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Zenith-Angle dependance of $\rho_{s,600}$ and $\rho_{\mu,600}$ in the giant air showers

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Abstract. The joint analysis results of Yakutsk and AGASA array data on the zenith-angle dependence of the paparameters $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ – densities of the charged distance of 600 m from the core of giant air showers (GAS) with the energy $E_o \geq 10^{19}$ eV are given. These results are compared with calculations by the QGSJET model for the primary protons. It is shown that at $E_o \leq 2\times10^{18}$ eV this model agrees well with data of both arrays and contradicts to GAS data. The experiments testify that at $E_o \geq (3–5)\times10^{18}$ eV the lateral structure of showers changes. This is probably related to some new processes of their development. The neglection of this peculiarity in development of GAS leads to the essentially overstated (by 1.5–2.5 times) estimations of the primary particle energy.

1 Introduction

Already the first observations of extensive air showers (EAS) at the largest arrays (Linsley, 1963; Edge, 1973; Bell, 1974; Krasilnikov, 1974) allowed to detect giant air showers (GAS) with $E_0 > 10^{19}$ eV. After the discovery of the cosmic microwave background it was shown by Greisen (1966) and Zatsepin & Kuzmin (1966) that due to interactions of the primary protons and nuclei with this radiation their flux at $E_0 > 3\times10^{19}$ eV must be sharply decreased. The observations of GAS with $E_0 \sim (1–3)\times10^{20}$ eV are in contradict with this prediction.

To study of the GAS energy spectrum the larger arrays are created. At present the AGASA of ~ 100 km^2 area operates. Also new arrays are projected and constructed with the area of ~ 1000–5000 km^2 with a distance of 1–1.5 km between the detectors (Khristiansen, 1992; Cronin, 1992; Teshima, 1993).

The giant arrays increase the numbers of GAS. However, the answer to the question about the limit of the cosmic ray energy should be sought, first of all, in more detailed study of the GAS structure. Data obtained at the Yakutsk EAS array show that at $E_0 > (3–5)\times10^{18}$ eV the showers develop otherwise, than at smaller energies (Glushkov, 1995; Glushkov, 1997; Glushkov, 1998; Glushkov, 1999; Glushkov, 2000a; Glushkov, 2000b).

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Here we give information about GAS registered at the Yakutsk EAS array for the 1974 to 2000 period. The obtained results are compared with our calculations by the QGSJET model of Kalmykov (1995) which reproduce very well a big set of experimental data of EAS with $E_0 \leq (2\text{-}3)\times10^{18}$ eV (Glushkov, 1995; Glushkov, 1997; Kalmykov, 1997; Glushkov, 1998; Glushkov, 1999; Glushkov, 2000a; Glushkov, 2000b). Our results have been added by experimental data of the AGASA collaboration (Nagano, 1998; Takeda, 1999).

2 Characteristics under investigation and discussions

Below we consider, mainly, the zenith-angular dependences $\rho_{\mu,600}(\theta)$ and $\rho_{s,600}(\theta)$ – densities of muons ($E_\mu \approx 1.0 \cdot sec\theta$ GeV) and all charged particles at a distance R = 600 m from the shower axis. To determine E_0 we use for Yakutsk array (the depth of the atmosphere X_{Ya} = 1020 g/cm^2) the following relations:

$$E_0 = (4.8 \pm 1.6)\times10^{17} \cdot (\rho_{s,\,600}(0°))^{1.0 \pm 0.02} \quad [\text{eV}], \qquad (1)$$
$$\rho_{s,600}(0°) = \rho_{s,\,600}(\theta) \cdot exp((sec\theta - 1) \cdot X_{Ya} / \lambda_\rho) \quad [\text{m}^{-2}], \qquad (2)$$
$$\lambda_\rho = (450 \pm 44) + (32 \pm 15) \cdot log(\rho_{s,600}(0°)) \quad [\text{g/cm}^2], \qquad 3)$$

obtained by the calorimetric method (Efimov, 1991). For the AGASA (X_A = 920 g/cm^2) the following dependences are used (Nagano, 1998):

$$E_0 = 2.0\times10^{17} \cdot (\rho_{s,\,600}(0°))^{1.0} \quad [\text{eV}], \qquad (4)$$
$$\rho_{s,600}(0°) = \rho_{s,\,600}(\theta) \cdot exp((sec\theta - 1) \cdot X_A / 500 + (sec\theta - 1)^2 \cdot X_A / 594) \quad [\text{m}^{-2}]. \qquad (5)$$

obtained as the average value of different models of EAS development.

Experimental data are compared with the QGSJET model for the primary protons. The calculation is made for the atmosphere depths X_{Ya} and X_A The lateral distribution functions (LDF) all charged particles are found as $\rho_{ch} = \rho_e(\geq 1.0\ \text{MeV}) + \rho_\mu\ (\geq 0.01\ \text{GeV})$. The parameters $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ are determined from the average LDF in groups with $\Delta cos\theta = 0.1$ and $\Delta log\ E_0 = 0.2$.

According to the QGSJET model we obtain for the Yakutsk array

$E_0 = 3.48\times10^{17}\cdot(\rho_{ch,600}(0°))^{\,1.0 \pm 0.01}$ [eV], (6)
$E_0 = 2.40\times10^{18}\cdot(\rho_{\mu,600}(0°))^{\,1.08 \pm 0.01}$ [eV], (7)

and for AGASA

$E_0 = 2.04\times10^{17}\cdot(\rho_{ch,600}(0°))^{\,1.04 \pm 0.01}$ [eV], (8)
$E_0 = 2.5\times10^{18}\cdot(\rho_{\mu,600}(0°))^{\,1.14 \pm 0.02}$ [eV]. (9)

It is seen that (1) in comparison with (6) leads to excessive values E_0 by ~ 1.4 times, and (4) and (8) are practically consistent with each other.

Figure.1 demonstrates LDF's of all charged particles (circles) and muons (triangles) in EAS with $E_0 = 2\times10^{18}$ eV and $cos\theta \geq 0.95$ by Yakutsk array data (dark symbols) and AGASA (open circles). The solid curves are LDFs calculated for X_{Ya}, the dashed ones – the same for X_A. It is seen that the calculation does not contradict to measured LDFs for the two components of EAS.

Figure2(*a*) shows the zenith-angular dependences $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ in EAS with $E_0 = 2\times10^{18}$ eV. The dark symbols and solid curves are experimental data and calculations relating to the Yakutsk array for the charged particles (1), muons (2) and electrons (3). According to the experiment, $\rho_e = \rho_s - k(\theta)\cdot\rho_\mu(E_\mu \geq 1.0\cdot sec\theta$ ГэВ). The multiplier $k(\theta) = 1.25–1.4$ has been taken from the calculation by QGSJET model. The open circles are experimental AGASA values $\rho_{s,600}(\theta)$, obtained by the equal-intensity method (Nagano, 1998), the open triangles are $\rho_{\mu,600}(\theta)$ with $E_\mu \approx 1.0\cdot sec\theta$ ГэВ at this array (Yoshida, 1994).

Here it is also observed the agreement in theory and experiment by all three EAS components. Besides, it is

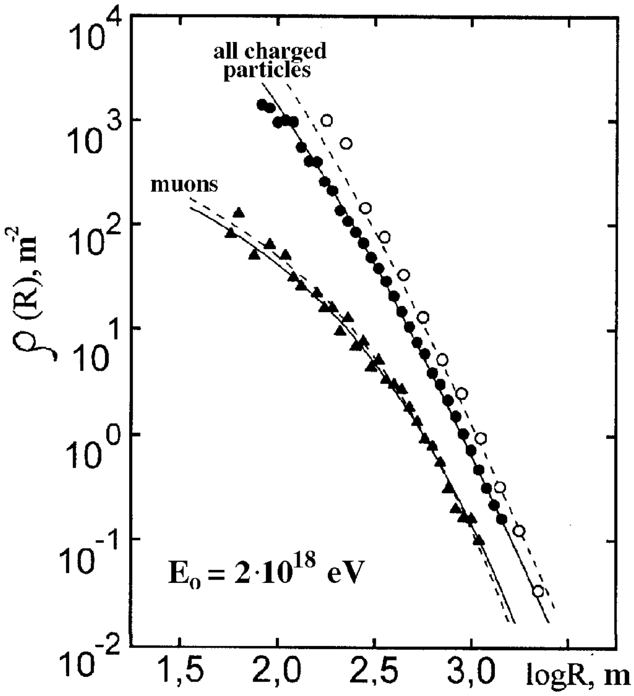

Fig.1

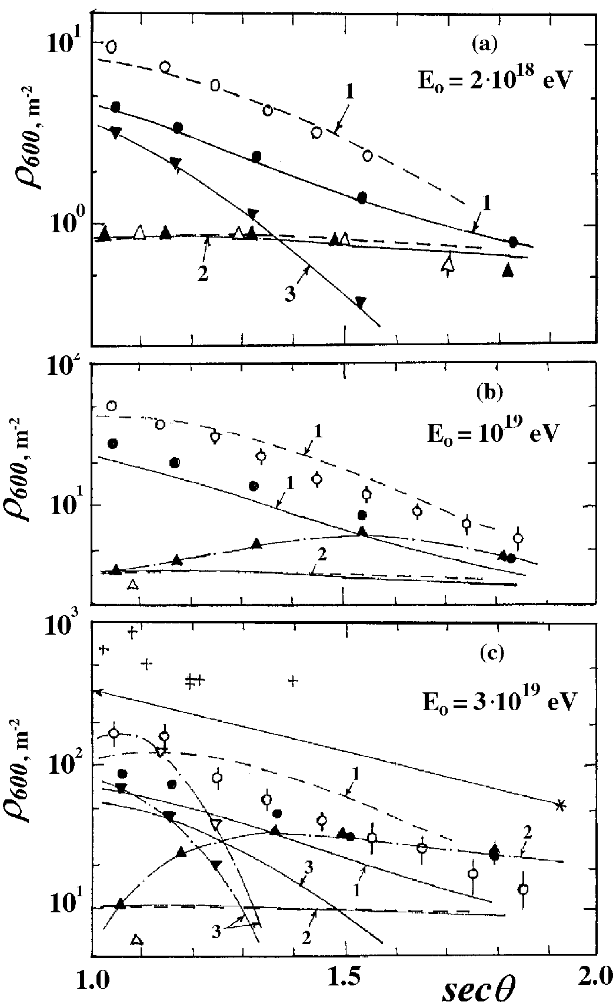

Fig.2

seen that the density $\rho_{\mu,600}(\theta)$ does not depend on the atmosphere depth at $\theta \leq 50°$ and it is a convenient parameter to estimate E_0 at the arrays with different location above sea level.

In GAS there is no such agreement. The Yakutsk array data show that at $E_0 = 10^{19}$ eV the measured E_0 are higher by 1.25 times than the calculated ones (Fig.2(*b*)). Values $\rho_{\mu,600}(\theta)$ (the dash-and-dot line), which coincide with $\rho_{s,600}(\theta)$ in the inclined events ($\theta \geq 52°$), undergo stronger changes. In AGASA data a tendency is evident to decrease experimental data of $\rho_{s,600}(\theta)$ by 1.25 times at $\theta \approx 35$-$50°$.

The above marked anomaly in GAS development is quickly intensified as E_0 increases. It is seen well in Fig.3(*c*). All experimental data at energy $E_0 = 3\times10^{19}$ eV completely contradict to the QGSJET model. The outlined change of $\rho_{\mu,600}(\theta)$ in Yakutsk array data (the dash-and-dot line 2) is still more intensified. It is about a triple increase in comparison with calculations at $\theta \geq 35°$.

Experimental values $\rho_{s,600}(\theta)$ for not so inclined GAS are by ~ 1.4 times more than the calculated ones, and at $\theta \geq 45°$ they coincide with $\rho_{\mu,600}(\theta)$. The measured AGASA values of $\rho_{s,600}(\theta)$ at $\theta \leq 30°$ are also more than calculated ones by ~ 1.4 times, and in more inclined EAS they quickly decrease. At $\theta \geq 37°$ they are lower by ~ 1.4 times than calculated ones and at $\theta \geq 45°$ they are analogous to the Yakutsk array data.

Hence it follows that in these showers at the mentioned distance from a core at $\theta \geq 45°$ only muons with the energy $E_\mu \geq 1.5$ GeV are registered. Here "softer" muons and especially electrons are absent as it is observed in the same inclined EAS with $E_0 \leq 2\times10^{18}$ eV (Fig.2(*a*)). The electron densities $\rho_{e,600}(\theta)$ not only anomalously quickly decrease with the increase of a zenith angle (the cross-dashed lines in Fig.3(*b*)) but also exceed the calculated values in near to the vertical ($\theta \leq 20°$) GAS by ~ 1.4 times.

Apparently, with the approach of the GAS energy to the limited value, the above-mentioned tendency will further increase. The neglection of this factor and the formal use of the relationships (1–9) can lead to the large mistakes in estimations of E_0.

By the asterisk in Fig.2(*c*) $\rho_{s,600}(58.7°) \approx \rho_{\mu,600}(58.7°) = 54$ m^{-2} – the largest shower from the registered ones at the Yakutsk EAS array is shown (Efimov, 1990). Arrows show the recalculation of this density to the vertical with λ_ρ = 530 g/cm^2, according to (3). The relationship (1) gives $E_0 = 1.55\times10^{20}$ eV.

Practically the energy of this GAS is considerably less. If to take into account the fact that the measured $\rho_{s,600}(\theta)$ in Fig.3(*b*) at $sec\theta \approx 1.9$ is more than the calculated one by a factor of ~ 2.5 (the corrected density – 54/2.5 = 21.6 m^{-2}), to recalculate it to the vertical case by the theoretical curve 1 ($\rho_{s,600}(0°) = 172$ m^{-2}) and use (6) then we obtain $E_0 \approx 6\times10^{19}$ eV. From $\rho_{\mu,600}(58.7°)$ (the more precise value – 54/2.3 = 23.5 m^{-2}) and (7) it follows $E_0 \approx 5.6\times10^{19}$ eV.

By the AGASA group (Takeda, 1999) $\rho_{s,600}(\theta)$ values of seven GAS with $E_0 \geq 10^{20}$ eV is shown by crosses in Fig.2(*c*). Curiously, that these events are observed at $sec\theta \leq 1.22$ ($\theta \leq 35°$) where $\rho_{s,600}(\theta)$ (open circles) have the relative peak. Nonrandom character of such distribution is confirmed by a histogram in Fig.3 from 48 GAS with $E_0 \geq 4\times10^{19}$ eV and $\theta \leq 45°$ (Takeda, 1999). The events in the intervals $\Delta cos(\theta) = 0.1$ are divided into $cos(\theta)$.

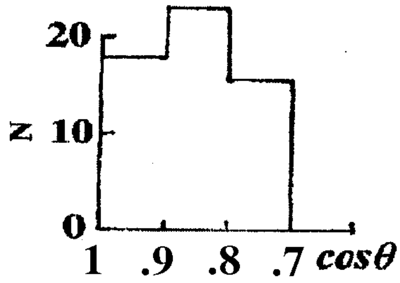

Fig.3

3 Conclusion

From the above and results (Glushkov, 1995; Glushkov, 1997; Glushkov, 1998; Glushkov, 1999; Glushkov, 2000a; Glushkov, 2000b) the following picture arises. In the energy region $E_0 \leq 2\times10^{18}$ eV the experimental data from the Yakutsk array and AGASA don't contradict to the QGSJET model for the primary protons. EAS with $E_0 \geq (3–5)\times10^{18}$ eV develop in another way. As the energy increases the lateral structure of EAS substantially changes. In the inclined events ($\theta > 35$-$40°$) the portion of muons noticeably increases. In this case the muon component undergoes stronger changes. This changes are not explained in the framework of the QGSJET model and require another notion about the GAS development. Any extrapolations of theoretical and experimental dependencies (made at $E_0 \leq (2–3)\times10^{18}$ eV) into this region are not allowed. They can lead to large mistakes in the estimations of the primary particle energy. Here the separate studies of the LDF of charged particles and muons at arrays with detector separations not more than 200–300 m are necessary.

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