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Estimation of the giant shower energy at the Yakutsk EAS Array

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The main relations used at the Yakutsk EAS array for determining the shower energy by the measured parameter S_{600} are presented. The calorimetric formula obtained for the vertical showers based on measurements the Cherenkov EAS light is used. The dependence of S_{600} on zenith angle has been defined more exactly. The individual giant showers detected at the Yakutsk array and main errors in the estimation of the energy in those events are analyzed.

1. Introduction

Intensity determination of particles with an energy below and above the spectrum cutoff predicted by K. Greisen [1] and G.T. Zatsepin, V.A. Kuzmin (GZK-cutoff near 10^{20} eV) [2] remains the important problem of cosmic rays research. The spectrum form by all experimental data [3,4,5] correspond to the assumption that the particles with the energy $E_0>10^{19}$ is of extragalactic origin [6,7]. In this case the GZK-cutoff should be observed. The previous results of the Yakutsk array and HiRes are in correspondence with it, but the AGASA data are contradictory to such a conclusion. The most reasonable explanation of this contradiction is a systematic difference in the estimation of energy in the individual showers in different experiments. So it is important to study all possible systematic and random errors in determination of shower parameters and estimation of energy.

2. Determination of EAS energy at the Yakutsk array

The relationship of parameter S_{600} to the energy of primary particle E_0 for showers close to the vertical at the Yakutsk array has been determined by the calorimetric method. The energy dissipated by the shower above the observation level is estimated using experimental measurements of EAS Cherenkov light [8]. For showers with a zenith angle θ=0° (the atmospheric depth X_0 = 1020 g/cm^2) the following formula has been obtained:

$$E_0 = (4.6 \pm 1.2) \cdot 10^{17} \cdot S_{600}(0^\circ)^{0.98\pm0.02}, \text{ eV} \tag{1}$$

The relative error of coefficient in (1) (≈25%) is mainly determined by the accuracy of calibration of Cherenkov light detectors and in the error in determination of the average atmosphere transparency. It doesn't influence the spectrum form but it is substantial for the estimation of intensity.

In order determine the primary energy in the individual showers using the formula (1), it is necessary to recalculate the value of $S_{600}(\theta)$ for a zenith angle θ to θ=0°. For this case we have used the dependence:

$$S_{600}(\theta) = S_{600}(0^\circ) \cdot \left[(1-\beta_{600}) \cdot \exp((X_0 - X)/\lambda_E) + \beta_{600} \cdot \exp((X_0 - X)/\lambda_M)\right] \tag{2}$$

where $X = X_0 / \cos(\theta)$, λ_E is the attenuation length of soft component, λ_M is the length of hard component (connected with muon), β_{600} is a portion of hard component in $S_{600}(0°)$ at the X_0. Earlier [8] we used the fixed value $\lambda_E = 200$ g/cm^2 and $\lambda_M = 1000$ g/cm^2 both for the parameters S_{300} and S_{600} and we determined β according to the experimental zenith-angular dependence. These values λ_E and λ_M have been chosen on the basis of calculation by QGS model for S_{300} but according to this model $\lambda_E = 250$ g/cm^2 and $\lambda_M = 2500$ g/cm^2 are better suited for S_{600}. If we use such values for attenuation, then the parameter β_{600} will be obtained:

$$\beta_{600} = (0.39 \pm 0.04)\cdot S_{600}(0^\circ)^{-0.12 \pm 0.03} \quad (3)$$

Fig. 1 presents the experimental data for zenith-angular dependence, the lines show the change of S_{600} by the formulae (2) and (3). It is seen that the curves are in a good correspondence with the experiment up to the depth 2800 g/cm^2 ($\theta \approx 70°$).

In energy determination for the account of different atmospheric conditions the parameter $S_{600}(\theta)$ is corrected to the Moliere unit R_0 = 68 m. It corresponds to the average temperature of season of Cherenkov light measurement. The value of this correction can reach 15% in absolute value.

The errors in determination of the parameter S_{600} and zenith angle directions make the considerable contribution into error of energy estimation in the individual events. For the largest events registered at Yakutsk and AGASA experiments the weight of data at large distances (R>1000 m) from the core is too high. So S_{600} depends on the lateral distribution function (LDF) of shower particles at such distances used in core location procedure. Earlier we have used the LDF which for showers with $E_0 > 10^{19}$ eV at R>1000 m is flatter than experimental data show. In 2004 for giant showers ($E_0 > 2\cdot 10^{19}$ eV) we have determined the axis by the adjusted lateral distribution [3]. As a result of new estimation parameters of S_{600} have increased, on the average, by ≈10 % for events inside array borders and by 20 % in the effective area outside the array.

One can obtain the shifted estimation of S_{600} if there are factors distorting the density of particles in measurements. At large distances from the axis (>1500 m) the temporal shower front is enough wide. At Yakutsk and AGASA a nearly similar RC–converters are used (τ=10 μs). At the Yakutsk array the input of converters is closed in 2 μs after the onset of signal. In the case when the shower front is wide, this may result in the underestimation of density. At AGASA input is constantly opened and in the case of a wide signal this may lead to a density overestimation due to converter's features.

To check the degree of influence of the front width we have simulated the reaction of converters at distances R>1000 m based on the particle distribution approximation obtained at AGASA [9]. The simulation has shown that for the system of density measurement at the Yakutsk array there is no the essential underestimation of the shower particle density up to 2000 m from the axis (<10%) [3].

In the case of AGASA, when the input of RC–converter is constantly opened, besides a wide distribution, there is a density overestimation because of delayed particles or because of casual additives from background muons. From the data in [9] one can conclude that delayed particles can overstate the density by factor 1.4 already at 500 m and more from the axis. Background muons may cause distortions in a wide range of axis distances. If one such particle hits within last 10 μs of RC–circuit discharge, then resulting density can be overestimated by factor of 2 and more independently of the real density. The last effects are excluded at the Yakutsk array due to closing of converter's input in 2 μs.

Errors in determination of the arrival direction and parameter S_{600} in the individual showers depends on the core location. For events with $E_0 > 2\cdot 10^{19}$ eV whose axis is located inside the array , the error in zenith angle is $\delta\theta = 2°$ and the error in arrival direction is about 3°. The relative error $\delta S_{600}/S_{600}$ is equal to 15% [10]. In the effective zone outside the array borders these errors increase and on the average $\delta S_{600}/S_{600}$=35% and $\delta\theta$=3.5°. The total arrival direction error is 5°.

3. Discussion and Conclusions

Table 1 presents a list of showers with the energy above $4 \cdot 10^{19}$ eV registered at the Yakutsk array before June 2004, whose axis is located inside borders. Table 2 shows the events registered in the effective area outside the array. In the column δE/E there is a random relative error of the energy estimation of individual event determined the average errors $\delta S_{600}/S_{600}$, zenith angle $\delta\theta$, parameter errors in formula 3 and error in the exponent in (1). The error determined by the uncertainty of coefficient in (1) is no taken into account. The mean error of energy estimation for showers from Table 1 is 23% and 41% for Table 2 respectively. At AGASA there exist the analogue experimental errors. According to [10] they account for 20% on the average.

The uncertainty of coefficient in formula (1) leads to the systematic shift of energy estimation of all events. The formula (1) has been obtained from experimental data of the Yakutsk array and doesn't depend on the model assumptions on the cascade development in the atmosphere. It establishes the relation between the energy and density measured by scintillation detectors. At AGASA to estimate the energy in vertical showers the relation between S_{600} and E_0 obtained on the basis of calculations by models is used [9]. This formula is between the energy and sum of electron and muon densities. Energy losses in the scintillation detector measured in equivalent muons can significantly differ from such a sum. Our formula (1) at $E_0 = 5 \cdot 10^{19}$ eV gives the estimation 15-20% higher than it follows from the calculations by analogous models.

As a result of more precise determination of LDF and additional exposition at the Yakutsk array at present there are four events with $E_0 > 9 \cdot 10^{19}$ eV that indicates to the absence of GZK-cutoff of the spectrum. But because of poor statistics and errors in the energy determination this conclusion is not so reliable.

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Table 1. List of events with $E_0 > 4 \cdot 10^{19}$ eV recorded at the Yakutsk EAS array within array borders. $\delta S/S(\theta)=0.15$, $\delta\theta=2^\circ$. The total error in direction determination is 3°.

N	E_0, eV	θ	δE/E	RA	Dec	N	E_0, eV	θ	δE/E	RA	Dec
1	5.4E+19	41.7	0.23	163.6	52.9	18	4.1E+19	54.9	0.30	8.7	36.3
2	7.0E+19	52.2	0.30	183.3	35.6	19	4.4E+19	36.9	0.21	167.8	78.0
3	4.2E+19	41.4	0.22	235.1	23.1	20	5.6E+19	23.9	0.19	108.9	37.8
4	1.1E+20	46.1	0.27	150.7	16.1	21	1.5E+20	58.7	0.40	75.2	45.6
5	6.4E+19	22.8	0.19	270.3	67.6	22	4.0E+19	58.5	0.32	23.8	57.5
6	5.3E+19	43.1	0.23	297.7	33.5	23	6.5E+19	49.1	0.28	283.5	29.4
7	4.2E+19	10.3	0.17	43.2	57.4	24	4.6E+19	29.3	0.19	119.6	37.3
8	5.3E+19	37.3	0.21	47.9	24.9	25	7.5E+19	34.2	0.21	69.1	74.8
9	4.5E+19	32.5	0.20	302.8	70.2	26	8.5E+19	55.7	0.34	131.3	60.6
10	5.4E+19	32.8	0.20	46.9	29.2	27	6.2E+19	41.0	0.23	92.6	74.0
11	4.8E+19	32.6	0.20	85.1	63.3	28	5.6E+19	27.4	0.19	315.0	57.8
12	4.4E+19	11.2	0.18	343.0	65.8	29	4.9E+19	16.1	0.18	21.3	45.7
13	6.4E+19	23.8	0.19	184.1	47.0	30	4.9E+19	12.3	0.18	58.1	60.9
14	8.2E+19	44.9	0.25	55.7	19.6	31	5.3E+19	20.6	0.18	274.3	54.5
15	6.8E+19	20.4	0.19	335.2	51.0	32	4.9E+19	26.2	0.19	351.0	72.9
16	6.2E+19	48.7	0.27	297.3	45.2	33	5.0E+19	9.2	0.18	128.7	59.6
17	4.6E+19	51.1	0.28	218.1	50.4	34	6.4E+19	44.2	0.24	191.0	42.9

Table 2. List of events with $E_0 > 4\cdot10^{19}$ eV recorded at the Yakutsk EAS array within the additional area, outside the main array area. $\delta S/S(\theta)=0.35$, $\delta\theta=3.5^\circ$. The total error in direction determination is 5°

N	E_0, eV	θ	δE/E	RA	Dec	N	E_0, eV	θ	δE/E	RA	Dec
1	6.6E+19	42.3	0.41	253.6	74.1	10	6.0E+19	34.7	0.39	94.7	29.3
2	5.5E+19	9.2	0.36	78.5	62.6	11	7.3E+19	16.5	0.36	126.6	63.1
3	4.0E+19	45.2	0.41	17.8	68.6	12	5.5E+19	5.7	0.36	270.5	64.5
4	5.2E+19	47.5	0.43	16.0	32.2	13	6.5E+19	57.4	0.48	123.5	5.0
5	9.8E+19	9.6	0.36	309.5	67.1	14	5.8E+19	42.6	0.41	356.3	23.9
6	4.1E+19	55.9	0.45	50.2	19.0	15	6.7E+19	18.9	0.36	167.0	69.4
7	6.5E+19	57.8	0.48	249.8	56.4	16	7.3E+19	42.8	0.42	179.1	62.5
8	7.3E+19	22.2	0.37	283.9	49.8	17	1.6E+20	47.7	0.46	70.9	70.6
9	4.5E+19	59.0	0.47	275.5	3.1						

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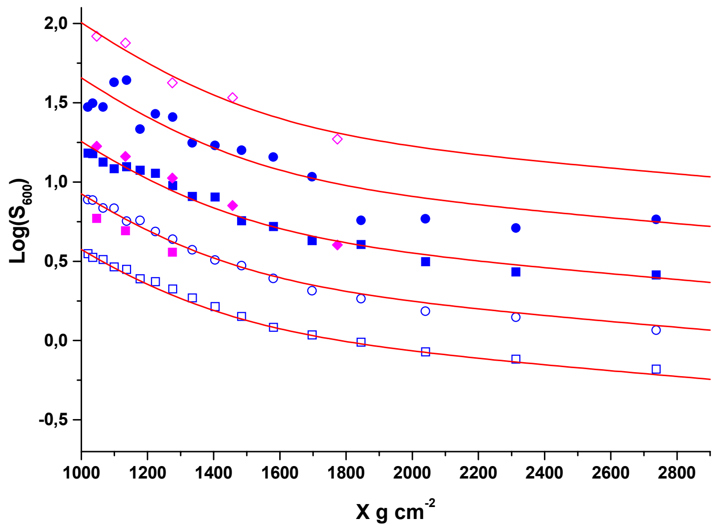

Figure 1. S_{600} versus the atmospheric depth X for different energies. The lines show the change of S_{600} by the dependence (2) with $\lambda_E = 250$ g/cm², $\lambda_M = 2500$ g/cm². Parameter β_{600} is determined by the formulae (3).