# MEASURING THE ENERGY SPECTRUM OF PRIMARY COSMIC RAYS WITH THE YAKUTSK EAS ARRAY

G. B. Khristiansen

Institute of Nuclear Physics, Moscow State University; Moscow 119899, USSR

The Yakutsk EAS array has been designed for detecting the showers generated by the $10^{17}$–$10^{20}$ eV primary cosmic rays and consists of numerous electron, muon, and Cerenkov light detectors arranged on a 20-km$^2$ area terrain (see Fig. 1). The array is featured by the feasibility to detect the EAS-produced Cerenkov light, hence, as will be shown below, to find the mean energy of the primary particles generating an ensemble of EAS of given size.

The Yakutsk array detectors are on the average spaced a relatively small distance apart (compared, for example, with the Haverah Park and University of Sydney arrays), thereby permitting a comparatively high accuracy in determining the basic parameters of the EAS detected. For instance, the Monte Carlo calculations allowing for the fluctuations of t e lateral distribution function of charged particles have shown[1] that (see Table 1) the error in finding the parameter $\rho_{600}$ of individual EAS, which is the particle density at a 600-m distance from the EAS axis*), does not exceed 25% if the shower axes fall within the effective detection area of the Yakutsk array for EAS of a given size. The calculations were carried out for the various values of $\rho_{600}$ and the various zenith angles of the EAS axes. The effective detection area is determined in terms of the requirement that the probability of EAS detection within the

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*) The value of $\rho_{600}$ can be determined most accurately with the Yakutsk array. Besides, $\rho_{600}$ is known to be a good measure of the primary energy.

area should be at least $\varepsilon = 0.9$, irrespectively of the possible fluctuations in the form of the lateral distribution function. Fig.2 shows the effective detection area for EAS with $E_0 \geqslant 10^{19}$ eV. The primary energy spectrum is inferred from the Yakutsk array data by finding, first, the EAS $\rho_{600}$ spectra for various intervals of the zenith angles of the detected EAS axes. The EAS axis direction and position and the EAS size ($\rho_{600}$) are found by the maximum likelihood method described in detail in [1].

Fig.3 shows the EAS $\rho_{600}$ spectra for the various zenith angles corresponding to the traversed atmospheric depths of 1046 g/cm$^2$, 1133 g/cm$^2$, and 1313 g/cm$^2$ [1]. The data of Fig.3 may be used to find the experimental absorption path of EAS with a given value of $\rho_{600}$, $\lambda \simeq 500$ g/cm$^2$ which, in turn, may be used to scale the observed spectra to the vertical direction $\vartheta = 0^\circ$ (it should be noted that the same procedure is used to infer the $\rho_{600}$ spectrum from the Haverah Park array data).

Fig.4 compares between the $\rho_{600}$ spectra inferred from the Yakutsk data within 38000 hours and from the Haverah Park data. The Haverah Park spectrum has been obtained by scaling $\rho_{600\,HP}$ from the water-tank data to the 5-cm thick scintillator readings using the formula [2]:

$$\rho_{600\,sc} = (1.72 \pm 0.25)\, \rho_{600\,HP}^{\,1.06 \pm 0.03}$$

on the basis of the $\rho_{600\,HP}$ spectrum data from [3] and the $\rho_{600}$ spectrum data of the Yakutsk array from [1]. From Fig.4 it is seen that the $\rho_{600sc}$ spectra measured at Yakutsk and Haverah Park are in a good agreement with each other at $\rho_{600sc} < 200$ (1/m$^2$) and differ somewhat at higher $\rho_{600sc}$. Because of a limited accuracy in measuring the particle flux densities with the Yakutsk array, the effect of its geometry (for example, at the boundary of the array) the limited accuracy in finding the axis position and direction and the parameter $\rho_{600}$, the inaccuracy in calculating the effective detection areas, and the detected EAS selection effect, the necessity arises to test the distorting role of all these factors in terms of the Monte Carlo method, that is, to find the $\rho_{600}$ spectrum distortion function. The distortion function was calculated in [1] on the assumption of the a priori power law $\rho_{600sc}$ spectrum $F(\rho)\sim\rho^{-2}$ allowing for the real errors in determining the densities with the Yakutsk array and for the real selection of the EAS to be studied. From Fig.5 it is seen that the distortion function differs little (by not more than 10-20%) from unity at $\rho_{600}\sim 1(1/m^2)$ and $\sim 10(1/m^2)$. The corrections at $\rho\sim 1$ and $10(1/m^2)$ arise from the effect of the EAS selection system on measuring the particle flux densities with scincillators if the latter are included in the system. At $\rho > 20(1/m^2)$, the corrections are even smaller. The EAS $\rho_{600}$ spectrum may be used to infer the energy spectrum of primary cosmic rays from the experimental time-integrated and differential Cerenkov light flux in an EAS ensemble with a given value of $\rho_{600}$. As was first shown in [4], the integral EAS Cerenkov light flux Q is directly related to the energy $E_i$ lost by the shower particles for ionization and for the excitation of the medium atoms above the EAS observation level, namely, $E_i = kQ$, where, according to the calculations [5], k depends little on the position of the EAS maximum. On the other hand, the data on the time-differential Cerenkov light flux at great distances from EAS axis make it possible to find the position of the maximum of an individual EAS [6] and, hence, to judge about the extent to which $E_i$ is close to the primary energy $E_o$. In the range of $\rho_{600} = 1-10(1/m^2)$, considering the altitude of the maxima of the respective showers, we obtain that the factor k in the relation $E_i = kQ$ is $3.8\times10^4$ eV/photon/eV to within several per cent. At the same time, because of the high location of EAS maximum for $\rho_{600} = 1-100(1/m^2)$, it appeared that $E_i = 0.8E_o$; in other words, the energy scattered by a shower above the observation level makes the major contribution to the energy of the primary particle generating an EAS ensemble with a given $\rho_{600}$ [1] *). When finding the value of $E_1$ (which is the major component of $E_0$) it is absolutely necessary to allow for the EAS Cerenkov light absorption in the atmosphere due to the Rayleigh scattering and the scattering by aerosols. The value of $Q$ measured directly may differ from the number of the generated photons involved in the relation $E_1 = kQ$.

Bearing in mind the above, we carried out the regular control of the atmospheric transparency above the Yakutsk array using the large optical detector described in [9]. The occurrence frequency of the Cerenkov light bursts in the detector exceeding a certain threshold is contingent on the atmospheric transparency at the moment of measurement and on the spectral index of the burst intensity spectrum $N(>q) \sim (q \times T)^{-\varkappa}$, where $T$ is the atmospheric transparency for the wavelengths studied by the detector; $q$ is the burst intensity; $\varkappa$ is the index of the burst spectrum.

Fig.6 shows the distribution of the burst occurrence frequency inferred from the 15-min observation intervals during several months of the Yakutsk array operations. The detected burst threshold is 17 photon/cm$^2$eV. The maximum value of $N = N_1 \simeq 400$. If the variations of the Cerenkov light flux are assumed to be due only to the changes of the atmospheric transparency, the distribution shown in Fig.6 may be transformed into the distribution of $T$ with the mean value $\bar{T} = 0.71T_1$ and $\sigma(T)/\bar{T} = 0.19$, where $T_1$ is the maximum transparency which corresponds to the Rayleigh scattering disregarding the aerosols. Considering the angular distribution of the axes of the EAS detected with the Yakutsk array, one may calculate [9] the value of $T_1$

*) In [1] it has been shown that, if the mean energy of EAS muons is taken to be $\bar{E}_\mu = 9$ GeV according to the experimental data [7] and the lateral distribution of electrons near EAS axis is determined by the NKG function with $S = 1.15$ [8], the energy carried by electrons and

which proved to be 0.85. Since $\bar{T} = 0.71T_1$, then $\bar{T} = 0.6$.

Thus, the true value of Q differs from its measured value by the factor $1/\bar{T} \simeq 1.65$. It should be noted that a a more rigorous allowance for the atmospheric transparency involves also the usage of the ratio $\sigma(T)/\bar{T}$ in making the scaling. However, the value of the ratio is sufficiently small and, to within several per cent, does not affect the results. It should also be noted that the large optical detector is a local selection system which gives an idea of photon absorption by a layer of several km thickness above the observation level [9]. The coincidence-mode functioning of the Samarkand array optical detectors spaced 120 meters apart has shown that [10] the number of coincidences in the spaced-apart detectors is in a good correlation with the number of coincidences in the local optical detectors at Samarkand ($K = 0.9$). This fact indicates that the EAS Cerenkov light absorption occures mainly within the layer immediately above the observation level, rather then uniformely throughout the atmosphere. This conclusion coincides with the present-day concepts concerning the atmospheric aerosol layer of a ~ 2-km thickness [11].

So, considering the correction for the atmospheric transparency, we may obtain [2] the following experimental relation between the value of $\rho_{600}$ in EAS and the mean energy $E_0$ of the primary particles responsible for an EAS ensemble with a given $\rho_{600}$:

$$E_0 = (5.0 \pm 1.4) \times 10^{17} \rho_{600}{}^{0.96 \pm 0.04} \quad (\vartheta = 0^\circ).$$

The error in the numerical factor is mainly due to the error (25%) in the absolute calibration of the Cerenkov detectors.

The statistical errors, which are of importance when

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muons below the observation level will be $\simeq 15\%$ of $E_0$. The rest energy belongs to neutrinos and to nuclear splitting.

deriving the above relation, can be seen in Fig.7. A given value of $\rho_{600}$ is, generally, in correspondence to a distribution of $E_0$. However, the width of the $E_0$ distribution is so small ( $\sqrt{D(E_0)}/E_0 \lesssim 0.2$) that the relation between $\bar{E}_0$ and $\rho_{600}$ is quite sufficient to use (to within several per cent) in making the transition from the $\rho_{600}$ spectrum to the primary particle energy spectrum.

Fig.8 shows the experimental differential energy spectra of primary cosmic rays inferred from the Yakutsk array data [1,2], from the Haverah Park data [3], and from the Fly's Eye data [12]. Fig.9 shows the experimental energy spectra obtained also in [1,2,12]. From Figs 8 and 9 it is seen that at energies below $10^{19}$eV the Yakutsk and Haverah Park data are in a better agreement with each other than with the Fly's Eye data. The deviations of the latter are probably due to the tentative character of the results of calculating the Fly's Eye geometric factors at low primary energies, as was noted in [12]. The minor disagreement between the Yakutsk and Haverah Park data arose probably from the fact that the Hillas model used for the Haverah Park array to scale from $\rho_{600}$ to $E_0$ is not sufficiently accurate in reflecting the true relation between $\rho_{600}$ and $E_0$. At $E_0 > 10^{19}$eV the experimental data of different works show a significant spread. Such a spread may be caused by trivial reasons, for example, a certain inaccuracy in the absolute calibration of optical detectors for the Yakutsk array and for Fly's Eye may result in a systematic disagreement of their data even in the range of high $E_0$ where Fly's Eye geometric factor has been known quite accurately. For instance, a 25% variation of the absolute value of energy leads to a complete agreement between the Yakutsk and Fly's Eye data at $E_0 > 10^{19}$eV, although it results in an increased disagreement between their spectra at $E_0 < 10^{19}$eV. A more essential disagreement is observed between, on the one hand, the data obtained at Haverah Park and the Univerversity of Sydney [13] where no direct energy calibration was madé and, on the other hand, the data obtained with the Yakutsk array and the Fly's Eye which were energy-calibrated*).

The Haverah Park and Sydney arrays give a flat spectrum in the range from $E_o > 10^{19}$ eV up to the highest detectable energies above $10^{20}$ eV. It is not clear what is the role played by the fluctuations of the charged particle lateraly distribution function in determining the value of $\rho_{600}$ for the Haverah Park array because the value of $\rho_{600}$ at $E_o > 10^{19}$ eV is not determined by interpolation, but is found by specifying a fixed mean lateral distribution function. This circumstance may prove to be even more important for the Sydney array because of a great distance between its detectors. With a falling $\rho_{600}$ spectrum (or the spectrum of $N_\mu$, the total number of EAS muons, in case of the Sydney array), the great errors in determining the EAS size may flatten the measured spectrum. An additional source of errors arises also when we treat the showers whose axes fall at the array periphery.

So, we think it necessary (1) to rigorously restrict, making allowance for the lateral distribution function fluctuations, the effective detection area for EAS with $E_o > 10^{19}$ eV by the region where the accuracy in determining the EAS parameters will make sure that errors would be absent and (2) to carry out the Monte Carlo simulation of the entire process of measuring and analyzing EAS with an experimental array in order to obtain a distribution function of the type shown in Fig.5.

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*) The energy spectrum inferred from the Sydney array data is not shown in Figs 8 and 9 because it is model-dependent. It is necessary to use the results of the Yakutsk array calibration [2] and to scale the muon number spectrum to the primary spectrum.

Thus, on examining the available Yakutsk and Fly's Eye data, one may arrive at the conclusion that they do not contradict qualitatively the Zatsepin-Greizen pattern of the cutoff of the cosmic ray energy spectrum due to the interactions with the 2.7K universal microwave radiation. Additional studies have to be carried out to demonstrate the existence of such a cutoff and to find the 'fine' spectral structure (bump).

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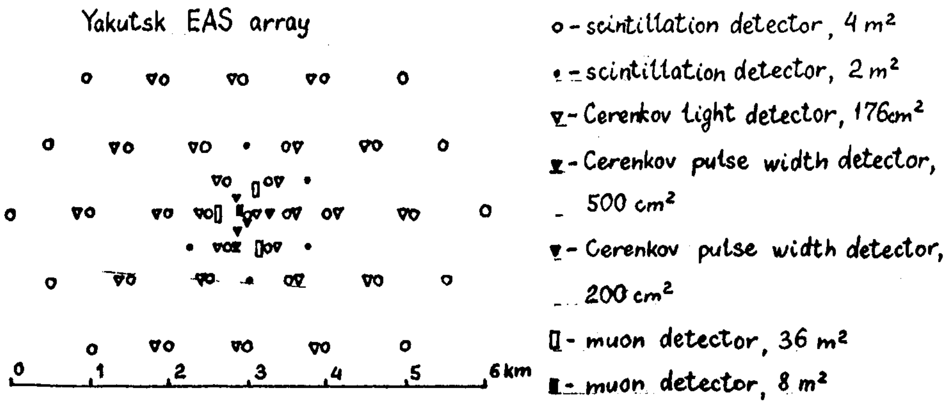



Fig. 1

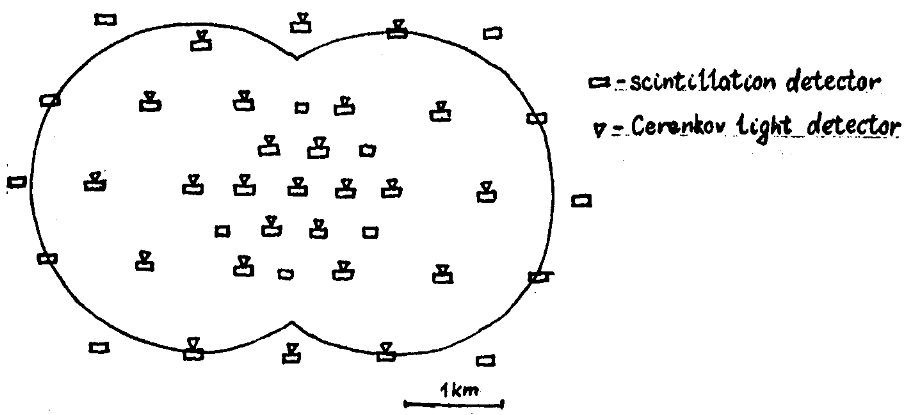



Fig. 2

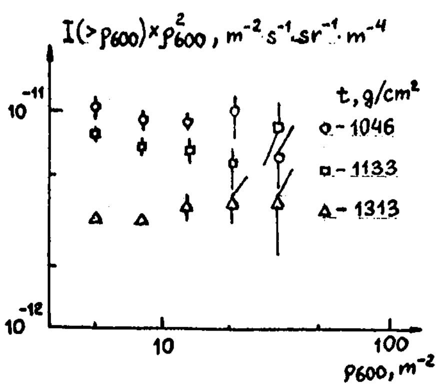



Fig. 3

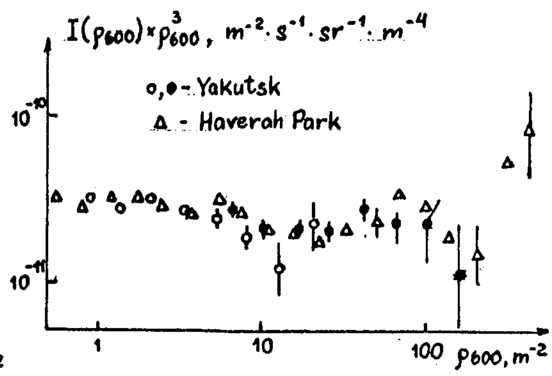



Fig. 4

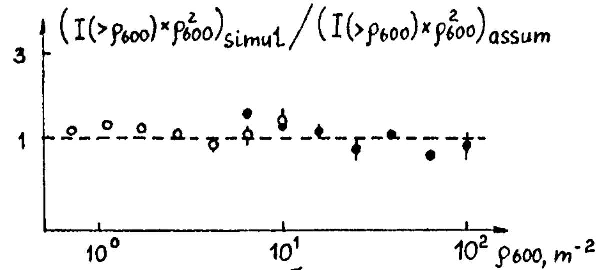
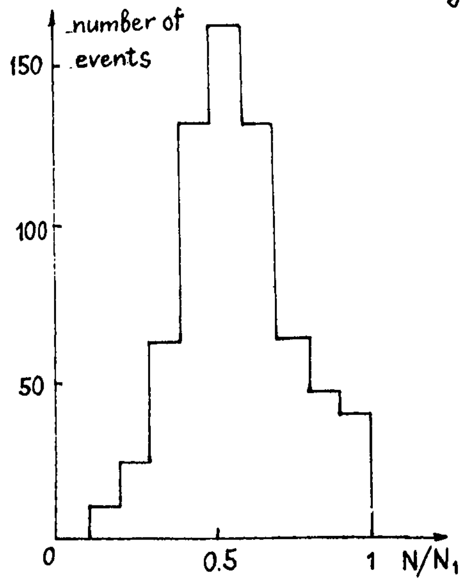



Fig. 5




Transparancy of the atmosphere

$$T = T_1 \times (N/N_1)^{1/æ}, \quad T_1 = 0.85$$

$N$ is the number per 15 min of EAS with the Cerenkov light density of $\geq 17$ photons/cm$^2\cdot$eV.

$N_1 \equiv N_{max} \sim 400$.

$$\frac{6(N/N_1)}{\overline{(N/N_1)}} = 0.31 \qquad \frac{6(T)}{\overline{T}} = 0.19$$

$$\overline{T} = 0.17 \cdot T_1$$

Fig. 6

$$E_0 = (5.0 \pm 1.4) \cdot 10^{17} \cdot \rho_{600}^{0.96 \pm 0.04}, \text{ eV}$$

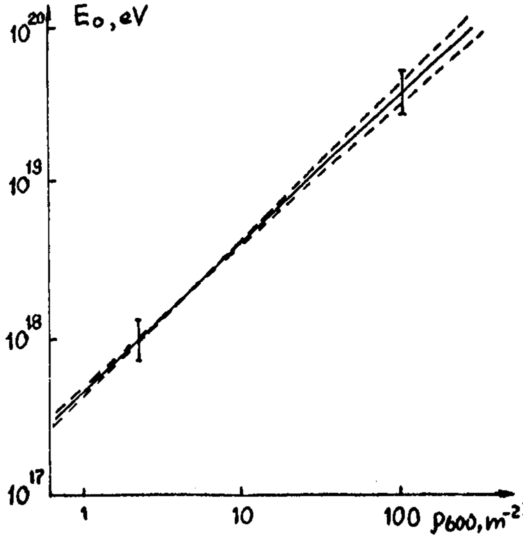



Fig. 7

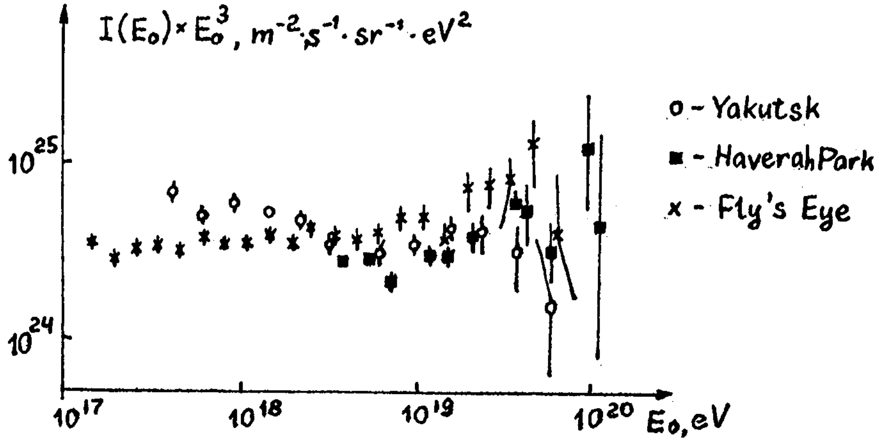



Fig. 8

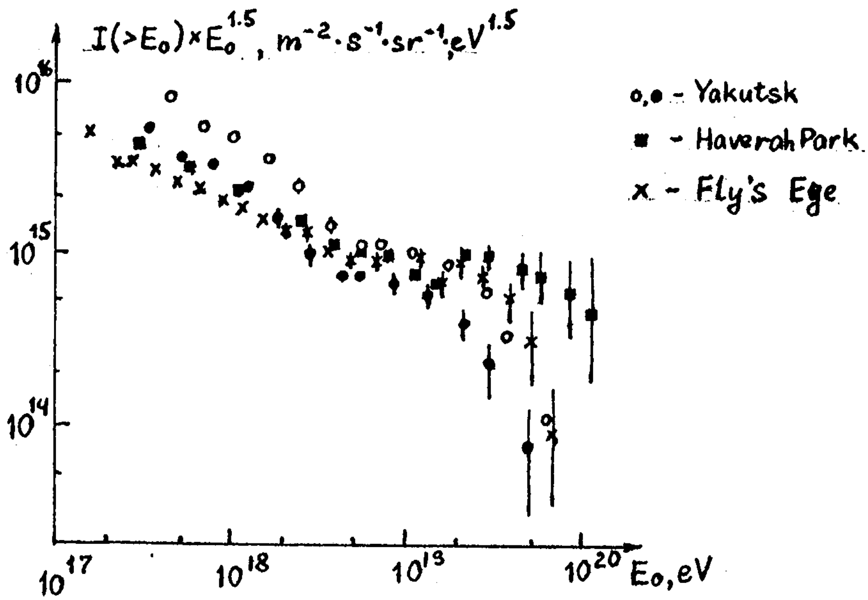



Fig. 9

| $\rho_{600}, m^{-2}$ | 5 | 10 | 20 | 50 | 100 | |
|---|---|---|---|---|---|---|
| $\frac{\delta(\rho_{600})}{\rho_{600}}, \%$ | 18 | 17 | 14 | 18 | 20 | $\theta = 13°$ |
| | 23 | 17 | 18 | 21 | 25 | $\theta = 39°$ |

Table 1