29th International Cosmic Ray Conference Pune (2005) 7, 247-250

Multipolar Anisotropy in the Arrival Directions of $E_0 \geq 8\times10^{18}$ eV Cosmic Rays

A.V. Glushkov and M.I. Pravdin
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy,31 Lenin Ave., 677980 Yakutsk, Russia
Presenter: M.I. Pravdin (m.i.pravdin@ikfia.ysn.ru), rus-pravdin-MI-abs2-he14-poster

The analysis results of the arrival directions of extensive air showers (EAS) with the energy $E_0 \geq 8\times10^{18}$ eV registered at the Yakutsk EAS array 1974-2003 and the SUGAR array (Australia) are presented. It is shown that the increased particle fluxes at the statistical level of (3−4)σ arrive from the different sky regions. The some of such extensive regions are located along the Supergalaxy (Local superclusters of galaxy) plane. These regions are interpreted as the manifestation of the local extragalactic sources.

1. Introduction

Anisotropy of giant air showers of energy in the region $E_0 \geq 10^{19}$ eV have aroused particular interest since the detection of the first events at the largest arrays worldwide, such as Volcano Ranch [1], Haverah Park [2], SUGAR [3], and the Yakutsk array [4]. To a considerable extent, this interest is motivated by the fact that a sharp change in the shape of the energy spectrum of primary cosmic rays toward a slower decrease with increasing energy was observed at all arrays in the above energy region. A great many experimental and theoretical studies have been devoted to solving the problem of the origin of giant air showers, but it still remains one of the most complicated and contradictory problems.

Recently, a local region in the arrival directions of primary cosmic rays of energy in the range $E_0 \approx (1–2)\times10^{19}$ eV was found at a significance level of 0.007 on the basis of data from the Yakutsk array by using the wavelet-analysis method [5]. Its pole featuring the maximum number of events has equatorial coordinates of $\alpha_{\max} \approx 35° \pm 20°$ and $\delta_{\max} \approx 52.5° \pm 7.5°$ and lies in the Supergalaxy plane. This supports the hypothesis of an extragalactic origin of the bulk of primary cosmic rays that have energies in the region $E_0 \geq 10^{19}$ eV. However, Mikhailov [6–8], who also relied on an analysis of data from the Yakutsk array, arrived at a drastically different conclusion; according to Mikhailov, primary cosmic rays of energy in the range $E_0 \leq 4\times10^{19}$ eV are predominantly of a galactic origin. He states that a few pulsars closest to the Earth that occur at the side of the inlet of a local arm of the Galaxy and which generate predominantly iron nuclei are sources of this radiation.

2. Method of analysis and results

In order to disentangle this contradiction, we revisit the anisotropy of arrival directions for giant air showers of energy in the region $E_0 \geq 8\times10^{18}$ eV that were recorded by the Yakutsk array over the period between 1974 and 2002 for zenith angles satisfying the condition $\theta \leq 60°$. For our analysis, we select only those events for which the arrival directions were found on the basis of data from four or more stations and in which the shower cores were within the perimeter of the array. The primary-particle energy E_0 was determined from relations:

$$E_0 = (4.8 \pm 1.6)\times10^{17}\cdot(\rho_{s,600}(0°))^{1.0 \pm 0.02} \quad [\text{eV}], \tag{1}$$

$$\rho_{s,600}(0°) = \rho_{s,600}(\theta)\cdot\exp((\sec\theta - 1)\cdot1020/\lambda_\rho) \quad [\text{m}^{-2}], \tag{2}$$

$$\lambda_\rho = (450 \pm 44) + (32 \pm 15)\cdot\lg(\rho_{s,600}(0°)) \quad [\text{g/cm}^2], \tag{3}$$

where $\rho_{s,600}(\theta)$ is the charged-particle density measured by ground-based scintillation detectors at a distance of R = 600 m from the shower axis. In all, we selected 559 showers in this way.

In addition, we use 522 events from the catalog presented in [9] that were recorded by the SUGAR array. These showers predominantly refer to the southern hemisphere of the Earth. Together with the data from the Yakutsk array, they provide a rather comprehensive pattern of the anisotropy of giant air showers in the surrounding space. The accuracy in determining the arrival directions of showers in [9] was about 5.

We have investigated the deviations of the observed number of events, N_1, from the expected mean number $< N > = N_2 \cdot (\Omega_1/\Omega_2)$ in units of a standard deviation $\sigma = \sqrt{< N >}$:

$$n_\sigma = (N_1 - < N >)/\sigma \ , \qquad (4)$$

where N_1 and N_2 are the numbers of showers in the solid angles $\Omega_1 = 2\pi(1 - \cos(\theta_1))$ and $\Omega_2 = 2\pi(1 - \cos(\theta_2))$ ($\theta_1 = 8°$, $\theta_2 = 45°$), respectively. The values of the deviation in (4) were found upon successively shifting a 1°×1° area over the entire sphere.

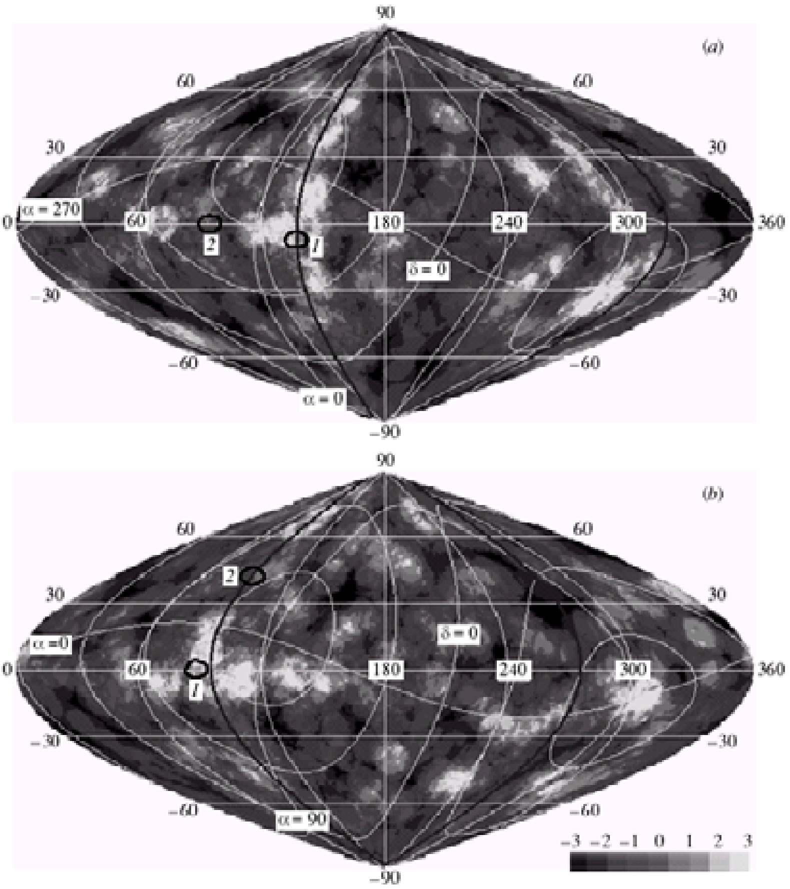

Figure 1. Deviations of the observed number N_1 of showers from the expected mean number $< N >$ in $n_\sigma = (N_1 - < N >)/\sigma$ units over the developed celestial sphere in (*a*) galactic and (*b*) supergalactic coordinates for giant air showers of energy in the region $E_0 \geq 8\times10^{18}$ eV and zenith angles in the range $\theta \leq 60°$ according to data from the Yakutsk array and SUGAR [9]. Circles *1* and *2* represent, respectively, the pole of a local excess of primary cosmic rays [5] and the outlet of a local arm of the Galaxy; the dark curves correspond to the (*a*) Supergalaxy and (*b*) Galaxy planes; and the shaded scale shows the range of n_σ.

Figure 1 shows the distribution of the quantities in (4) over the developed celestial sphere in terms of (*a*) galactic and (*b*) supergalactic coordinates. Circles *1* and *2* represent, respectively, the pole of a local excess of primary cosmic rays [5] and the outlet of a local arm of the Galaxy. The range of n_σ is shown at the bottom of the figure by the shaded scale. The darkest and the lightest regions correspond to the deviation of the giant-air-shower flux from the mean value by $| n_{\sigma}| \geq 3\sigma$.

A few interesting and important features immediately attract attention in Fig. 1. First, numerous local regions where the fluxes of giant air showers are relatively high or low are seen over the entire sphere. Second, there is virtually no excess of radiation in the Galaxy disk, apart from the locus of intersection of the Galaxy and Supergalaxy planes at $l_G \approx 137°$. There is no indication of excess radiation even from the center of the Galaxy, where there occur the most vigorous processes of matter transformation. Nonetheless, a significant anisotropy is observed in this region according to AGASA [10] and SUGAR [11] data in the energy range $E_0 \approx (8–20)\times10^{17}$ eV. One cannot see excess radiation of giant air showers at the outlet of the local arm of the Galaxy (circle *2*) either. In his studies, Mikhailov erroneously interpreted, as this excess, radiation from neighboring regions occurring approximately in the Galaxy disk, but $\Delta l_G \approx 25°–45°$ aside. The error resulted from a very rough partition of the sphere into plates of dimensions $\Delta l_G \times \Delta b_G = 30° \times 10°$ (see, for example, [8]).

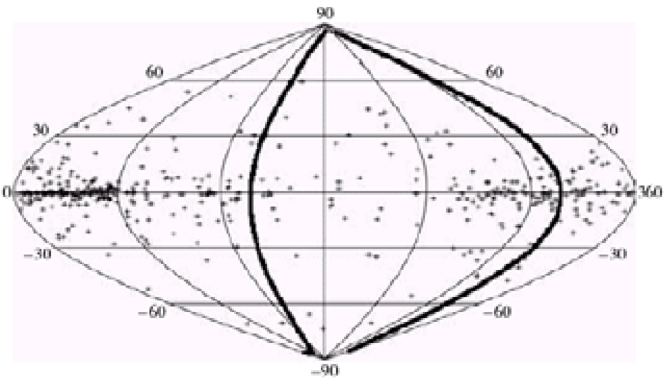

Figure 2. Distribution of 450 pulsars [12] over the developed celestial sphere in galactic coordinates. The thick curve represents the Supergalaxy plane.

There is yet another argument against the point of view advocated in [6–8]. It is provided by the distribution of pulsars in the Galaxy itself. This distribution is shown in Fig. 2 for 450 objects [12] in galactic coordinates. There, one can see a high concentration of pulsars in the vicinity of the Galaxy plane, but their concentration at the inlet of the local arm of the Galaxy ($l_G \approx 90°$, $b_G \approx 0°$) is rather low. If these objects had indeed been sources of ultrahigh-energy primary cosmic rays, they would have determined, to a considerable extent, the anisotropy of the arrival directions of giant air showers.

However, a totally different pattern emerges in fact from observations. In Fig. 1, a correlation between the arrival directions of giant air showers and the Supergalaxy plane is clearly seen in the northern hemisphere of the Earth. This correlation can be characterized by the average values:

$$< n_\sigma > = (\sum_{i=1}^{k} (n_\sigma)_i)/k \,, \qquad (5)$$

which are shown in Fig. 3. These values were obtained by averaging all n_σ for $\delta \geq 0°$ in intervals of width $\Delta b_{SG} = 1°$. At $b_{SG} \approx -3°$, a pronounced peak can be seen here, which was reported previously in [13,14].

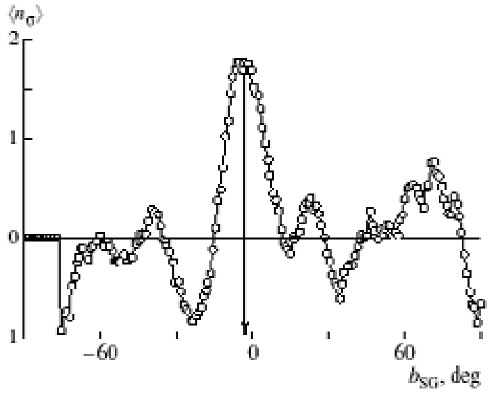

Figure 3. Distribution of $E_0 \geq 8\times10^{18}$ eV showers in units of $< n_\sigma >$ values obtained by averaging all n_σ in Fig. 1 over the intervals $\Delta b_{SG} = 1°$ for $\delta \geq 0°$ (in the northern hemisphere of the Earth) versus the supergalactic latitude.

3. Conclusions

The results in Figs. 1–3 evince an extragalactic origin of primary cosmic rays whose energies lie in the region $E_0 \geq 8\times10^{18}$ eV. Some of these particles are formed in the Supergalaxy [13−16]. It can be assumed that they are formed in collisions of neutral particles [15] generated by quasars [16] with a supergalactic gas. Here, further investigations are required, and they are under way now.

4. Acknowledgements

This work has been supported by Russian Foundation for Basic Research (grant N 05-02-117857-a) and the Russian Ministry for Science (grant N 01-03)

References

[1] J. Linsley, Phys. Rev. Lett. **10**, 146 (1963).
[2] D.M. Edge, A.C. Evans, H.J. Garmston, et al., J. Phys. A**6**, 1612 (1973).
[3] C.J. Bell, et al., Phys. A**7**, 990 (1974).
[4] D.D. Krasilnikov, A.I. Kuzmin, J. Linsley et al., J. Phys. A.**7**, 176 (1974).
[5] A.A. Ivanov, A.D. Krasilnikov, M.I. Pravdin, 28th ICRC, Tsukuba, **1**, 2003, p. 341.
[6] A.A. Mikhailov, 26th ICRC, Salt Lake City, **3**, 1999, p. 268.
[7] A.A. Mikhailov, 27th ICRC, Hamburg, **5**, 2001, p. 1772.
[8] A.A. Mikhailov, G. Nikolayeva, 28th ICRC, Tsukuba, **1**, 2003, p. 417.
[9] M.M. Winn et al.,Catalog of Highest Energy Cosmic Rays. Giant Extensive Air Showers, N2, World Data Center C2 for Cosmic Rays, Japan (1986).
[10] N. Hayashida, M. Nagano, D. Nishikawa, et al., Astropart. Phys. **10**, 303 (1999).
[11] A. Bellido, B.W. Clay, R.B. Dawson, and M. Johnston-Hollitt, astro-ph/0009039.
[12] A.G. Lyne and F. Graham-Smith, Pulsar Astronomy (Cambridge University Press, 1990).
[13] A.V. Glushkov and M.I. Pravdin, Zh. r Eksp. Teor. Fiz. **119**, 1029 (2001) [JETP **92**, 887 (2001)].
[14] A.V. Glushkov and M.I. Pravdin, Pis'ma Astron. Zh. **27**, 577 (2001) [Astron. Lett. **27**, 493 (2001)].
[15] A.V. Glushkov, Yad. Fiz. **67**, 983 (2004) [Phys. At. Nucl. **67**, 961 (2004)].
[16] A.V. Glushkov, Yad. Fiz. **68**, 262 (2005) [Phys. At. Nucl. **68**, 237 (2005)].