Peculiarities of the EAS structure with $E_0 \geq 10^{17}$ eV arriving from different regions of the sky by Yakutsk array data

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Abstract: The energy spectrum of primary cosmic radiation (PCR) jointly with the lateral distribution function (LDF) of electrons and muons in extensive air shower (EAS) with the energy $E_0 \geq 10^{17}$ eV by data of the Yakutsk array for the 1974–2005 are presented. It is shown that in the separate energy intervals the spectrum and LDF are of different form for the events coming from the Supergalaxy (Local supercluster of galactics) disk and the rest part of the sky. It is interpreted as a manifestation of the possible interaction of the extragalactic PCR with a Supergalaxy gas under which, perhaps, new particles of superhigh energies are arisen.

Introduction

The lateral structure of extensive air showers (EAS) is one of the most information channel, when nuclear-physical EAS characteristics and the composition of primary cosmic radiation (PCR) in the ultrahigh energy region are studied. The investigation results of the lateral distribution function (LDF) for the muons with the threshold energy $E_\mu \cong 1.0 \sec\theta$ GeV and for all charged particles (electrons and muons) are presented in [1–7]. In those papers, the anomalous behavior of the two LDFs at $E_0 \geq (3–5)\times10^{18}$ eV has been discovered. It is related to some new development process of EAS. There are experimental evidences [8–17] of possible existence of two PCR component at $E_0 \geq (3–5)\times10^{18}$ eV, where irregularities in the EAS development are observed. The results of joint analysis of astrophysical and nuclear-physical characteristics of EAS which contain new information on the origin of PCRs.

Investigated characteristics and discussion

It is shown [17] that a form of the energy spectrum depends on sky regions from which PCRs arrive. This is evident in Fig.1, where open circles are the integral spectrum of primary particles arriving immediately from the equatorial region of the Supergalaxy (Local supercluster of galaxies). The solid circles are "background" spectrum constructed in just the same way from 22465 showers whose the arrival directions have latitude $|b_G| >$ 10° and $|b_{SG}| >$ 10°. In our opinion, some important moments have engaged our attention at once. In the first place, in the Supergalaxy disk, the excess radiation exceeding "background" spectrum is clearly seen. It is noticeable enhanced (crosses), if the more narrow sector ($100° < l_{SG} < 130°$) is taken with the maximum flux of particles in the direction with the equatorial coordinates $\alpha \approx 79°$ and $\delta \approx 74°$. Secondly, at $5\times10^{17} < E_0 < 2\times10^{18}$ eV from the Supergalaxy disk the particles arrive by (10-15)% less then it is observed as a whole for the rest part of sky.

Further, consider LDFs of muons with a threshold energy $E_\mu \approx 1.0\cdot\sec\theta$ GeV and all charged particles. Let us assume the methods to construct LDFs of the two components from [4]. The structural parameters b_s and b_μ of LDF are one of the most sensitive to the models of EAS development and PCR composition:

$$\rho_s(R) \propto (R/R_m)^{-1.3}(1+R/R_m)^{1.3-bs}(1+R/2000)^{-1}, \quad (1)$$

$$\rho_\mu(R) \propto (R/R_0)^{-0.75}(1+R/R_0)^{0.75-b\mu}(1+R/2000)^{-6.5}, \quad (2)$$

where R_m is the Moliere radius (for the Yakutsk array $< R_m > \approx 70$ m), $R_0 = 280$ m. Their dependencies on E_0 are shown in Fig.2 for the showers with zenith angles $\cos\theta \geq 0.9$ by the solid and open circles. The straight lines *1* and *2* are the calculated dependencies by the QGSJET model for the primary proton (*p*) and iron nucleus (*Fe*) [4].

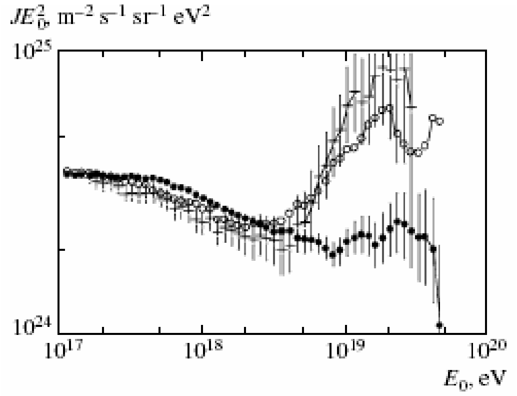

Figure 1: Integral energy spectra: filled circles—for 22465 air showers with arrival directions outside the equatorial regions of the Galaxy and the Supergalaxy ($|b_G| > 10°$ and $|b_{SG}| > 10°$); open circles—for 4295 air showers in the Supergalactic latitude band $-8° < b_{SG} < 2°$; and crosses— for air showers from the sky region with $-8° < b_{SG} < 2°$ and $100° < l_{SG} < 130°$.

We see from Fig. 2 that the parameter b_S is roughly consistent with the QGSJET model under the assumption that the PCR composition changes from iron nuclei at $10^{17} < E_0 < 3\times10^{18}$ eV to protons at $E_0 \approx 3\times 10^{18}$ eV and then again rapidly returns to iron nuclei with increasing energy. In contrast, the parameter b_μ is in conflict with this change in PCR composition. Note, however, that the energy dependencies of both b_s and b_μ in Fig.2 change sharply approximately at the same place where the above changes in energy spectrum are observed.

In this connection it is of interest to find the LDF of muons for the events from the different regions of sky. We constructed this LDF for two regions of sky relating to different spectra in Fig.1. The parameter b_μ for LDF of muons with $\cos\theta \geq 0.9$ relating to the "background" spectrum in Fig.1, i.e. to showers whose the arrival directions have $|b_{SG}| > 10°$ is presented in Fig.3 by solid circles. The open circles are the parameter b_μ that relates to the LDF of muons for the events with $|b_{SG}| < 10°$. To eliminate any methodological distortions of this function related to the large change in the number of events at small and large distances from the EAS axis with E_0, we will study the distribution function only in the distance range $\Delta R = 150$–600 m, which is statistically fully represented in the entire primary energy range.

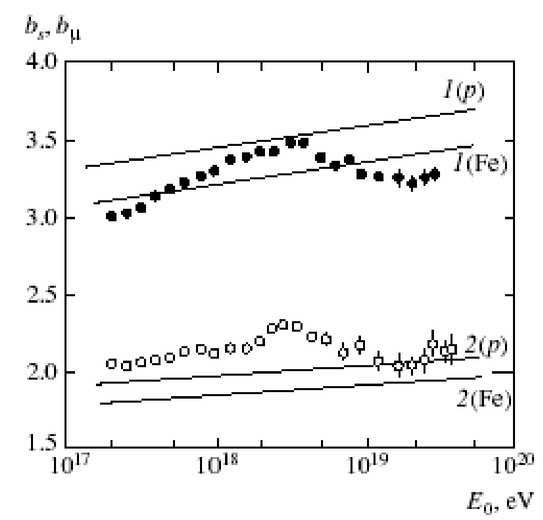

Figure 2**:** Parameters b_S (filled circles) and b_μ (open circles) of fits (1) and (2) versus E_0 in air showers with zenith angles $<\cos\theta> = 0.95$.

We see that the two samples of air showers at $E_0 \leq 10^{18}$ eV yield approximately the same result. In contrast, at $E_0 > 10^{18}$ eV, the picture is completely different; it suggests a different EAS development for events from different sky regions, with it being similar, within the experimental error limits, for air showers referring separately to the Supergalactic and Galactic disks. There fore, we combined these two sky regions when constructing the lateral distribution functions to increase the statistical accuracy. Here, we emphasise once again that Fig.3 (like Fig.2) indicate not $< b_\mu >$ found by averaging the individual values of this parameter in each EAS, but $< b_\mu >$ from the mean distribution functions including all the events in the energy bin $\Delta \log E_0 = 0.2$ when this bin is successively shifted by $\Delta \log E_0 = 0.1$.

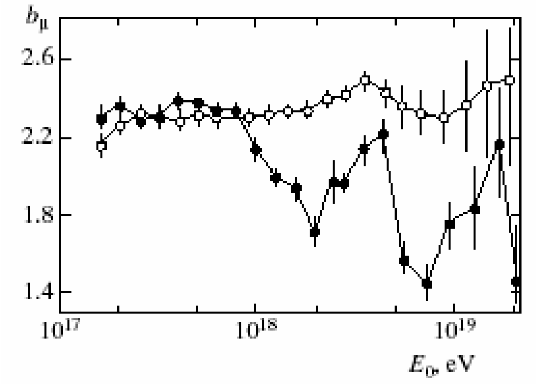

Figure 3: Parameter b_μ of fit (2) versus energy E_0 of EASs with zenith angles $<\cos\theta> = 0.95$: open circles — air showers with arrival direction from the equatorial region of the Galaxy and the Supergalaxy latitude ($|b_G| < 10°$ and $|b_{SG}| < 10°$); filled circles — air showers with arrival directions outside these regions (included in the "background" spectrum in Fig.1).

The results in Fig.3 can be understood if some new particles are assumed to be produced as extragalactic PCRs collide with the Supergalactic and Galactic gas. This process can be arbitrarily represented as the reaction

$$x + p \rightarrow y + s \qquad (3)$$

for the interaction of as yet unknown primary particles x with protons (p) of atomic hydrogen, the main gas component of the Supergalaxy and the Galaxy; y is the new ultrahigh energy particle that produces EAS; and s is one or more additional particles required for the laws of conservation of energy, momentum, etc. to be obeyed. We assume that both particles, x and y, can produce EASs with different characteristics. This is probably reflected in the different dependencies b_μ (E_0) in Fig.3. Reaction (3) is probably a threshold one and does not take place at $E_0 \leq 10^{18}$ eV.

Conclusions

We analysed the series of experimental data obtained on the Yakutsk EAS array in an effort to refine further the possible PCR composition. As a result, we found the following correlated astrophysical and structural peculiarities of EASs. At energies $E_0 \geq (3–5)\times10^{18}$ eV, the spectrum from the Supergalactic disk in Fig.1 runs above the background spectrum. This is accompanied by an anomalous change in the shape of the lateral distribution functions for muons and all charged particles in the form of a decrease in the structural parameters b_S and b_μ of fits (1) and (2) in Fig.2. The distribution function of the muons from primary particles with $E_0 \geq 10^{18}$ eV arriving from the Galactic and Supergalactic disks proved to be completely different than that for events from the remaining sky regions (Fig.3).

We believe that the PCRs with $E_0 \geq 10^{17}$ eV consist of two components [8–17]. One of these components is extragalactic in origin, consists of neutral particles, and can be generated by quasars [16]. On their way to the Earth, the ultrahigh energy neutral particles pass through the Supergalaxy and the Galaxy. It can be assumed that some fraction of them enter into nuclear regions (3) with the gas of these structures. The gas is most densely concentrated in the Galactic and Supergalactic disks, in regions with angular sizes in latitude $|b| \approx 5°–10°$. The excess PCR flux at $E_0 \geq$. $(3–5)\times 10^{18}$ eV in Fig.1 and the irregularities of the lateral distribution functions for all charged particles and muons in Fig.2 and Fig.3 may be attributable to this factor.

As regards the energies $(3–5)\times 10^{17} \leq E_0 \leq 2\times 10^{18}$ eV, a substantial fraction of extragalactic PCRs is also present here. The decrease in intensity in Fig.1 compared to the "background" spectrum can be interpreted as the absorption of extragalactic particles interacting with the Supergalactic matter.

Acknowledgements

This work was supported by the Russian Foundation for Basic Research (project N 05-02-17857).

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