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Zenith angle distribution of cosmic ray showers measured with the Yakutsk array

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The Yakutsk array dataset in the energy interval $(3\times 10^{16}, 10^{19})$ eV is re-visited in order to interpret the zenith angle distribution of extensive air shower event rate. The close relation of the distribution to the attenuation of the main measurable parameter of showers, S_{600}, is examined. Knowledge of the threshold effect on fluctuations of the parameter is essential in order to calculate surface array exposure.

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1. Introduction

The zenith angle distribution of extensive air showers (EASs) of cosmic rays (CRs) has been a target of investigations since the very beginning of EAS measurements. The results of the classical period of observations were summarized in a monograph [1] where the interconnection between the omnidirectional frequency of showers and attenuation of EASs in the atmosphere was analyzed using the *Gross transformation*. In those times, EAS density was measured necessarily without knowing the incident direction.

Modern EAS arrays measure both the sizes and incident directions of showers. Examples of zenith angle distributions of showers measured with extended surface arrays equipped with scintillation counters and/or water tanks can be found in [2, 3, 4, 5, 6] and elsewhere.

The attenuation of shower size and particle density, $\rho(r,\theta)$, at zenith angle θ and core distance r has been studied in a number of ground-based experiments, most notably - Haverah Park [7], AGASA [8], and KASCADE [9]. The *constant intensity cuts* method is in operation used in the papers cited and elsewhere to evaluate the attenuation length of EAS parameters in the atmosphere. A detailed description and possible applications of the method are given, for example, in [10].

In the rest of this paper, we focus mainly on the Yakutsk array data. Our aim is to elucidate the zenith angle distribution, $f(\theta,E)$, of EAS event rate varying with energy owing to absorption of showers in the atmosphere. Henceforth, this can make it possible to use more data at lower energies in the analysis of CR arrival directions that were not involved previously because of variations in array exposure that were not interpreted.

2. The Yakutsk array: data acquisition and selection for analysis

The geographical coordinates of the Yakutsk array are 61.7^0N, 129.4^0E, about 100 m above sea level ($x_0 = 1020$ g/cm^2). The array is formed by 58 ground-based and four underground scintillation counters of charged particles (electrons and muons) supplemented with 48 detectors of atmospheric Cherenkov light consisting of photomultiplier tubes [2, 11, 12].

Stations on the ground with approximately 500 m of separation contain a pair of scintillation counters (2 m^2 each). The total area covered by the stations was $S \approx 17$ km^2 in the period 1974–1990; $S \approx 10$ km^2 between 1990 and 2000; and currently 8.2 km^2 [13, 14]. The energy range of EAS investigations is 10^{15} to 10^{20} eV [15, 17, 16, 18].

EAS events are selected from the background using a two-level trigger for detector signals (particle density $\rho > 0.5$ m^2). The first level involves the coincidence of signals from two scintillation counters at a station within 2 μs; the second level involves the coincidence of signals from at least three nearby stations within 40 μs [2, 13].

Several algorithms have been developed to evaluate the energy of the primary particle initiating EAS [19, 20, 21, 22]. In this paper, two conventional methods proposed in [23] and [24] are used. In the first case, the energy is estimated as

$$E = (0.48 \pm 0.16) \times S_{600}(0)^{1.0\pm0.02}, \mathrm{EeV}, \tag{2.1}$$

where $S_{600}(0) = S_{600}(\theta) exp((\sec\theta - 1)x_0/\lambda)$, m^{-2}; $\lambda = (450\pm44) + (32\pm15) lg(S_{600}(0))$, g/cm^2.

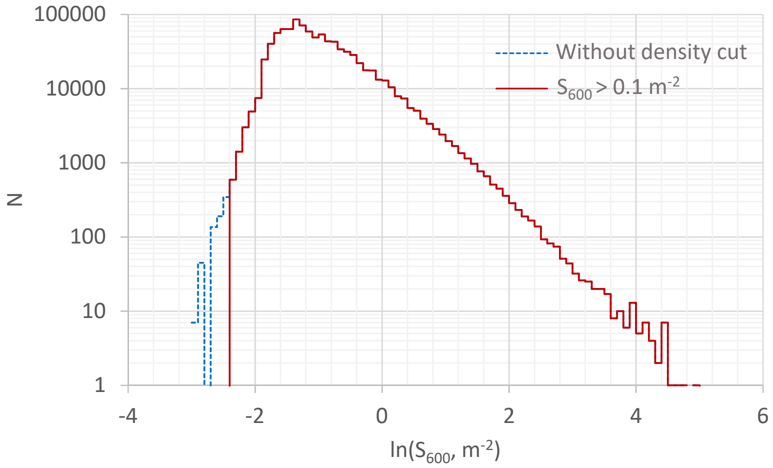

Figure 1: Distribution of the measured S_{600} parameter.

The second method assumes that

$$E = (0.46 \pm 0.12) \times S_{600}(0)^{0.98 \pm 0.02}, \mathrm{EeV}, \tag{2.2}$$

where $S_{600}(\theta) = S_{600}(0)((1-\beta)\exp(x_0(1-\sec\theta)/250) + \beta\exp(x_0(1-\sec\theta)/2500))$, m^{-2}; $\beta = (0.39 \pm 0.04)S_{600}(0)^{-0.12 \pm 0.03}$.

The selected sample of the Yakutsk array data consists of EAS events detected in the period of January 1974–June 2008 [14] with axes within the stage II array area at energies above 0.03 EeV ($= 3 \times 10^{16}$ eV), at zenith angles within $(0^0, 60^0)$.

3. Zenith angle distribution of EAS event rate

This distribution is a result of shower absorption in the atmosphere as well as the arrival directions of the primaries. In turn, the absorption rate is linked to the threshold energy of showers, which depends on the particle density threshold of the detectors, shower core coordinates, etc. To simplify the treatment, we use in the following S_{600} threshold equal to 0.1 m^{-2}, which is chosen to be well above the intrinsic instrumental threshold of the array. A benefit of using this technique is *a posteriori* selection of showers almost independent of shower core position within the array area. The S_{600} distribution of showers detected with the Yakutsk array is illustrated in Fig. 1 with and without the density threshold at 600 m.

It was shown long ago that fluctuations of some shower parameters in a narrow energy bin, e.g., shower sizes, N_e, N_μ, and particle density can be approximated at sea level by a log-normal distribution [25, 26]. In particular, it was demonstrated with the experimental data of AGASA [27], and with a CORSIKA simulation of the scintillation counter signal [28] that $y = \ln(S_{600})$ in EAS events can be approximated by a Gaussian. Assuming additionally an isotropic flux of CRs in the energy range of $(0.03, 1)$ EeV, one can derive an analytic expression to describe the zenith angle distribution of showers detected at sea level.

Constraints on anisotropy of arrival directions in the range were set using harmonic analysis [29, 30, 31] and the South-North method [32]. The stringent upper limit for the first harmonic

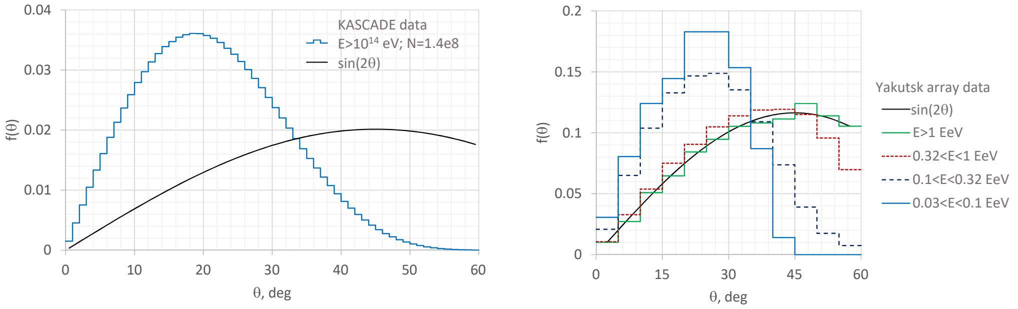

Figure 2: Zenith angle distribution of showers measured in energy bins. For the Yakutsk array data, primary energy is estimated using Eq. 2.2, while the energy estimation algorithm for KASCADE data is given in [6].

amplitude was 0.1% at a primary energy of 7×10^{14} eV, and 1.25% around $E\approx1$ EeV. This bounds our isotropic flux approximation and the accuracy of the final formula.

Experimental distributions in energy bins provided by the Yakutsk array observations ($\theta<60^0$) are shown in Fig. 2 on the right panel. At energies above 1 EeV, the absorption of showers is negligible, so the distribution is compatible with the 'isotropic' $f(\theta)=\frac{4}{3}\sin(2\theta)$ [33, 34]. At lower energies, the particle density threshold cuts the right-hand tail of the distribution. For comparison, the zenith angle distribution measured with KASCADE [6] at energies above 10^{14} eV is illustrated in the left panel together with the distribution expected when showers are not absorbed in the atmosphere.

To fit the clipped distribution measured with the Yakutsk array under log-normal fluctuations of S_{600}, we use

$$f(\theta)=C\sin(2\theta)\mathrm{erfc}\left(\frac{y_{thr}-\overline{y(\theta)}}{\sqrt{2}\sigma}\right), \tag{3.1}$$

where C is a constant; $y_{thr}=-2.303$; and σ is the r.m.s. deviation. The mean density is attenuated

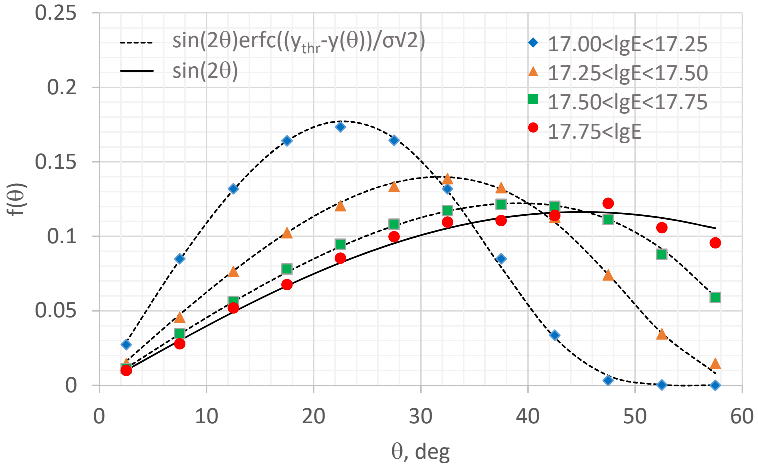

Figure 3: Zenith angle distribution of the EAS event rate observed with the Yakutsk array in energy intervals. Approximations are shown by curves.

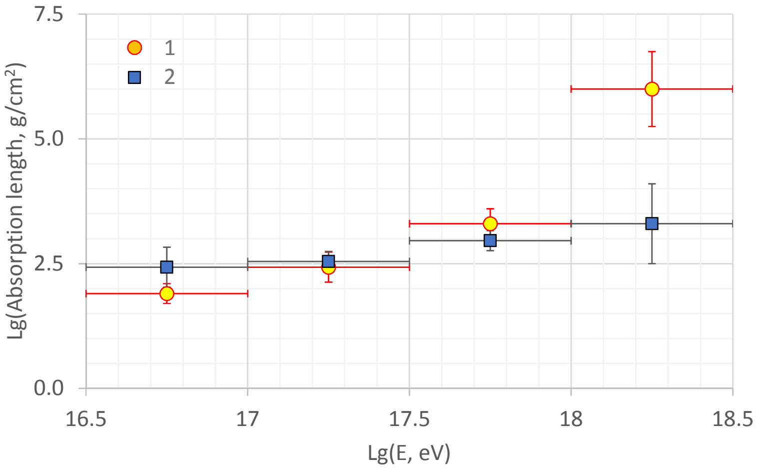

Figure 4: Absorption length of showers in the atmosphere as a function of energy. Two energy estimation algorithms for the same showers: 1 - Eq. 2.1; 2 - Eq. 2.2.

exponentially (as in Eq. 2.1), or as a sum of two exponentials according to the second method (as in Eq. 2.2) – in terms of the depth in the atmosphere, $x = x_0 \sec(\theta)$, g/cm^2, in inclined showers [35, 36, 4]. Hence, two parameters in the formula are adjustable in order to fit the experimental data.

In Fig. 3, zenith angle distributions are shown in four energy intervals together with fitted Approx. 3.1, where data histograms are represented by points in the middle of the bins for convenience. Energy is estimated using Eq. 2.1.

4. Absorption of showers in the atmosphere

In our approach, EASs are absorbed where S_{600} is under threshold. Asymptotically, at the highest energies, the zenith angle distribution of showers reaches that formed by the isotropic CR flux (no absorption). In terms of depth in the atmosphere, absorption of EAS is approximated by exponential with the length, λ, depending on energy. The EAS flux at x is

$$J(x) = \frac{4}{3} J_0 \sin(2\theta) \frac{d\theta}{dx} exp(-\frac{x - x_0}{\lambda}), \tag{4.1}$$

where $d\theta/dx = x_0/(x\sqrt{x^2 - x_0^2})$; $\theta < 60^0$.

Experimental data from the Yakutsk array demonstrate that the absorption length of showers is indeed rising with energy (Fig. 4) to the asymptotic value of infinity, at least, in the case of the energy estimation using Eq. 2.1.

Analogous values were gathered previously from measurements [9, 38, 39], but a difference is that they used ‘the attenuation length’ in exponential conversion factor of the observed density at zenith angle θ to the vertical direction.

Attenuation of the particle density in detectors below the threshold value results in reducing the effective detection area of the array, S_{eff}. The effect is related to the zenith angle distribution

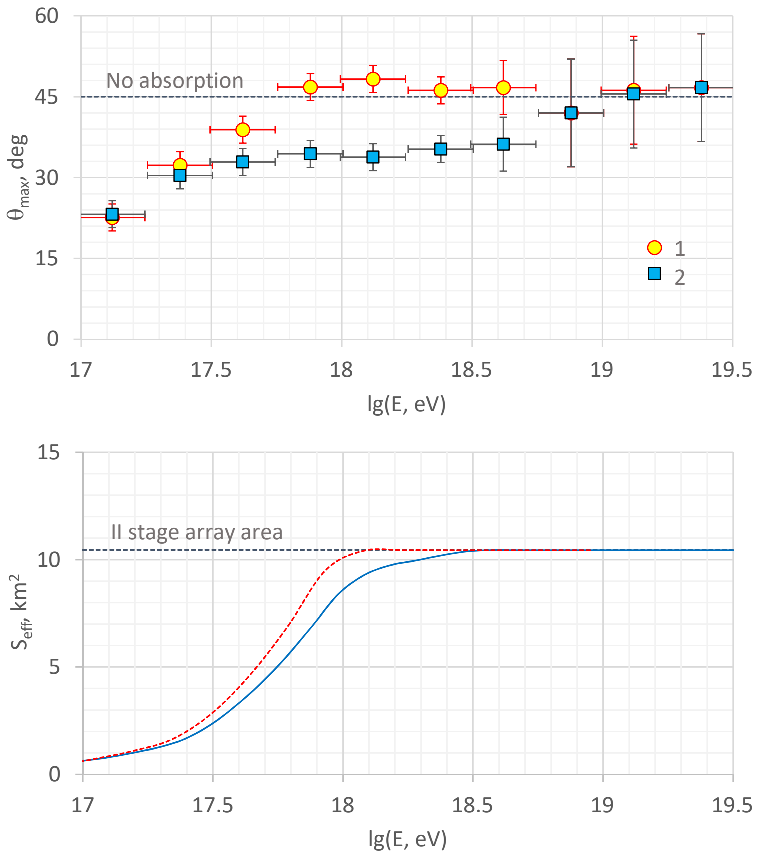

Figure 5: Upper panel: Zenith angle distribution maximum versus energy. Data symbols are the same as in the previous figure. Bottom panel: Effective area of the Yakutsk array (stage II) for the vertical showers as a function of energy.

of showers shifting to small angles (Figs. 2 and 3) at lower energies. Two effects can be used to test the validity of the energy estimation algorithms: (Eqs. 2.1 and 2.2), in our case.

In order to digitize the displacements of distributions, the position of the maximum, θ_{max}, is used as a function of energy in Fig. 5 (upper half). The Monte Carlo method is applied to calculate the effective area of the Yakutsk array for the artificial vertical showers shown in the bottom panel.

EAS event selection steps described in Section II were simulated numerically. The actual configuration of the stage II array stations (in the period 1990–2000) was used to trigger events with axes within the array area. An NKG-type approximation of the average lateral density distribution of particles measured with the array was used to calculate the signal in the detectors [2, 37]. The results are given in Fig. 5. Two energy estimation methods were consistent qualitatively with $S_{eff}(E)$ behavior but none of them met the demands of quantitative agreement. Therefore, we used both equations in the analysis.

5. Conclusions

The absorption of cosmic ray showers in the atmosphere was analyzed using data from the

Yakutsk extensive air shower array. In particular, the zenith angle distribution of the event rate measured with a predetermined density threshold for the particle density at 600 m from the shower core, $S_{600} > 0.1$ m^{-2}, was described analytically assuming log-normal parameter dispersion and isotropic CR arrival directions.

A necessary condition for effective modeling is controllable absorption of showers in the atmosphere, which is provided by the S_{600} threshold in the case of the Yakutsk array data. The measured absorption length of showers rose with energy to the asymptotic value inherent for isotropic CRs with no absorption.

The results are applicable in testing for uniformity of CR arrival directions and in searching for their sources using data from surface arrays.

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