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Correlations of arrival directions of ultrahigh energy cosmic rays with the large-scale structure of the universe

A. V. Glushkov and I. Ye. Sleptsov

Institute of Cosmophysical Research and Aeronomy 31 Lenin Ave., 677891 Yakutsk, Russia

Abstract. The analysis results of arrival directions of cosmic rays with the energy $E_o \geq 10^{18}$ eV and zenith angles $\theta \leq 45°$ registered at the Yakutsk array for 1974–2000 are presented. It is found that the increased particle fluxes with (4–5)σ excess relative to the expected levels for random distribution are observed from the Galaxy's plane at $E_o \approx (2\text{–}4)\times10^{18}$ eV and from the Supergalaxy's plane at $E_o \geq 8\times10^{18}$ eV.

1 Introduction

A search of sources of superhigh energy ($E_0 \geq 10^{17}$ eV) cosmic rays is a difficult task in astrophysics. Studies along this line are carried out all over the world more than 40 years but little is known about it. On a global scale the cosmic rays don't contradict to the isotropic distribution although at $E_0 \geq 10^{19}$ eV they point to a weak correlation in arrival directions with the galactic plane (see, for a example, Szabelsy et al., 1986; Afanasiev et al., 1995; Mikhailov, 1999) and also with supergalactic one (Stanev et al., 1995; Glushkov & Sleptsov, 2001). There are also some indications (Glushkov, 1988; Uryson, 1999) that active galactic nuclei can be the sources of them. It is shown by Glushkov & Pravdin (2001) and Glushkov & Sleptsov (2001) that cosmic ray flax varies with time.

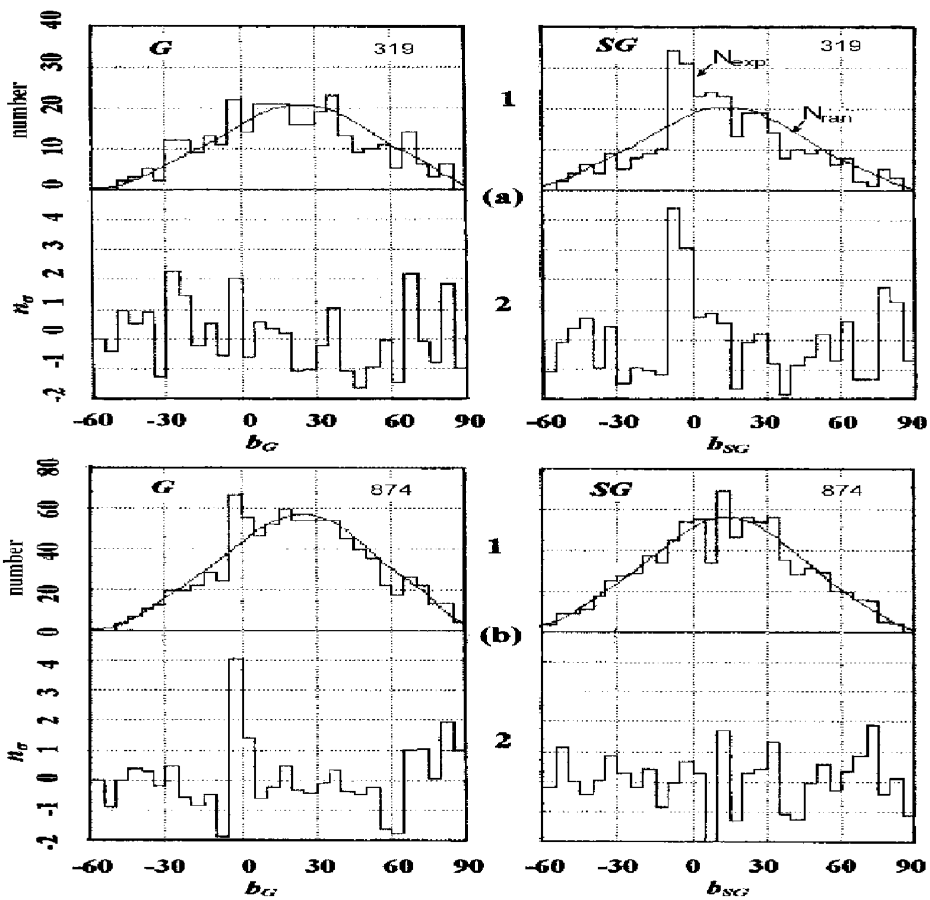

Fig.1

2 Characteristics under investigation and discussions

Below EAS with $E_0 \geq 4\times10^{17}$ eV and zenith angles $\theta \leq 45°$ registered at the Yakutsk array for 1974 to 2000 period are considered. The correlations of their arrival directions with the galactic and supergalactic planes have been investigated. EAS whose arrival directions were determined by data at ≥ 5 stations have been analyzed.

Fig.1*a* shows the distributions of in direction of 319 showers with $E_0 \geq 8\times10^{18}$ eV in galactic (G) and supergalactic (SG) coordinates depending on the latitude of their arrival. In the top (*1*) the observed (N_{exp}) and expected (N_{ran}) distributions are shown and at the bottom (*2*) there are deviations $n_\sigma = (N_{exp} - N_{ran})/\sqrt{N_{ran}}$. Values N_{ran} are found by a Monte-Carlo simulation.

It is seen that in the supergalactic plane there is a considerable excess of events. Thus, n latitude range Δb_{SG} = -10–0° there are 65 showers (expected ones are 35), with the excess $(65\text{- }35)/\sqrt{35} \approx 5\sigma$. The galactic plane in this energy region is not manifested itself except for a fact that in the range Δb_G = -5–0° there is a weak (≈ 2σ) positive burst.

Fig.1*b* shows the distributions in arrival directions of 874 EAS with $E_0 = (3\text{–}4)\times10^{18}$ eV. A noticeable peak is observed in the galactic plane ($|b_G| \leq 5°$) with the excess over the expected value by a factor of $(121\text{- }87)/\sqrt{87} \approx 3.6\sigma$. As to the Supergalaxy, it is not manifested itself in tuis energy region.

Fig.2 illustrates the distributions of values n_σ for showers arriving from the equatorial galactic region ($|b_G| \leq 10°$) with different E_0. Smooth curves show a behavior on the average. The magnetic fields of arms in the galactic disk (Lyne & Graham-Smith, 1999) are shown in Fig.2*e*. Open circles are an orientation of the field towards the observer, the dark ones – from the observer. The field intensity is proportional to the sizes of the circles.

We call attention to the consecutive change of the separate fragments of histograms. Here is seen the excess of particles from the anti-center at $E_0 = (2.5\text{–}4)\times10^{18}$ eV (*b*), which is also observed at high energies $E_0 \geq 5\times10^{18}$ eV (*a*). At $E_0 \approx (1.5\text{–}2.5)\times10^{18}$ eV (*c*) it becomes weaker and at $E_0 \approx (1\text{–}1.5)\times10^{18}$ eV (*d*) completely disappear. In the direction $l_G \approx 75°$(the exit of the Local arm of the Galaxy), on the contrary, at $E_0 \geq 5\times10^{18}$ eV (*a*) there is a trough which with the decrease of the primary particle energy up to $E_0 \approx 2\times10^{18}$ eV goes into a peak (*c*). The peaks in the sector $\Delta l_G \approx 105\text{–}145°$ at $E_0 < 4\times10^{18}$ eV (*b–d*) stand out sharply. At $E_0 = (2.5\text{–}4)\times10^{18}$ eV (*b*) the excess is $(690\text{-}581)/\sqrt{581} \approx 4.6\sigma$. Arrows are the line of the crossing of Galaxy and Supergalaxy disks ($l_G \approx 137°$).

Locations of the above mentioned peaks correlate with the locations of the galactic magnetic arms (Fig.2*e*). So, it is not improbable that the peaks and the dynamics of their changes at $E_0 < 4\times10^{18}$ eV are caused by the activity of these arms. In different energy intervals the a role of individual arms in origin of cosmic rays appears to be different.

The above-mentioned facts of the noticeable correlations in the arrival directions of cosmic rays with the Galaxy and Supergalaxy planes became possible due to a large statistics of the showers registered at the Yakutsk EAS array (about 37000 at $E_0 \geq 10^{18}$ eV). At the AGASA which is similar to our array by the type of detectors and methods of treatment of the shower, there are no analogous results yet. Here there is no contradiction. It is follows from Fig.3 where the distributions of arrival directions of EAS with energy $E_0 \geq 10^{19}$ eV in supergalactic coordinates (with a step $\Delta b_{SG} = 10°$) by both array data are given. The distribution by AGASA data has been obtained by us as a sum of there distributions (Takeda et al., 1999). Values n_σ are shown by histograms *2* (the Fig.1*b*).

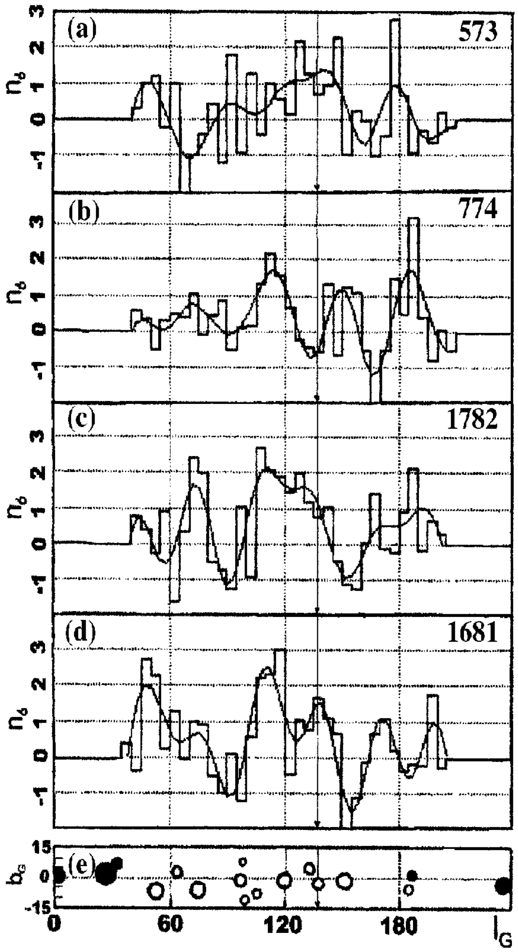

Fig.2

It is seen that although the initial distributions *1* in Fig.3 are different, the distributions *2* are similar with each other. Note some their important details. Firstly, the excesses of the registered events over expected ones by $(1.8\text{–}2.1)\sigma$ are observed in the range of latitudes $|b_{SG}| \leq 10°$ in both cases. Secondly, there are the troughs by ≈ -1.5σ symmetrically to the supergalactic plane at $|b_{SG}| \approx$ 10–20°. Against the background of these troughs the peaks from the supergalactic plane become more significant. It is indicative of there nonrandom character.

From the comparison of our data in Fig.1 and Fig.3 it is seen that the choice of the step $\Delta b_{SG} = 10°$ is inexpediently because it leads to the lower significance of results obtained. The real accuracy of the experiment is not worse than 2–3°.

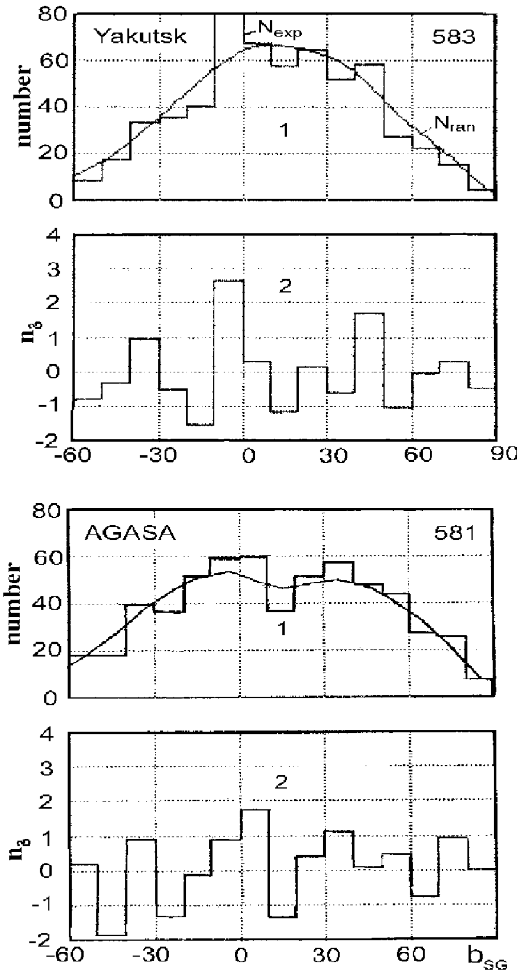

Fig.3

From the fact of the correlation between the arrival directions of primary particles at $E_0 \geq 8\times10^{18}$ eV and the Supergalaxy plane it follows that the particles of extragalactic origin should be electrically neutral. Otherwise, with the availability of the electric charge z the particle, depending on E_0, should move in the magnetic field along their trajectories of curvature radius $R = E_0/300Hz$. Even the protons with E_0 ~10^{19} eV B would have in the Galaxy (H ~ 3×10^{-6} G) R ~ 3 кpc, which is considerably smaller than the radius of the galactic disk (≈ 15 кpc). The intergalactic magnetic fields also, though they are weak (H ~ 9×10^{-10} G), give for the protons of the mentioned energies R ~ 10 Mpc, considerably less of the Supergalaxy diameter ≈ 50 Mpc. Under this conditions cosmic rays would lose the relation in the direction of movement with the structures of Galaxy and Supergalaxy but it is not observed.

It is unlikely that such particles are the neutrons. At E_0 ~ 10^{19} eV they have the Lorenz-factor ~ 10^{10} and can cover the distance up to its decay ~ 100 кpc which is many less than the size of the Supergalaxy. Most likely, they might be some other neutral particles.

We've come to a conclusion on the radical change of the composition of the primaries in the region $E_0 \geq 5\times10^{18}$ eV independent of the above considered data – as a result of the complex analysis of the spatial-temporal EAS structure by Yakutsk array data (Glushkov et al., 1998; Glushkov et al., 2000a; Glushkov et al., 2000b). In those works it is shown that at $E_0 \leq (1\text{–}3)\times10^{18}$ eV the experimental data are in agreement with calculations by the model QGSJET (Kalmikov et al., 1995) under the assumption, of the primary particles from the mixture enriched at E_0 ~ 10^{17} eV with the heavy nuclei (with z = 10–30 they are ≈ 63 ± 7% (Vishnevskaya et al., 1999)) to the easier one with E_0 ~ 10^{18} eV protons predominanting. At energies $E_0 \geq (3\text{–}5)\times10^{18}$ eV the showers develop by other way. They considerably change their lateral structure. These changes are not explained in the framework of the QGSJET model (at any composition of the primaries from protons to iron nuclei) and require other notions about the EAS development in these energy regions.

3 Conclusion

It is seen from the above data that the cosmic rays with $E_0 \leq 4\times10^{18}$ eV have the definite correlation on the arrival directions with the Galaxy plane and at $E_0 \geq 8\times10^{18}$ eV – mainly with the Supergalaxy plane. The above facts and results (Glushkov et al., 1998; Glushkov et al., 2000a; Glushkov et al., 2000b) count in favor of a hypothesis on the possible existence of neutral particles in the cosmic rays of the extragalactic origin.

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