Energy Spectrum of Primary Cosmic Rays in the Energy Region of $10^{17} - 10^{20}$ eV by Yakutsk Array Data

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Abstract

The energy spectrum of primary cosmic rays by Yakutsk EAS array data obtained by using the more precise relation of $S300$ and $S600$ parameters to the energy has been presented. The spectrum is compared with the results of other arrays.

1. Introduction

Experimental results concerning the energy spectrum in the $> 10^{17}$ region obtained at the different arrays [1, 3, 4, 6] show the same form of spectrum but they differ by a factor ~ 2 in absolute intensity. The intensity change is not described by the single power dependence. Detailed investigations of cosmic rays and features of showers in this energy region remain actual. The spectrum form is indicative of a source of cosmic rays in the ultrahigh energy region. In the work [2] the results obtained are interpreted as the confirmation that the active nuclei galaxies are the main source of $E_0 > 10^{19}$ particles. At $E_0 > 10^{20}$ eV in the AGASA experiment the intensity exceeds considerably the value estimated by HiRes and Yakutsk data.

2. Selection of Events and Determination of Energy

The Yakutsk EAS array is of two triggers. The *trigger-1000* consists of the stations located at the total area and forming a grid of triangles with each side equal to 1000 m. The *trigger-500* occupies a part of area of the array and consists of triangles with the 500 m side. After 1992 the area of *trigger-500* is increased from 2.5 km^2 to 7.5 km^2. It allows to investigate the spectrum in the region of $2 \cdot 10^{17} - 3 \cdot 10^{19}$ eV using uniform conditions for the selection of events.

Events are selected in which the particle density > 2 m^{-2} is registered at 3 stations forming the trigger triangle. As a classified parameter, characterizing

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the shower size for events selected by the *trigger-500*, a parameter $S300$ is used that is the density at the distance of 300 m from a shower core, and $S600$ for the *trigger-1000*. These parameters depend to a smaller degree on the change of the lateral distribution function (LDF) which is used in the standard treatment of experimental data. To determine the intensity we use the effective area, within limits of which the probability to detect events taking into account fluctuations in the LDF slope is ≥ 0.9. The summary exposure (ST is area $\times$ time) depending on $S300$ or $S600$ and the zenith angle ϑ is calculated taking into account the stations operated really in the given moment.

Here we use the more precise correlations between $S300$, $S600$ and the primary particle energy which are presented in another our work at the present conference in detail. For the atmospheric depth $X = 1020$ g cm^{-2} ($\theta = 0^o$) by using a calorimetric method the following relationship are found:

$$E_0 = (6.5 \pm 1.6) \cdot 10^{16} \cdot S300(0^o)^{0.94 \pm 0.02} \text{ eV} \tag{1}$$

$$E_0 = (4.6 \pm 1.2) \cdot 10^{17} \cdot S600(0^o)^{0.98 \pm 0.03} \text{ eV} . \tag{2}$$

To determine the primary energy for the individual shower by (1), (2), the value $S300$ or $S600$ for the zenith angle θ must be recalculated to $\vartheta = 0^o$. For this purpose we use the dependence in the form [4]

$$S(\vartheta) = S(0^o) \cdot (1 - \beta) \cdot \exp\left((X_0 - X)/\lambda_E\right) + \beta \cdot \exp\left((X_0 - X)/\lambda_M\right), \tag{3}$$

where $\lambda_E = 200$ g cm^{-2} is the path length for the soft component, $\lambda_M = 1000$ g cm^{-2} is the path length for the hard component, β is a portion of the hard component in the whole response of $S300(0^o)$ or $S600(0^o)$ at the depth 1020 g cm^{-2}.

For the dependence of β on $S300(0^o)$ and $S600(0^o)$ from experimental data the following formulae are found:

$$\beta_{300} = (0.563 \pm 0.032) \cdot \ S300(0^o)^{-0.185 \pm 0.02} \tag{4}$$

$$\beta_{600} = (0.62 \pm 0.06) \cdot \ S600(0^o)^{-0.076 \pm 0.03}, \tag{5}$$

which allow to estimate the energy in a shower with $\vartheta < 60^o$.

3. Energy Spectrum

The Figure 1 presents the energy spectrum by Yakutsk EAS array data determined by a sampling of showers with $\theta < 60^o$. Trigger-500 (solid circles) data are mainly used. Solid triangles are the intensity at $E_o > 3 \cdot 10^{19}$ eV by trigger-1000 data. New data confirm the irregular behavior of the spectrum from 10^{18} to $3 \cdot 10^{19}$ eV, and in this energy region peculiarities noted previously are observed ("deep", "bump").

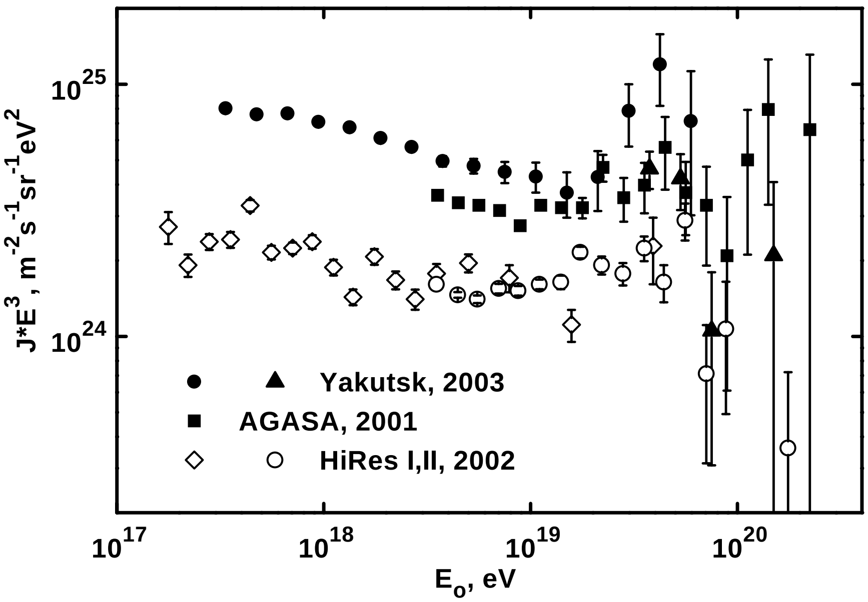

Fig. 1. The differential energy spectrum of cosmic rays with $E_0 > 10^{17}$ eV

Spectra obtained by AGASA [6], HiRes [1] array data are also given in this Figure. Results of different arrays in the region of ultra-high energies are contradictory. At present, at the AGASA array 17 events with $\theta < 60^o$ and $E_0 > 10^{20}$ eV have been registered. Although new formulae give the several increase in estimations of E_0 in the ultra-high energy region, at the Yakutsk array only one shower with $E_0 > 10^{20}$ eV (1.3×10^{20} eV) has been detected. If the effective area is not limited by an array area and if to use data with $\theta \leq 60^o$ then the total exposure for the largest size showers will be 3.1×10^{16} m^2 s sr. In this case, ~ 6 such events must be observed. At the HiRes array just as in Yakutsk one event with $E_0 > 10^{20}$ eV has been detected.

The energy spectrum obtained at the HiRes array is consistent with Yakutsk data in form quite well but it is distinguished in intensity by a factor of 2.5. Most likely it is associated with the difference in the energy determination. If in Yakutsk data the energy estimation will be decreased by a factor of 1.5, then results for two the experiments are consistent with each other quite well.

4. Conclusions

The analysis results of Yakutsk EAS array data by using more precise estimations in the energy determination by $S300$ confirm the irregular behavior of the spectrum at $10^{18} - 3 \cdot 10^{19}$ eV and are consistent with the previous results and data of other arrays. However, in the region of $E_0 > 10^{20}$ eV there is the contradiction in results obtained at the Yakutsk and HiRes arrays in comparison with the AGASA array.

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