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Energy Spectrum of Cosmic Rays at $E_O>10^{17}$ eV by Yakutsk EAS Array Data

M.I. Pravdin[1], M.N. Dyakonov[1], A.V. Glushkov[1], T.A. Egorov[1], V.P. Egorova[1], A.A. Ivanov[1], G.B. Khristiansen [2], S.P. Knurenko[1], V.A. Kolosov[1], A.D. Krasilnikov[1], I.T. Makarov[1], S.I. Nikolsky[3], V.A. Orlov[1], I.Ye. Sleptsov[1], V.R. Sleptsova[1], G.G. Struchkov[1]

[1] *Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677891 Yakutsk, Russia*

[2] *D.V.Skobeltsyn Institute of Nuclear Physics, MSU, Vorob'evy gory, 119899 Moscow, Russia*

[3] *P.N.Lebedev Physical Institute, 53 Leninsky Prospect, 117274 Moscow, Russia*

Abstract

The energy spectrum of primary cosmic rays with the energy $E_O > 10^{17}$ eV by using the Yakutsk EAS array data is presented. The experimentally obtained relation between E_O and S300 (the particle density at the distance of 300 m from a shower core) and the comparison with calculations according to the QGSJet model are given. The irregularity of a spectrum form in the region of $2\cdot10^{18}$ - $4\cdot10^{19}$ eV using the single parameter S300 is also investigated. The obtained energy spectrum is compared with the last AGASA results.

1 Introduction:

Experimental results on the energy spectrum in the energy region of 10^{18} - $4\cdot10^{19}$ eV obtained at different arrays (Afanasiev et al., 1995), (Yoshida et al., 1995, Takeda et al., 1998), (Bird et al., 1994) differ by a factor of 2 with each other in absolute intensity but their spectrum form is the same. The change of intensity is not described by the unique power dependence. At the energy 10^{18} eV the spectrum becomes steeper in comparison with lower energies ("dip") and beginning with $\approx10^{19}$ eV it becomes flatter ("bump"). In spite of the coincidence of the spectrum form in different experiments, the detailed investigations of cosmic rays and shower features in this energy region remain actual. At present time it cannot be excluded that the observed peculiarities are not associated with a distortion when the energy is determined either because of the change of shower peculiarities or due to the reasons of methodical character. The earlier published results from the Yakutsk array are based on the joint consideration of two different trigger data. It creates the additional methodical uncertainty.

At the Yakutsk array the events are selected when the signals from three neighboring stations forming equilateral triangle are in coincidence. The trigger system is of two types of combinations. The trigger-1000 is consists of the stations arranged in the whole area in the form of a grid of triangles of side 1000 m. The trigger-500 occupies a part of the array area. It consists of the triangles of side 500 m.

In 1990 – 1992 a scheme of the station arrangement was changed (Afanasiev et al., 1996). 10 stations at the periphery of array were disassembled. As a result, the total area is 10 km^2 instead of 16 km^2 and the number of 1000m triangles is 24 instead of 40. However, in this case 18 new stations were located on the remained area in such a way that the number of 500m triangles increased from 24 to 63 and their total area increased from 2.5 km^2 to 7.2 km^2. Such a configuration of the array is aimed at the complex investigation of primary radiation characteristics in the energy interval of $2\cdot10^{17}$ - $2\cdot10^{19}$ eV with more uniform selection conditions of events. In this paper we present the results on the energy spectrum by using new data.

2 Selection and Classification of Events:

To investigate the energy spectrum we select the events when at three stations forming the trigger triangle the density more than 2 m^{-2} is registered. As a classification parameter which characterizes the shower value we use a density at the distance 300 m from a core (S300) for events selected by the trigger-500 and S600 for the trigger-1000. Such parameters to a lesser degree depend on a change of the lateral distribution function (LDF) which is used at the standard treatment of experimental data.

To define the intensity of events we use the effective area within of which the registration probability of events is not less than 0.9 taking into account the LDF slope fluctuations. A summary exposure (ST – area*time) depending on S300 or S600 and zenith angle θ is calculated with regard for substantively operating stations.

3 Determination of Energy:

The relation between parameters S300, S600 and primary particle energy for showers close to the vertical has been determined by the calorimetric method (Diminstain et al., 1975). The basis of this method is an experimental estimation of the energy dissipated by a shower above the observation level, by using Cerenkov EAS light measurements. By these measurements the main portion of primary energy (>80%) is controlled. The other components are estimated by measurements of the electron and muon flux at the observation level. A contribution of the negligible part of the total energy (≈5%) which cannot be determined from experimental data we took according to calculations for modern models of shower development.

By this procedure for the atmospheric depth X=1020 g·cm^2 (θ=0°) we obtained the following relations:

$$E_O = (5.87 \pm 1.23)\cdot 10^{16}\cdot S300(0°)^{0.96 \pm 0.02} \quad (1)$$

$$E_O = (4.85 \pm 1.06)\cdot 10^{17}\cdot S600(0°)^{0.98 \pm 0.02} \quad (2)$$

The uncertainty of the absolute calibration of the Cerenkov light detectors makes a main contribution into the error in (1), (2). This uncertainty is constant for all energies and doesn't influence the energy spectrum form .

In calculations by the QGSJet model (Glushkov et al., 1999) the constant multiplier in (1), (2) is 30-35% less and a power index is 0.98 for S300 and 1.02 for S600.

To determine the primary energy in individual showers by formulae (1), (2) it is necessary to re-calculate S300 or S600 for the zenith angle θ to θ=0° by corresponding absorption path length λ300 for S300 and λ600 for S600. For determination of the absorption path length we studied a change of S300 and S600 depending on the parameter Q400 (a Cerenkov light flux density at a distance 400 m from a core) for the different zenith angles. Q400 is a good equivalent of the primary energy which does not practically depend on θ, if to take into account the light absorption in the atmosphere. In the framework of such a consideration we obtained the following formulae for λ300 and λ600:

$$\lambda 300 = (288 \pm 18) + (60 \pm 7)\cdot \mathrm{Log}(E_O/10^{18}) + (191 \pm 12)\cdot(\sec(\theta) - 1) \quad (3)$$

$$\lambda 600 = (458 \pm 43) + (45 \pm 12)\cdot \mathrm{Log}(E_O/10^{18}) + (300 \pm 52)\cdot(\sec(\theta) - 1) \quad (4)$$

The same parameters may be determined from the relevant spectra in different intervals of zenith angle. Figure 1 demonstrates S300 at different atmospheric depth X which correspond to the fixed intensity for spectra in different angular intervals. For comparison, S300(X) are given which were calculated for the energy corresponding to this intensity by formulae obtained by Q400. The analysis was carried out for showers with θ < 45°. Both these methods give close results in the energy region of $4\cdot 10^{17}$ - $2\cdot 10^{18}$ eV and X<1400 g·cm^2 within the experimental error. However, for most inclined showers some systematic difference is observed as the energy increases.

4 Energy Spectrum:

The energy spectrum was determined by data of the showers with $\cos(\theta)<0.7$ separately for each trigger. The energy for individual events was determined by formulae (1 – 4).

For the trigger-500 the maximum area was 2.5 km^2 from September 1979 to June 1992 and it was 7.2 km^2 from September 1992 to May 1998. The total exposure equals $2.2 \cdot 10^{15}$ $m^2 \cdot s \cdot sr$ that is 1.64 times more than in previous paper (Afanasiev et al., 1995). The exposure for the trigger-1000 ($9.9 \cdot 10^{15}$ $m^2 \cdot s \cdot sr$ for the period from September 1974 to May 1998) increased only by 15%.

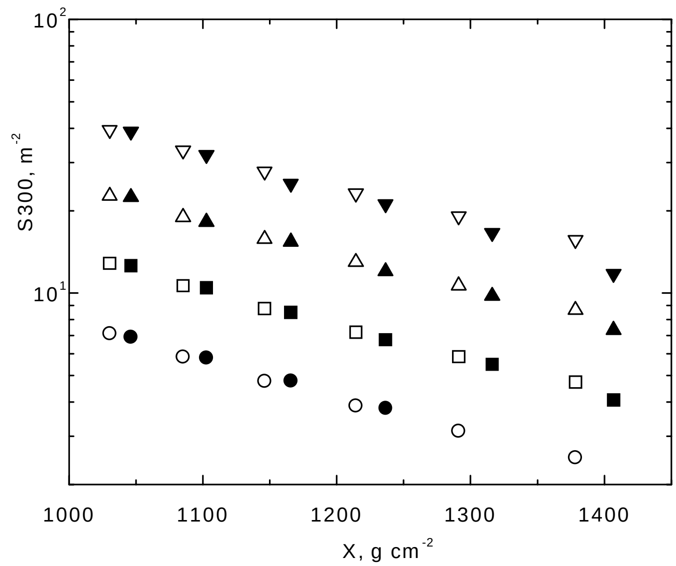

Fig.1 S300 versus the atmospheric depth X. The dark symbols are values obtained at fixed intensity in spectra on S300(θ) in different intervals of a zenith angle, the light symbols are values corresponding to formulae (1) and (3) obtained in the analysis on Q400.

Figure 2 presents the energy spectrum obtained from data on S300 (open circles) and S600 (closed circles). The analysis only on S300 confirms the irregular behaviour of the spectrum from 10^{18} to $3 \cdot 10^{19}$ eV and in this region the above mentioned peculiarities ("dip", "bump") are observed. In Figure 2 the energy spectrum for AGASA (Takeda et al., 1998) is also shown. At $E_O<10^{20}$ eV the intensities in both experiments are in a good agreement although one could expect some difference, because the model estimations of E_O from S600 applied at AGASA give the energy by 30-40% less than by calorimetric formula (2).

In the region of highest energies the results of different arrays are contradictory. At present at the AGASA 6 events with $E_O>10^{20}$ eV have been registered. The shower with $\theta=59°$ registered by the Yakutsk array on May 7, 1989 is still the largest one. By (2), (4) the energy of this shower is $8 \cdot 10^{19}$ eV that is lower than $(1\text{-}1.5) \cdot 10^{20}$ eV according to previous estimations. Not bounding the effective area by the array boundaties and when the range on zenith angle is extended up to 60° then the total exposure for the largest showers is $2.8 \cdot 10^{16}$ $m^2 \cdot s \cdot sr$. It is the same as the AGASA exposure ($2.6 \cdot 10^{16}$ $m^2 \cdot s \cdot sr$). The reasons of disagreements are not evident. Probably, it is associated with the change of nuclear interaction features at $E_O>10^{19}$ eV. In the event on May 7, 1989 the readings as underground muon detectors as ground-based stations are completely coincided in a sufficient wide distance range. The energy for this event is $3 \cdot 10^{20}$ eV according to detailed simulation by the QGS model (Dedenko et al., 1999).

5 Conclusion:

The analysis results of the Yakutsk EAS array data by using the uniform sampling on S300 confirm the irregular behaviour of the spectrum in the energy region of 10^{18} - $3 \cdot 10^{19}$ eV and are in a good agreement with our previous results and data from other arrays. At $E_O>10^{20}$ eV there is a discrepancy in estimation of the intensity between the Yakutsk data and new data of the AGASA.

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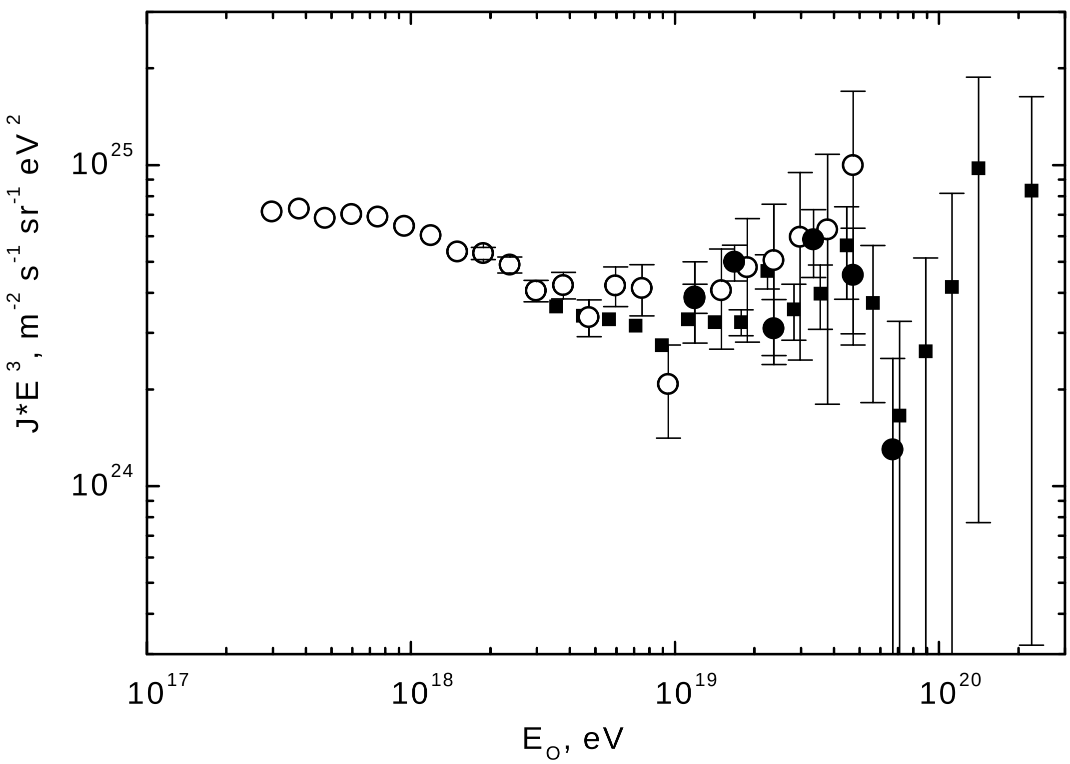

Fig.2 The differential energy spectrum of cosmic rays with $E_O > 10^{17}$ eV.
The open circles are the trigger-500 data, the closed circles are the trigger-1000 data; the squares are the AGASA data

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