Cosmic Ray Spectrum at Ultrahigh Energies

M.I. Pravdin, A.V. Glushkov, V.P. Egorova, A.A. Ivanov, S.P. Knurenko, V.A. Kolosov, A.D. Krasilnikov, I.T. Makarov, A.A. Mikhailov, A.V. Sabourov, I.E. Sleptsov, G.G. Struchkov

Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 678980 Yakutsk, Russia

Abstract

In this work the energy spectrum of cosmic rays based on Yakutsk EAS array data is presented. After inclusion in the analysis last data and revision of shower parameters at Yakutsk array there are four events with energy $E_0 > 10^{19.99}$ eV higher than a threshold of GZK-cutoff. There are some discrepancies in the results on the energy spectrum from Yakutsk, AGASA and HiRes experiments.

1 Introduction

First estimations for the flux of cosmic rays with energy above 10^{17} eV had been obtained with extensive air showers (EAS) in the USA at Agassis [1] and Volcano Ranch [2] arrays almost 50 years ago. In the Volcano Ranch experiment the first event with the energy estimated to be higher than 10^{20} eV was registered. After that, the construction of several new EAS arrays with large exposure had been initiated: Haverah Park in England (detectors were allocated at the area of 12 km^2) [3], Sidney University array in Australia (SUGAR, 55 km^2) [4] and Yakutsk EAS array in USSR (18 km^2) [5, 6]. In 1966 Greisen, as well as Zatsepin and Kuzmin [7] showed that due to interaction with microwave relic photons a cutoff of the energy spectrum must be observed (GZK-cutoff) at $E_0 > (3-5) \cdot 10^{19}$ eV in the case if a lifetime of cosmic rays is long enough ($> 10^9$ years). Due to this result, the interest in the field of extra-high energy research increased significantly.

In Yakutsk the research is still carried on nowdays, Haverah Park and SUGAR arrays closed since the 1980's, but two other new experiments was initiated. In Japan, the array of large exposure was created on the base of the compact Akeno array in the 1980's. In 1985 observations at Akeno-20 of an area about 20 km^2 started, and in 1992 the array of an area of $\simeq 100$ km^2 started operating, which was called AGASA — Akeno Giant Air Shower Array [8].

In the Fly's Eye experiment [9] the showers were registered by atmospheric fluorescence. Since 1981 observations have started at first detector consisting of 67 mirrors, in 1986 the second detector started operating, which had 36 mirrors and located at 3.4 km from the first. From 1993 to 1997 a reconstruction was carried out on this array to increase the resolution and the exposure and nowdays there are new results obtained at HiRes Fly's Eye [10].

2 Yakutsk EAS Array

The registration of showers at the Yakutsk array began in 1973. At that time 35 stations, taking part in the selection of events, occupied an area more than 17 km^2. During the reconstruction in 1990 – 1992 the total area occupied by stations was restricted, but their number increased by almost 1.5. Nowdays 49 such stations located in the circle of 2 km radius. In each of them there are 2 scintillation detectors (2 m^2). In the central circle of a radius equal to 250 m more 9 such detectors are mounted at different points.

From the very beginning the Yakutsk array had been created as a complex air shower detector. Measurements of $\hat{\mathrm{C}}$erenkov light from EAS with $E_0 \geq 10^{17}$ eV are provided only at the Yakutsk array. As a light detector, one or more photomultiplier tubes (a diameter of photocatode equal to 15 cm) are used. At present they are mounted at 19 stations in the circle of 1 km radius, 12 additional detectors are mounted in the very center.

Measurements of the muon flux with the threshold energy 1 GeV at the Yakutsk array are provided by 5 underground points. The total area of scintillation detectors in each point is about 20m^2. Furthermore there is muon detector of the area 180 m^2 and muon threshold 0.5 GeV.

A plan of the location of detector stations at the Yakutsk EAS array is

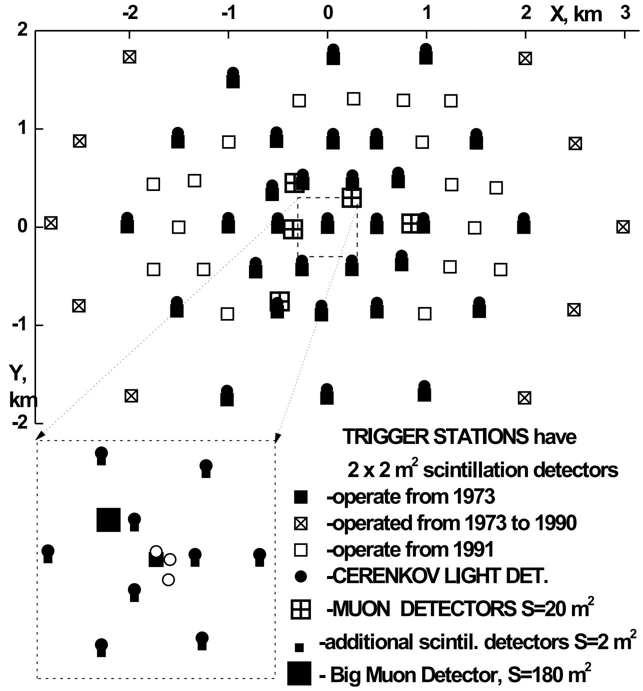

Figure 1: A plan of the location of detector stations at the Yakutsk EAS array

given in Fig. 1.

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 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.

To determine spectra the 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 the shower size for events selected by the *trigger-*

500, a parameter S_{300} is used that is the density at the distance of 300 m from a shower core, and S_{600} 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 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 S_{300} or S_{600} and the zenith angle θ is calculated taking into account the stations operated really in the given moment. Limiting area is bounded by outline of the corresponding trigger. To determine the intensity of showers with $E_0 > 4 \cdot 10^{19}$ eV, extended area together with an efficient zone outside the array is used.

At the standard procedure for the determination of core coordinates, the Greisen–Linsley approximation of LDF with parameters obtained at the Yakutsk array is used [5]. In [11] it was shown that for shower energies above 10^{19} eV this LDF badly corresponded with experimental data at distances $R > 1000$ m from a core. A modificated approximation was proposed:

$$f(r) \sim \left(\frac{r}{R_0}\right)^{-1.3} \left(1 + \frac{r}{R_0}\right)^{-(b-1.3)} \left(1 + \frac{r}{2000}\right)^{-3.5} \qquad (1)$$

For the showers with $E_0 > 2 \cdot 10^{19}$ eV the parameter b does not depend on the energy but depends on θ. In large events ($> 2 \cdot 10^{19}$ eV) the core was determined repeadetly using this adjusted LDF. As a result, in average estimated S_{600} values increase in comparison to preliminary ones.

3 Estimation of EAS Energy

The primary energy E_0 at the EAS arrays is estimated by a base parameter determined experimentally. Usually the relation between such a parameter and E_0 at the atmospheric depth X_0 corresponding vertical showers ($\theta = 0^o$) is found. To estimate E_0 in the events with $\theta \geq 0^o$, the found value of parameter is recalculated to the vertical level according to a zenith angular dependence. In the most experiments this relation is determined for the vertical showers by means of model calculations. At the EAS Yakutsk array three main components are measured: the charged particle flux, Ĉerenkov light and muon component. It allows to use the calorimetric method to estimate the energy and obtain experimental relations between the base parameters (S_{600}, S_{300}) and the primary energy [6].

Calorimetric Method. The basis for this method is the experimental estimation of the energy, dissipated by a shower over the observation level, by using EAS Ĉerenkov light measurements. The showers with $\theta < 20^o$ are selected in the groups with different values of S_{600} (S_{300}). The total energy E_0 in each group is determined as a sum of several components:

$$E_0 = E_i + E_{el} + E_\mu + E_{\mu i} + E_\nu + E_h, \qquad (2)$$

where E_i is energy lost by a shower over the observation level, it is $\sim 70\%$ and is estimated by measurements of total Ĉerenkov light flux; E_{el} is the energy conveyed below the array level, it is estimated by the attenuation of the number of charged particles through the atmosphere depth; $E_\mu + E_{\mu i}$ is the energy of the muon component, it is estimated by the total number of muons at the observation level; $E_\nu + E_h$ is the energy of the neutrino and on nuclear reactions in the atmosphere, it is added on the basis of model calculation results ($< 5\%$).

If S_{300} and S_{600} will be recalculated to $X_0 = 1020$ g cm^{-2}, corresponding to $\theta = 0^o$, then we obtain:

$$E_0 = (5.66 \pm 1.4) \cdot 10^{17} \cdot (S_{300}(0^o)/10)^{0.94\pm0.02} \text{ eV} \qquad (3)$$

$$E_0 = (4.6 \pm 1.2) \cdot 10^{17} \cdot S600(0^o)^{0.98\pm0.03} \text{ eV} . \qquad (4)$$

The main contribution to an error for the constant multiplier in (3) and (4) gives the uncertainty of the absolute calibration of the Ĉerenkov light detectors which is constant for all energies and cannot influence on the energy spectrum form. The experimental dependence of the energy on $S_{300}(0^o)$ is given in Fig. 2.

Zenith-Angular Dependence of S_{300} and S_{600}. To determine the primary energy for the individual shower from (3) and (4), the value of S_{300} or S_{600} for the zenith angle θ must be recalculated to $\theta = 0^o$ according to the corresponding attenuation length λ_{300} for S_{300} and λ_{600} for S_{600}. To determine λ_{300} and λ_{600}, the change of these parameters depending on θ at the fixed energy must be studied. For this purpose, besides of the equi-intensity method, at the Yakutsk array the experimental parameter Q_{400} (density of Ĉerenkov light flux at the 400 m distance from a shower core) is used. Q_{400} is a good equivalent of the primary energy which is practically independent of θ, if the absorption of light in the atmosphere is taken into account.

In Fig. **??** the open indices ($S1 - S7$) are the values of S_{300} at the different atmospheric depth X, corresponding to 7 different values of fixed intensities for the spectra in different angular intervals. Solid indices ($Q1$ – $Q6$) are $S_{300}(X)$ for 6 energy intervals by using Q_{400}. Experimental points for the two methods are consistent with each other quiet well.

The parameter S_{300} reflects the behavior of a charged particle. Electrons and muons contribute to the scintillation detector response. The electron component damps in depth considerably more quickly than the muon component. Therefore we assume that the actual change of S_{300} (S_{600}) depending on the atmospheric depth must be described as a sum of soft and hard components having the different attenuation lengths:

$$S(\theta) = S(0^o) \cdot (1-\beta) \cdot \exp\left((X_0 - X)/\lambda_E\right) + \beta \cdot \exp((X_0 - X)/\lambda_M), \quad (5)$$

where λ_E is the attenuation length for the soft component (electrons), λ_M is the same for the hard component (muons), β is a portion of the hard component in the total response of $S(0^o)$ at the depth of 1020 g cm^{-2}. As the number experimental points is small for each energy, in the fitting procedure we taken $\lambda_E = 200$ g cm^{-2}, $\lambda_M = 1000$ g cm^{-2} which are approximately consistent with the attenuation length for electrons and muons, respectively. Determining parameters $S_{300}(0^o)$ and β_{300} and in (4) we use values X corresponding to $\theta < 45^o$.

The experimental dependence of parameter β_{300} on $S_{300}(0^o)$ can be described by the formula:

$$\beta_{300} = (0.368 \pm 0.021) \cdot \ (S_{300}(0^o)/10)^{-0.185 \pm 0.02}. \quad (6)$$

The solid lines in Fig. **??** are the change of S_{300} depending on the atmospheric depth by using (5) and (6). It is seen that the curves describe well experimental data for $\theta < 45^o$ and are consistent with the points for $X = 1750$ g cm^{-2} which did not take into account at the selection of parameters.

The analogous consideration by (6) and using the same λ_E and λ_M leads to the following formula for β_{600}:

$$\beta_{600} = (0.62 \pm 0.06) \cdot \ S_{600}(0^o)^{-0.076 \pm 0.03}. \quad (7)$$

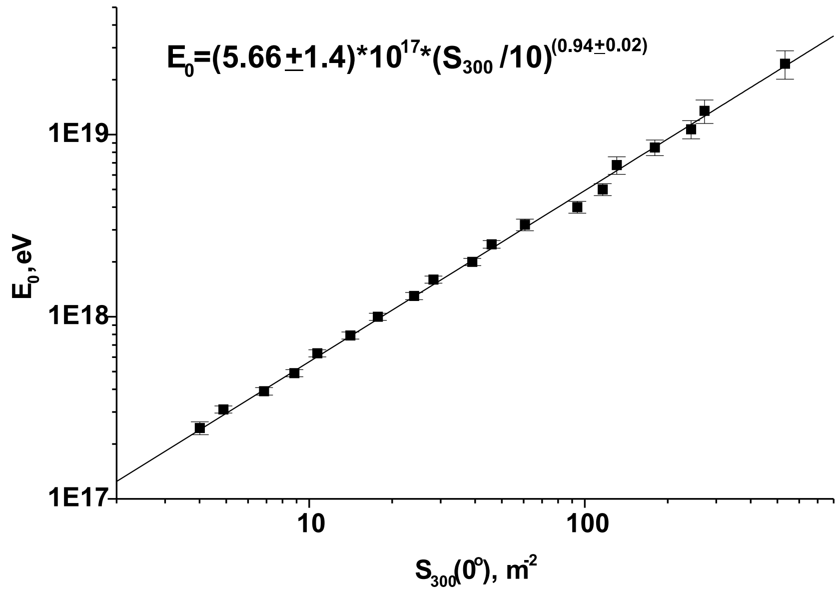

Figure 2: Relation between shower energy E_0 and $S_{300}(0^o)$ determined by the calorimetric method

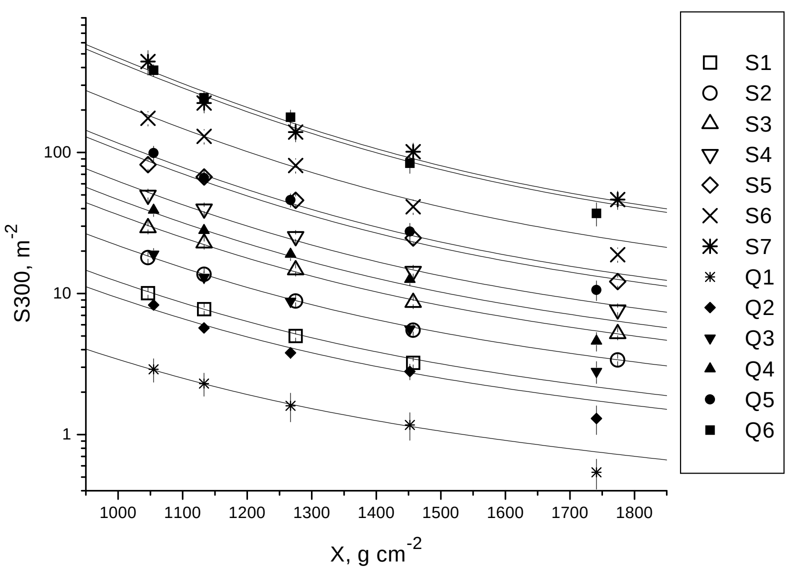

Figure 3: S_{300} versus the atmospheric depth X for different energies. ($S1$ - $S7$)– equi-intensity method, ($Q1$- $Q6$)– Q_{400} method
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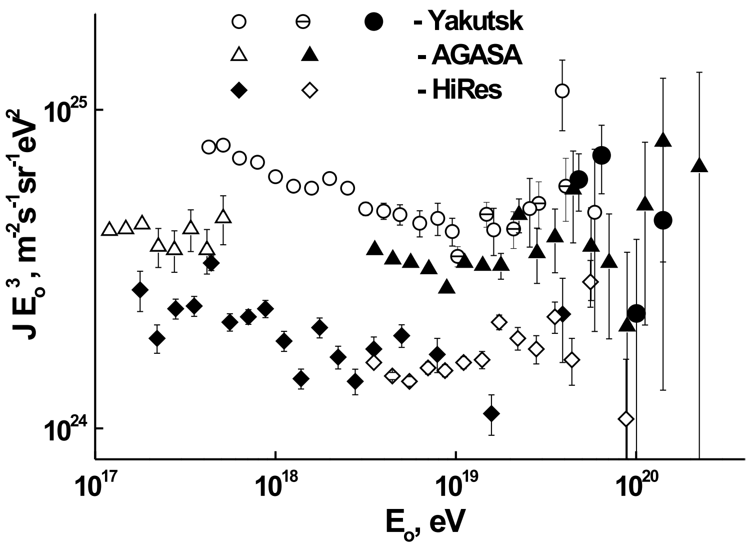

Figure 4: Differential energy spectrum of UHECR multiplied by E_0^3

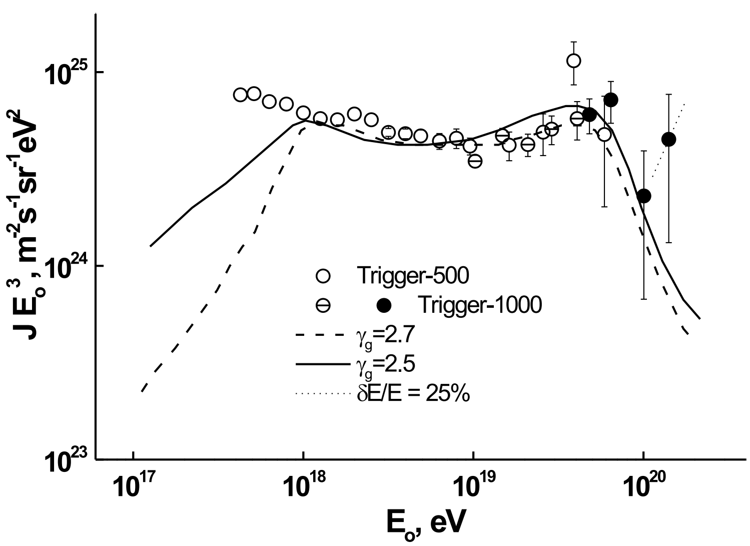

Figure 5: Comparison of calculation results from [15] with the Yakutsk data

4 Energy spectrum

In Fig. 4 the differential energy spectrum obtained at the Yakutsk array for events with $\theta < 60^o$ is represented together with results of AGASA [12] and HiRes [10]. Energy spectra obtained in different experiments correspond quite well in shape but differ in intensity. The data from the Yakutsk array near 10^{19} eV are higher by a factor of $\simeq 2.5$ than HiRes data and $\simeq 30\%$ than AGASA's.

At energies greater than the GZK-cutoff the results are inconsistent. At HiRes there is only one event with $E_0 > 10^{20}$ eV and the spectrum is cut off. AGASA have registered 11 such events ($\theta < 45^o$), this could be an evidence for absence of a cutoff. Recent results from the Yakutsk array correspond better to AGASA. There are 4 events with $E_0 > 10^{19.99}$ eV registered in Yakutsk, whose coordinates are presented in Table 1.

Systematic discrepancy of intensity in different experiments could be associated with the difference in energy estimation for showers. At AGASA to estimate the energy in vertical showers a relationship between S_{600} and E_0 obtained from model computations is used. Energy estimations obtained from calorimetric formulae (3) and (4) in Yakutsk are poorly dependent on model assumptions. They are 30%–40% higher at $E_0 \approxeq 5 \cdot 10^{17}$ eV than it should be according to model computations. To agree the energy estimated for AGASA, the energy of events measured in Yakutsk shoud be decreased. It is possible since according to (3) and (4) there is systematic discrepancy about 25%. In individual events there is the additional contribution made by errors in determination of core coordinates and angles. In special column of Table 1 relative errors for the energy determination in individual showers taking into account all uncertainties are listed. If the energy is reduced by one standard error then it slightly exceeds the 10^{20} eV threshold only in the first event. Therefore the GZK-cutoff of spectrum cannot be rejected based on Yakutsk EAS data.

Table 1: The most energetic events detected with the Yakutsk array

N	Date	Time, UT	θ^o	$\log E_0$	δE_0,%	b^o	l^o
1	02.18.04	22:20:38	47.7	20.16	42	16.3	140.2
2	05.07.89	22:03:00	58.7	20.14	46	2.7	161.6
3	12.21.77	18:45:00	46.0	20.01	40	50.0	220.6
4	02.15.78	03:35:00	9.6	19.99	32	15.5	102.0

Similar errors are observed at AGASA. According to [13] their averaged value is about 20%. Taking into account this circumstance a conclusion was made in [14] that yet there are too few events recorded to approve of the spectrum cutoff absence. Besides, estimations of the energy at AGASA depend on model conclusions.

According to all the data, the shape of the energy spectrum in the region from 10^{18} to $5 \cdot 10^{19}$ eV corresponds to the suggestion that the sources of particles with $E_0 > 10^{19}$ eV are galaxies with active nuclei [15]. (See Fig. 5) If so, then particles with the energy the above GZK threshold should arise in other unknown sources.

5 Conclusion

The HiRes results are consistent with the GZK-cutoff of spectrum, the AGASA and Yakutsk data are inconsistent. But because of small statistics and errors in the energy estimation while it is impossible to final conclude about this problem. To solve this and investigate of properties of the particles with energies above GZK-cutoff, data with high statistics and good accuracy in the energy estimation are necessary available. Today new giant arrays are designed already.

The Pierre Auger Observatory [16] will have two arrays disposed in the Southern and Northern hemispheres, each array will be covering 3000 km^2 area. In the Argentina the Southern site is in progress, the design start of the Northern site will be in 2006 in USA. Except of water $\hat{\text{C}}$erenkov detectors the installation includes fluorescence telescopes.

At the beginning of 2004 the recording at the AGASA array terminated. Instead in USA new project "Telescope Array" will be realized in which a combination of surface array and fluorescence telescopes will be used [17]. The surface array with scintillation detectors is similar to AGASA but it's area will be greater by an order of magnitude. The two projects combine two different methods to record EAS between of which there is a discrepancy at present.

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