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 parameters $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ – densities of the charged distance of 600 m from the core of giant air showers (GAS) with the energy $E_0 \geq 10^{19}$ eV are given. These results are compared with calculations by the QGSJET model for the primary protons. The calculation is made for $E_0 \geq (2\text{–}3) \times 10^{19}$ eV (Glushkov, 1995; Glushkov, 1997; Kalmykov, 1997; Glushkov, 1998; Glushkov, 2000a; Glushkov, 2000b). Our results have been added by experimental data of the AGASA collaboration (Nagano, 1998; Takeda, 1999).

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 $E_0 > 10^{15}$ 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 $E_0 > 3 \times 10^{19}$ eV must be sharply decreased. The observations of GAS with $E_0 \sim (1\text{–}3) \times 10^{20}$ eV are in contrast with this prediction.

To study of the GAS energy spectrum the larger arrays are created. At present the AGASA of ~ 100 km² area operates. Also new arrays are projected and constructed with the area of ~ 1000–5000 km² 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 $E_0 > (3\text{–}5) \times 10^{18}$ eV the showers develop otherwise, than at smaller energies (Glushkov, 1995; Glushkov, 1997; Glushkov, 1998; Glushkov, 1999; Glushkov, 2000a; Glushkov, 2000b).

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 GAS with $E_0 \leq (2\text{–}3) \times 10^{19}$ 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 $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ – densities of muons ($E_\mu = 1.0 \text{ sec} \theta$ 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 $X_{100} = 1020$ g/cm²) the following relations:

\[ E_0 = (4.8 \pm 1.6) \times 10^{17} \cdot (\rho_{s,600}(0^\circ))^{1.0 \pm 0.02} [\text{eV}], \]  
\[ \rho_{s,600}(0^\circ) = \rho_{s,600}(\theta) \cdot \exp((\sec \theta - 1) \cdot X_{100} / \lambda_p) \text{[m}^2\text{]}, \]  
\[ \lambda_p = (450 \pm 44) + (32 \pm 15) \cdot \log(\rho_{s,600}(0^\circ)) \text{[g/cm}^2\text{]}. \]

obtained by the calorimetric method (Efimov, 1991). For the AGASA ($X_A = 920$ g/cm²) the following dependences are used (Nagano, 1998):

\[ E_0 = 2.0 \times 10^{17} \cdot (\rho_{s,600}(0^\circ))^{1.0} [\text{eV}], \]  
\[ \rho_{s,600}(0^\circ) = \rho_{s,600}(\theta) \cdot \exp((\sec \theta - 1) \cdot X_A / 500 + (\sec \theta - 1)^2 \cdot X_A / 594) \text{[m}^2\text{]}]. \]

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 $X_{100}$ and $X_A$. The lateral distribution functions (LDF) all charged particles are found as $\rho_{l,h} = \rho_{l}(\geq 1.0$ MeV) + $\rho_{p} (\geq 0.01$ 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

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\[ E_0 = 3.48 \times 10^{17} \cdot (\rho_{ch,600}(0^\circ))^{1.0^{+0.01}} \cdot (\rho_{ch,600}(0^\circ))^{1.0^{+0.01}} \quad [\text{eV}], \] (6)
\[ E_0 = 2.40 \times 10^{18} \cdot (\rho_{\mu,600}(0^\circ))^{1.08^{+0.01}} \cdot (\rho_{\mu,600}(0^\circ))^{1.08^{+0.01}} \quad [\text{eV}], \] (7)

and for AGASA

\[ E_0 = 2.04 \times 10^{17} \cdot (\rho_{ch,600}(0^\circ))^{1.04^{+0.01}} \cdot (\rho_{ch,600}(0^\circ))^{1.04^{+0.01}} \quad [\text{eV}], \] (8)
\[ E_0 = 2.5 \times 10^{18} \cdot (\rho_{\mu,600}(0^\circ))^{1.14^{+0.02}} \cdot (\rho_{\mu,600}(0^\circ))^{1.14^{+0.02}} \quad [\text{eV}]. \] (9)

It is seen that (1) in comparison with (6) leads to excessive values \( E_0 \) by \( \sim 1.4 \) 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 \( E_0 = 2 \times 10^{18} \) 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.

Figure 2(a) shows the zenith-angular dependences \( \rho_{\mu,600}(\theta) \) and \( \rho_{\mu,600}(\theta) \) in EAS with \( E_0 = 2 \times 10^{18} \) 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, \( \rho_s = k(\theta) \cdot \rho_s(E_\mu \geq 1.0 \cdot \sec \theta \Gamma \geq B) \). The multiplier \( k(\theta) = 1.25 \) has been taken from the calculation by QGSJET model. The open circles are experimental AGASA values \( \rho_{\mu,600}(\theta) \), obtained by the equal-intensity method (Nagano, 1998), the open triangles are \( \rho_{\mu,600}(\theta) \) with \( E_\mu = 1.0 \cdot \sec \theta \Gamma \geq B \) at this array (Yoshida, 1994).

Here it is also observed the agreement in theory and experiment by all three EAS components. Besides, it is seen that the density \( \rho_{\mu,600}(\theta) \) does not depend on the atmosphere depth at \( \theta \leq 50^\circ \) 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 \( \rho_{\mu,600}(\theta) \) in the inclined events (\( \theta \geq 52^\circ \)), undergo stronger changes. In AGASA data a tendency is evident to decrease experimental data of \( \rho_{\mu,600}(\theta) \) by \( 1.25 \) times at \( \theta \approx 35-50^\circ \).

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 \( E_0 = 3 \times 10^{19} \) 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 \( \theta \geq 35^\circ \).

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

Hence it follows that in these showers at the mentioned distance from a core at $\theta \geq 45^\circ$ 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 $E_0 \leq 2 \times 10^{18}$ eV (Fig.2(a)). The electron densities $\rho_{s,600}(\theta)$ 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 ($\theta \leq 20^\circ$) GAS by $\sim 1.4$ times.

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

By the asterisk in Fig.2(c) $\rho_{s,600}(58.7^\circ) = \rho_{s,600}(58.7^\circ) = 54$ m$^{-2}$ − the largest shower from the registered ones at the Yakutsk EAS array is shown (Efimov, 1990). Arrows show the recalculations of this density to the vertical with $\lambda_\rho = 530$ g/cm$^2$, according to (3). The relationship (1) gives $E_0 = 1.55 \times 10^{20}$ 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 $\sec \theta = 1.9$ is more than the calculated one by a factor of $\sim 2.5$ (the corrected density $\sim 54/2.5 = 21.6$ m$^2$), to recalculate it to the vertical case by the theoretical curve 1 ($\rho_{s,600}(0^\circ) = 172$ m$^2$) and use (6) then we obtain $E_0 = 6 \times 10^{19}$ eV. From $\rho_{s,600}(58.7^\circ)$ (the more precise value $\sim 54/2.3 = 23.5$ m$^2$) and (7) it follows $E_0 = 5.6 \times 10^{19}$ 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 $\sec \theta \leq 1.22$ ($\theta \leq 35^\circ$) 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 $E_0 \geq 4 \times 10^{19}$ eV and $\theta \leq 45^\circ$ (Takeda, 1999). The events in the intervals $\Delta \cos(\theta) = 0.1$ are divided into $\cos(\theta)$.

### 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 $E_0 \leq 2 \times 10^{18}$ eV the experimental data from the Yakutsk array and AGASA don’t contradict to the QGSJET model for the primary protons. EAS with $E_0 \geq (3-5) \times 10^{18}$ eV develop in another way. As the energy increases the lateral structure of EAS substantially changes. In the inclined events ($\theta > 35-40^\circ$) 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 $E_0 \leq (2-3) \times 10^{18}$ 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.

### References