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Spectra of Above 10^{17}eV Cosmic Rays from the Different Sky Regions by Yakutsk EAS Array Data

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The analysis results of the energy spectrum of the primary cosmic rays with $E_0 \geq 10^{17}$ eV based on Yakutsk EAS array data for the period of 1974-2004 are presented. It is shown that the spectra from the different sky regions are differed among themselves in form. The increased particle fluxes at $E_0 \geq 5\times10^{18}$ eV and the decreased fluxes at $E_0 \leq (2–3)\times10^{18}$ eV arrive from the Galaxy and the Supergalaxy (Local superclusters of galaxy). It is interpreted as the manifestation of the possible interaction of extragalactic primary cosmic rays with the matter of the above space structures.

1. Introduction

Ultrahigh energy cosmic rays ($E_0 \geq 10^{17}$ eV) are registered at the Yakutsk extensive air shower (EAS) array from 1970 and under stable operating conditions from 1974. For that period, as the experimental data were accumulated, we reported our results on the energy spectrum of primary cosmic rays (PCRs) [1–5]. The form and intensity of the spectrum in the cut-off region (~ 10^{20} eV) predicted by Zatsepin, Kuzmin and Greisen [6,7] are of great importance to reveal the PCR composition and sources of their generation. The intensity is not described by the single power dependence. The spectrum form at $E_0 > 10^{19}$ eV corresponds to the assumption that the main PCR flux is formed in the extragalactic sources [8,9].

So far the energy spectrum was studied without considering the location of the sky region from where PCRs were arrived. Further we consider the influence of this factor on the energy spectrum and a problem of origin of PCRs with $E_0 \geq 10^{17}$ eV on the whole.

2. Method of analysis and results

The determination of the primary particle energy and their flux intensity at the Yakutsk array is made using classification parameters which are found with minimum distortions [5]. However, the severe selection of showers for the energy spectrum in [1–5] leads to the loss of almost all data with $E_0 < 4\times10^{17}$ eV. The reason is that only the showers registered most effectively are selected (with the probability ≥ 0.9), which are detected with the master stations when ≥ 8 particles passage through them. In fact, this criterion is necessary to estimate correctly the collection area of events (at given E_0 and θ), which is calculated by a numerical simulation of the whole of experiment. Here the fluctuations of EAS development play an important role, which is not always and in full measure known.

We analyze in addition the events with $10^{17} \leq E_0 < 10^{18}$ eV from the point of view of the possibility of the more full their use to construct the energy spectrum. It is turned out that the effective area for the registration of such showers can be determined empirically. It demonstrates the spectrum in Figure1 shown by the open circles. It is found for the EAS with $\cos\theta \geq 0.6$ when all data are divided into intervals with a step of $\Delta \lg E_0 = 0.05$. To estimate the EAS energy the following relations are used:

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

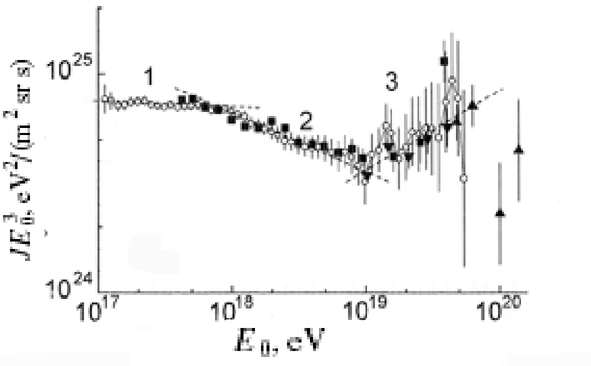

Figure 1. Differential energy spectrum by the Yakutsk EAS array data: o – the present work; our results [5] for the small (■) and big (▼) masters within boundaries of the array; ▲ – the sampling of events with $E_0 \geq 4\times10^{19}$ eV in extended area with the exit of cores beyond the array; the dashed lines are approximations $J(E_0) \sim E_0^{-\gamma}$ with $\gamma_1 = 3.02 \pm 0.02$, $\gamma_2 = 3.27 \pm 0.05$ и $\gamma_3 = 2.62 \pm 0.17$.

$$\rho_{s,600}(0°) = \rho_{s,600}(\theta) \exp((\sec\theta - 1)\, 1020/\lambda_\rho) \quad [\mathrm{m}^{-2}], \tag{2}$$
$$\lambda_\rho = (450 \pm 44) + (32 \pm 15)\, \lg(\rho_{s,600}(0°)) \quad [\mathrm{g/cm^2}], \tag{3}$$

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 core. In all, we selected 35935 showers in this way.

In the energy region of $10^{17} \leq E_0 < 10^{18}$ eV we consider only 6 master triangles inside the central circle of array with the radius R = 500 m. The spectrum contains all showers selected by any of those triangles without the selection in the number of particles passed through the stations. Thereby, it is necessary that a shower core should be fallen into a circle with the radius r inscribed in one of 6 master triangles. The unknown intensity (at given E_0 and θ) was found by increasing the size of these circles (beginning with r_1 = 20 m) by way of the sequential increase of their radius $r_i = 20 + 10(i - 1)$ until it begins to fall. In this case, $i + 1$ iteration for the intensity in the given range of energies (with a step $\Delta\lg E_0 = 0.05$) stopped and restored (with r_1 = 20 m) in the following energy region.

In [10–16] it is shown that at $E_0 \geq 10^{17}$ eV in the arrival directions of PCRs there are the noticeable deviation of the particle flux from the isotropy. We suppose that this PCR peculiarity can be reflected in the energy spectrum found for the events from the different regions of the sky. Figure2*a* presents the spectra from north and south latitudes of the Galaxy. Here the north-south asymmetry is well noticeable at $5\times10^{18} < E_0 < 2\times10^{19}$ eV which has been noted by us earlier [10–16]. The PCR statistically significant excess from south latitudes is also observed in the lower energy region with the maximum at $E_0 \approx 5\times10^{17}$ eV. Figure2*b* demonstrates two approximately identical samplings of the showers arriving from south latitudes. The spectrum of one of them has the events from the latitude band of $10° < b_G < 0°$ immediately related to the Galaxy's disk. The second sampling includes more southern latitudes $b_G \leq -10°$. It is seen that namely it forms the above spectrum irregularity at $E_0 \approx 5\times10^{17}$ eV.

The spectrum of particles arriving directly from the Galaxy's disk (Figure3*a*) is of special interest. We consider the sampling (3713) of showers with the arrival directions in the latitude band $|b_G| \leq 5°$ (open circles). Here the disk is in the sector with galactic longitude $40° < l_G < 200°$ accessible to observe at the Yakutsk array. The dark circles denote a "background" spectrum constructed in the same way from 22465 showers whose arrival directions have $|b_G| > 10°$, i.e. lie outside of the equatorial region of the Galaxy.

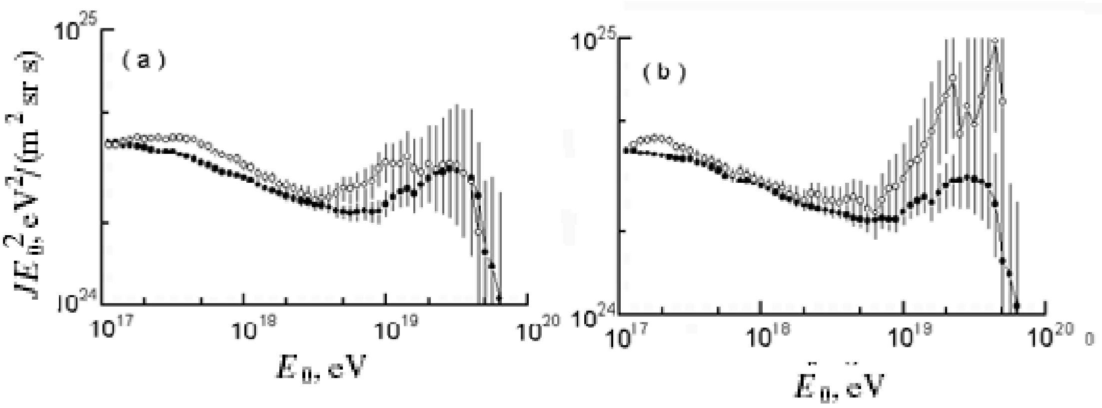

Figure 2. Integral energy spectra: *a* is for 28431 and 7504 showers with the arrival directions in the north (•) and south (o) hemispheres of the Galaxy; *b* is for 3270 and 4234 showers with arrival directions $-10° < b_G < 0°$ (•) and $b_G \leq -10°$ (**o**).

Figure3*a* shows the excessive radiation from the Galaxy's disk at $E_0 > (5–7)\times10^{18}$ eV noticeable exceeding the background radiation. The maximum contribution is in the region of intersection of the Galaxy and Supergalaxy planes at the galactic longitude $l_G \approx 137.4°$ [14–17]. At $E_0 < 5\times10^{18}$ eV the two spectra are almost indistinguishable. It is not apparently in agreement with the results of [18] where the particle flux is detected from the central region of the Galaxy. In Figure3*a* there is only some systematic decrease of intensities in the spectrum from the Galaxy's disk in the interval of $5\times10^{17} < E_0 < 2\times10^{18}$ eV with the small peak at $E_0 \approx 10^{18}$ eV.

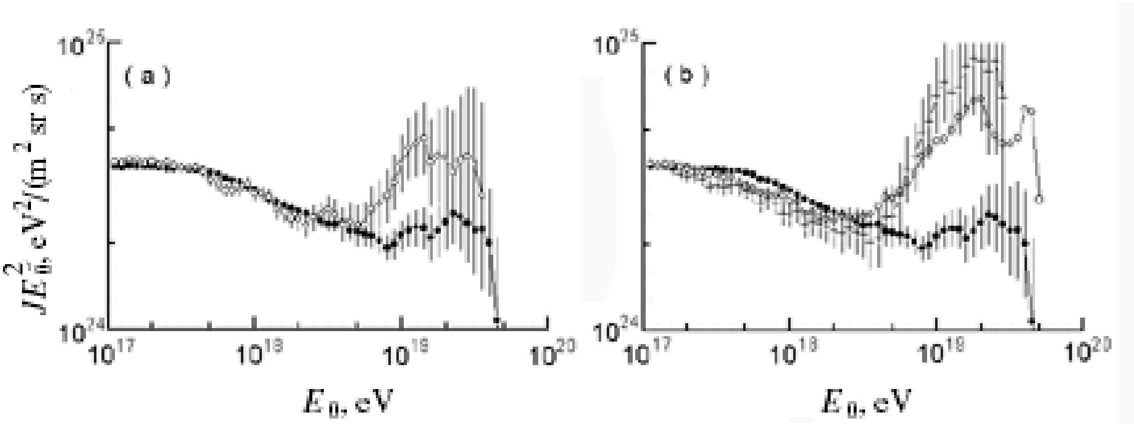

Figure 3. Integral energy spectra: • for 22465 showers with the arrival directions outside of the equatorial regions of the Galaxy and the Supergalaxy ($|b_G| > 10°$ and ($|b_{SG}| > 10°$); **o** for 3713 showers with latitude $|b_G| \leq 5°$ of the Galaxy (*a*) and 4295 showers in the latitude band $-8° < b_{SG} < 2°$ of the Supergalaxy (*b*); + for the showers from the sky region with $-8° < b_{SG} < 2°$ and $100° < l_{SG} < 130°$.

Consider in addition the spectrum from the Supergalaxy's disk from where according to our data the exceeding PCR flux arrives. It is plotted in Figure3*b* as the open circles and includes 4295 showers. We constructed the spectrum for the events from the regions with supergalactic latitudes $-8° < b_{SG} < 2°$. The errors of the intensities are not shown in order for the picture is not overloaded (they are approximately the same as in the spectrum from the Galaxy's disk in Figure3*a*).

Here the some important moments have engaged our attention. In the first place, the excess radiation exceeding the radiation from the Galaxy's disk is clearly seen at $E_0 \geq 5\times10^{18}$ eV in the equatorial region of the Supergalaxy. If the more narrow sector ($100° < l_{SG} < 130°$) is taken in the Supergalaxy's disk, then it is noticeable enhanced (crosses) with the maximum of the particle flux in the direction with equatorial coordinates $\alpha \approx 79°$ и $\delta \approx 74°$. Second, at $5\times10^{17} < E_0 < 2\times10^{18}$ eV from the Supergalaxy's disk the number of particles arrives by ≈(10−15)% less than it is observed for the rest part of the sky in the "background" spectrum.

3. Conclusions

Previously we reported [10−12] that PCRs with $E_0 \geq 10^{17}$ consist, probably, of two components. One component is of extragalactic origin and can be generated by the quasars [12]. The Supergalaxy and Galaxy matter structure is visible through the ultrahigh energy particles on their way to the Earth. It is believed that a portion of the particles enter into the nuclear reactions with a gas of these structures. The gas is concentrated more compactly in the disks of the Galaxy and Supergalaxy in the regions with the angular sizes in latitude $|b| \approx 5° - 10°$. The excessive PCR fluxes at $E_0 \geq 5\times10^{18}$ eV in Figs.2 and 3 are probably due to by this property. In the region of visible intersection of the Galaxy and Supergalaxy planes (at $\alpha \approx 40.6°$ and $\delta \approx 59.5°$) the fluxes are probably summed and lead to a local extremum with the absolute maximum detected in the work [13]. The intensity at $E_0 \geq 2\times10^{19}$ eV is about 4 times more than the "background" spectrum intensity (Figure3*b*). As $(3–5)\times10^{17} \leq E_0 \leq 2\times10^{18}$ eV, here also apparently there is the noticeable portion of extragalactic PCRs [12]. The decrease of intensities in Figure3*b* in comparison with the "background" spectrum can be interpreted as the absorption of extragalactic particles interacting with the matter of the Supergalaxy and Galaxy. It is not improbable that the two structures are the targets for the particles generated by the quasars and other galaxies with active nuclei.

4. Acknowledgements

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