than ever before. At the same time, our measurements carried out with facilities of the Baksan Neutrino Observatory and their analysis allowed us to make conclusions radically different from those declared in papers [1, 2]. In this connection it is appropriate to discuss the situation with measurements of GCR anisotropy and the ways of interpretation of available experimental data.

Anisotropy of GCR and Diurnal Wave of Intensity

Let the anisotropy of GCR be represented as a vector whose magnitude is equal to ξ. It is directed to a celestial point with coordinates α_0, δ_0 in equatorial coordinates (or l_0, b_0 in galactic coordinates). In the first approximation, the directional distribution of cosmic ray intensity has the following form [3]:

$$I(\theta) = I_0 + i_0 \cdot Cos\theta, \qquad (1)$$

where θ is the angle between the true anisotropy direction and the direction of observation at a given time instant. Due to rotation of the Earth this angle varies with time as

$$Cos\theta(t) = Sin\delta_0 Sin\delta_T + Cos\delta_0 Cos\delta_T Cos(t-t_0), \quad (2)$$

where δ_T is the declination of an observing telescope (for a wide-angle telescope this is a certain effective declination, and for narrow-angle telescope it represents simply the direction of measuring the intensity). Substituting (2) into (1) we obtain the sidereal daily wave of GCR intensity as the following sum

$$I(t) = I_0 + i_0(Sin\delta_0 Sin\delta_T + Cos\delta_0 Cos\delta_T Cos(t-t_0)), \quad (3)$$

After normalization to the isotropic part of intensity formula (3) takes on the following form

$$\frac{I(t)}{I_0} = 1 + \xi \cdot Sin\delta_0 Sin\delta_T + \xi \cdot Cos\delta_0 Cos\delta_T Cos(t - t_0)\,. \qquad (4)$$

In this expression the sum of the first and second terms in the right-hand side represents zero (time-independent) harmonic. The third term is the first harmonic in sidereal time that is usually measured. Its amplitude is proportional to the degree of anisotropy, cosine of telescope declination, and cosine of anisotropy declination. Analyzing the first harmonic one can derive its phase t_0, corresponding to right ascension α_0, which, due to this fact, is the directly measured parameter of sidereal anisotropy. At the same time, it follows from the structure of formula (4) that the amplitude of the first harmonic, even if reduced to the equator (correction for $Cos\delta_T$) still includes an uncertain factor $Cos\delta_0$. Thus, not only one is unable to determine the anisotropy declination by analyzing the daily wave first harmonic, but this unknown declination introduces uncertainty into the anisotropy magnitude, which is not equal to the first harmonic amplitude even after reduction to the equator.

Results of SK and Tibet ASγ Collaborations

In paper [1] the Super-Kamiokande collaboration presented the celestial map (Fig. 1) with an excess of events (0.104 ± 0.020)% from the region of Taurus constellation, the center of gravity of this excess being located at the declination –5° ± 9°. A similar map was published by the Tibet AS collaboration [2], and their excess of events is also at zero declination. The Super-K collaboration identify the Taurus excess with the true direction of GCR anisotropy, claiming that this excess and Virgo deficit form together complicated structure of the GCR intensity distribution. This conclusion is much advertised (see, for example, [4]). However, before analyzing more complicated structures, it is worthwhile to look at the behavior of the simple structure of formula (1). The first harmonic in (4) has a maximum on the equator due to the factor $Cos\delta_T$ (which, we repeat, for narrow-angle telescopes corresponds to the direction of observation). Thus, the Taurus excess (as well as Virgo deficit) found by Super-K may be associated with the structure of formula (4) rather than with real structure of GCR anisotropy. The map of Fig. 1 just measures the mentioned cosine dependence. As was discussed above, the real anisotropy declination remains unknown.

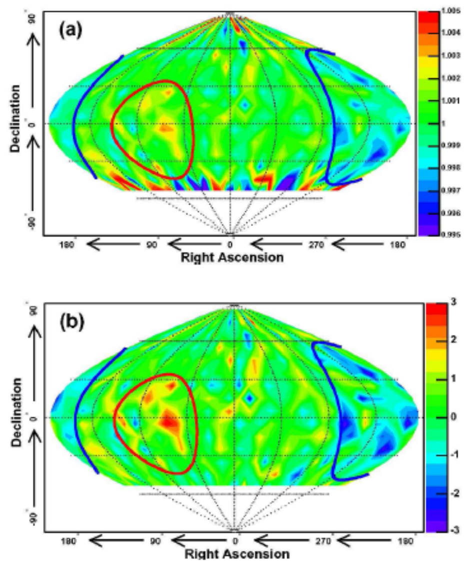

Figure 1: GCR flux intensity according to SK. Upper panel show deviation percentage (scale from –0.5% to +0.5%), while lower panel presents standard deviations.

Determination of True Anisotropy Parameters

The situation can be improved by measuring the zero harmonic. In paper [5] we suggested to determine the value of δ_0 using measurements of zero and first harmonics by two identical telescopes with differing δ_T. In this case the desired quantity is reconstructed according to the following formula

$$tg\delta_0 = \frac{K_{(1/2)} - 1}{P(Sin\delta_{T1} - K_{(1/2)} \cdot Sin\delta_{T2})}, \qquad (5)$$

where $K_{(1/2)}$ is the ratio of counting rates of the telescopes with declinations δ_{T1} and δ_{T2}, while $P = \xi \cdot Cos\delta_0$ is the projection of the anisotropy vector onto the equatorial plane (measured value, the amplitude of the first harmonic reduced to the equator. Instead of two identical arrays, one can divide a single array in two telescopes, which is much easier. We applied this method to the analysis of data of the Baksan air shower array [6]. This array possesses a high degree of symmetry. The distributions of signal delays in a pair of detectors symmetrical about the array's center are under analysis. Positive and negative delays in each detector correspond to the events arriving from different halves of the celestial hemisphere (Fig. 2). One can consider the number of showers with negative delays *(N-)*, for which $T_i < T_0$, and the number of showers *(N+)*, for which $T_i > T_0$, as recorded by two different detectors. In this case these detectors have different values of $Sin\delta_T$ and fully satisfy the requirements of the anisotropy measurement problem. The distribution of delays in a single detector is slightly asymmetrical due to methodological reasons, and it is impossible to measure very small anisotropy effect directly. Therefore, we used a symmetrical pair of detectors located on the opposite sides from the array center. The similar branches (N-) of the distributions of delays in these detectors were considered as representing the counting rates of crossed telescopes. The 1-ns time resolution used in the experiment is insufficient for this analysis. So, the maximum positions in the delay distributions were found using approximation by 10-degree polynomials. In addition, each distribution was cut (as it is shown in Fig. 2) within the limits ± 35 ns in order to avoid possible distortions of inclined showers by surrounding mountains. The crossed telescopes organized in this manner are wide-angle, and the effective declinations for them were calculated numerically by representing each wide-angle detector as a sum of narrow-angle cells. Declinations of all narrow angular cells were averaged with weights equal to counting rates of these cells in the experimental angular distribution. The preliminary result of this analysis corresponds to $\delta_0 = 62° \pm 5°$. The error in this case is determined by the accuracy of measuring the value of P in formula (5). This value was taken from measurements made by the Andyrchi air shower array [7] approximately at the same energy (100 TeV). Now, since $P = \xi \cdot Cos\delta_0$, taking, for example, $P = 0.1\%$ (as measured by the Baksan Underground Scintillation Telescope, see below) the true anisotropy value must be equal to $\approx 0.2\%$ ($\alpha_0 = 1.5\ h$ RA). In the galactic coordinates the direction of this anisotropy turns out to be $l \approx (120\text{-}130)°$, $b \approx 0°$.

Discussion and Conclusions

The anisotropy of GCR in the solar time is related to the velocity of orbital motion of the Earth around the Sun (Compton-Getting effect). If there were an analog of Compton-Getting effect in the sidereal time, the degree of anisotropy would be higher by a factor equal to the ratio of the velocity of the Solar System motion in the Galaxy to the orbital velocity of the Earth. However, nothing of this kind is observed, and the first harmonic in the sidereal time has approximately the same value as in the solar time (they differ by no more than a factor of two). This fact probably has two implications: 1. cosmic rays co-rotate with the Galaxy (this is also a confirmation of their galactic origin), and 2. the anisotropy measured in the sidereal time has non-trivial nature and, possibly is related to the distribution of sources of cosmic rays. It is precisely this fact that makes studies of the GCR anisotropy especially interesting.

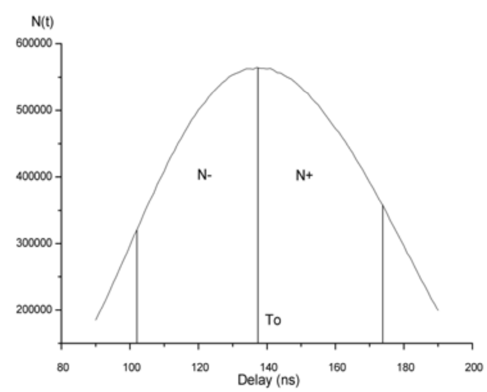

Figure 2: Distribution of delays of a single detector of the pair used for anisotropy measurements.

The data of shower arrays Andyrchi and Kovyor used for reconstruction of the true magnitude and direction of the anisotropy are obtained for primary cosmic rays with energies about 100 TeV. The Super-K data discussed above are related to the energy approximately an order of magnitude lower. It is appropriate to compare them with the diurnal wave measured by another detector of the Baksan Neutrino Observatory, Baksan Underground Scintillation telescope (BUST), see Fig. 2. These data are related to the primary energy of cosmic rays 2.5 TeV. The wave amplitude measured in the period from 1982 to 1998 is equal to $(3.79 \pm 0.27) \cdot 10^{-4}$. Since the effective declination calculated for the BUST measurements is 68°, the wave shown in Fig. 2 corresponds to the projection of anisotropy degree onto the equator plane $(10.11 \pm 0.72) \cdot 10^{-4}$. This almost exactly coincides with the value (0.104 ± 0.020)% given by Super-K team for their excess on the equator (with the only difference that the BUST data have statistical significance of 14 standard deviations against 5 standard deviation of Super-Kamiokande). Thus, both experimental data under discussion are in perfect agreement. The point is that the authors of papers [1, 2] interpret their data in the wrong way.

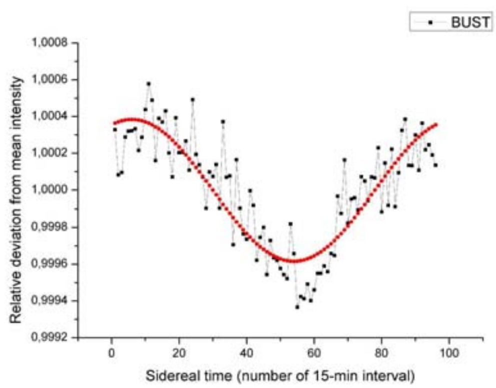

Figure 3: Muon flux daily wave measured by the BUST from 1982 to 1998.

The surprising fact is that in paper [1] the authors in addition to the celestial map presented the counting rate of muons as a function of right ascension. The first harmonic of this distribution (which should be, obviously, assigned to the effective declination of the detector) has the amplitude $(5.3 \pm 1.2) \cdot 10^{-4}$ and phase 40° ± 14°. This means that the amplitude of equatorial excess twice exceeds the amplitude at the effective declination, which most pictorially confirms our statement that the Super-Kamiokande detector measured the cosine dependence of formula (4).

One more remark can be made. The results of measurements in the range from 1 to 100 TeV show a certain tendency to a decrease of amplitude of the diurnal wave with energy. This could be associated with the fact that muon detectors have on average lower energies. Since muon detectors are sensitive to the primary spectrum per nucleon, while shower arrays – to the spectrum per nucleus, these two types of facilities deal with differing charge composition of GCR. Diffusion in the interstellar medium depends on charge, and so measured anisotropy should be somewhat different. This difference, probably, is not so large, but since it should exist we basically compared in this paper the results of two detectors of one type.

Acknowledgments

The work is supported in part by the Russian Foundation for Basic Research, grant no. 06-02-16355, and by the RF State Program of Support for Leading Scientific Schools, grant NSh-4580.2006.02.

References

[1] Y. Oyama (For Super-Kamiokande collaboration). Anisotropy of the Primary Cosmic-Ray Flux in Super-Kamiokande. arXive: astro-ph/0605020v2, 8 May, 2006.

[2] M. Amenomori et al. (The Tibet AS Collaboration). Anisotropy and Corotation of Galactic Cosmic Rays. arXive: astro-ph/0610671v1, 23 Oct. 2006.

[3] V.S. Berezinsky et al. Astrophysics of Cosmic Rays. Moscow, 1990.

[4] B. Mathiesen, Super-Kamiokande Finds Structure in the Cosmic Ray Sky, http://www.physorg.com, May 15, 2006.

[5] V.A. Kozyarivsky, A.S. Lidvansky, T.I. Tulupova, On Measurements of the True Anisotropy of Cosmic Rays, 29th ICRC, Pune, 2005, vol. 2, pp. 97-100.

[6] V.A. Kozyarivsky, A.S. Lidvansky, T.I. Tulupova, Direction of the Anisotropy Vector of TeV Cosmic Rays, Bull. Russ. Acad. Sci. Physics. vol. 71, no. 4, pp. 484-490. doi: 10.3103/S1062873807040144.

[7] V.A. Kozyarivsky, A.S. Lidvansky, V.B. Petkov, T.I. Tulupova, Mean Diurnal Variations of Cosmic Ray Intensity as Measured by the Baksan Surface and Underground Detectors, 29th ICRC, Pune, 2005, vol. 2, pp. 93-97.