Anisotropy of ultrahigh-energy cosmic rays

N. N. Efimov and A. A. Mikhaĭlov
Institute of Space-Physics Research and Aeronomy, Siberian Branch of the Academy of Sciences of the USSR, Yakutsk Branch, 677891, Yakutsk

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An anisotropy has been found in the arrival directions of cosmic rays with energies $\sim 10^{19}$ eV. The galactic plane is predominant.

A study has been made of the arrival directions associated with extensive air showers generated by ultrahigh-energy cosmic rays which were detected at the Yakutsk extensive-air-shower apparatus, with an area ~ 18 km^2. Showers with zenith angles up to 60° over the years 1974–1990 were analyzed. A total of $\sim 30\,000$ showers with energies $E_0 > 10^{17}$ eV, including 275 with $E_0 > 10^{19}$ eV, were examined. The error in the determination of the energy of the primary particle generating the shower was $\sim 30\%$, and the error in the arrival angle was ~ 5–7°. No statistically significant anisotropy was found up to $E_0 \sim 5 \times 10^{18}$ eV. All showers with $E_0 > 5 \times 10^{18}$ eV were lumped in a single group, and the following values were found for the first two harmonics of a Fourier series: $A_1 = 13.8 \pm 4.4\%$, $\phi_1 = 7°$ and $A_2 = 6.5\%$, $\phi_2 = 44°$. The probability that the amplitude of the first harmonic could have resulted by chance from an isotropic particle distribution is $\sim 8 \times 10^{-3}$. The phase of the first harmonic indicates an anisotropy, specifically, a predominance of the galactic plane. With increasing energy, the amplitude of the first harmonic increases (at $E_0 > 8 \times 10^{18}$ eV, for example, we have $A_1 = 23.1 \pm 6.8\%$, $\phi_1 = 343°$ and $A_2 = 8.6\%$, $\phi_2 = 69°$).

We also determined the intensity ratio of the particles coming from the polar and equatorial directions of the local galaxy (Fig. 1). The same ratios were found from the catalog[1] of extensive air showers with $E_0 > 10^{19}$ eV detected at the Havera Park installations (Fig. 1).

At energies above 5×10^{18} eV, the flux of particles coming from the equatorial region of the galaxy is predominant. It is increasing with energy. The probability that this is a chance deviation from isotropy at $E_0 \sim 5 \times 10^{18}$–$4 \times 10^{19}$ eV is $\sim 10^{-10}$. At a qualitative level, this increase in the particle flux from the vicinity of the galactic plane agrees with a galactic model for the origin of these particles.

At $E_0 \geqslant 4 \times 10^{19}$ eV, the experimental data are sparse, so we cannot say that there is anything approaching a clearly defined trend. There is a possible hint of a predominance of the flux from high galactic latitudes.

Figure 1 shows the expected intensity ratios $I(|b| > 30°)/I(|b| < 30°)$ versus E_0 according to a galactic-origin model. The expected intensity was found by calculating individual trajectories of antiprotons starting at the earth by the method of Ref. 2, for a bisymmetric model of the disk magnetic field.[3] Outside the disk, in the halo, the magnetic field is assumed to be regular, with a predominant azimuthal component. Along with the regular components, it is assumed that there are field irregularities with average values equal to the regular components. These irregularities randomly

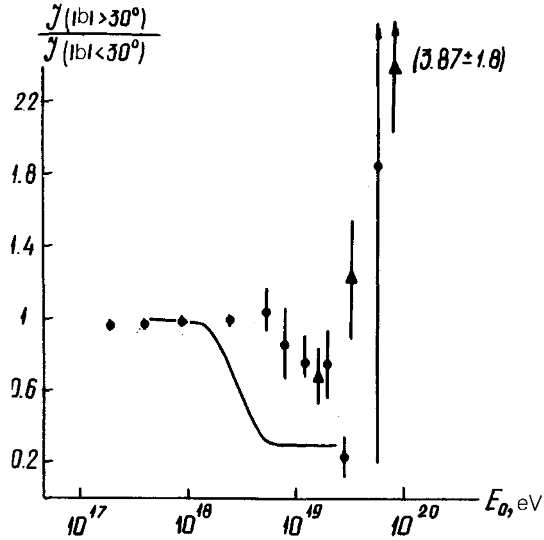

FIG. 1. Polar-equatorial ratio of particle intensities. ●—Yakutsk; ▲—Havera Park; curve—ratio expected in the case of protons from galactic sources. Shown in parentheses is the value of the intensity for the given point.

change in magnitude and direction at intervals of 0.1 kpc in the disk and 0.5 kpc in the halo. The disk has a half-height of 0.4 kpc and a radius of 15 kpc. The radius of the spheroidal halo is 15 kpc. The average value of the field in the disk is $\sim 2\ \mu$G, and the average value in the halo is $<1\ \mu$G.

It can be seen from Fig. 1 that the behavior observed experimentally does not agree with that expected on the basis of galactic sources, under the assumptions made here.

If we retain all the assumptions except the composition, the experimental dependence would correspond to a composition with $z \sim 8$ for the primary radiation.

In summary, the experimental data agree with the idea that cosmic rays with energies up to $\sim 4\times 10^{19}$ are primarily galactic and that the average nuclear composition may be $z \sim 8$.

[1]M. Wada (Editor), *Catalogue of Highest Cosmic Rays, Vol. 1,* 1980, p. 71.
[2]V. S. Berezinskiĭ and A. A. Mikhaĭlov, Pis'ma Astron. Zh. **10**, 269 (1984) [Sov. Astron. Lett. **10**, 112 (1984)].
[3]R. J. Rand and S. R. Kulkarni, Astrophys. J. **343**, 760 (1989).

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