Electrons and Muons in EAS at $E_o > 5{\cdot}10^{17}$ eV

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Abstract

Results of the analysis of the Yakutsk array muon ($E_\mu \approx 1.0{\cdot}\sec\theta$ GeV) and all charged particle data for 1974-1998 are presented. Their comparison with simulations in the framework of the QGSJET model for primary protons is discussed. It is shown that this model describes properly showers with $E_0 \le 2{\cdot}10^{18}$ eV and zenith angles $\theta \le 45°$. But the agreement disappears as the primary energy increases. Experimental data show that the spatial EAS structure changes at $E_0 \ge (3\text{-}5){\cdot}10^{18}$ eV. It may be caused by a new type of nuclear interactions at the initial stage of EAS development.

1. Introduction:

Experimental lateral distribution functions (LDFs) of muons with threshold energy $E_\mu \approx 1.0{\cdot}\sec\theta$ GeV and of charged particles in EAS obtained at the Yakutsk array were presented by Glushkov et. al. (1995, 1997). In these works an anomalous behaviour of LDF for the two components with $E_0 \ge (3\text{-}5){\cdot}10^{18}$ eV were noted. By the authors' opinion, it is associated with the some new prosesses of EAS development in the ultrahigh energy region.

To appreciate this, there is a need to have the EAS development model enough close to the experiment at $E_0 \le (1\text{-}3){\cdot}10^{18}$ eV. In present work we compare LDFs of charged particles and muons obtained at the Yakutsk array with calculations by the QGSJET model (Kalmykov, Ostapchenko & Pavlov, 1997) for primary protons. Deviations of EAS electrons and muons by the geomagnetic field have been taken into account since its influence is appreciable for all showers, among them the largest one (Antonov et al., 1998). The calculation has been carried out taking into account real conditions of experiment, selection method and data averaging.

2. Comparison of Experimental Results and Calculations:

We analyzed showers with zenith angles $\theta \le 60°$ and to treat experimental data and construct averaged LDFs used methods by Glushkov et al. (1995, 1997).

The lateral distribution of muons above 1 GeV is expressed by the following equation

$$\rho_\mu(r) = C_\mu \cdot r^{-0.75} \cdot (1+r)^{0.75-b_\mu} \cdot (1+r/r_\mu)^{-g_\mu}, \qquad (1)$$

where C_μ is a normalization factor, $r = R/280$, $r_\mu = 2000/280$, $g_\mu = 6.5$, b_μ is a parameter.

The lateral distribution of all charged particles is expressed by the following equation

$$\rho_s(r) = C_s \cdot r^{-1.3} \cdot (1+r)^{1.3-b_s} \cdot (1+r/r_s)^{-g_s}, \qquad (2)$$

where C_s is a normalization factor, $r = R/70$, $r_s = 2000/70$, b_s is a parameter. For $E_0 \le 10^{18}$ eV the parameter $g_s = 1$, and for $E_0 \ge (3\text{-}5){\cdot}10^{18}$ eV - $g_s = 3.5$.

Figures 1 and 2 show the measured (circles) LDFs in EAS with $\cos\theta \ge 0.95$ and $E_0 = 2{\cdot}10^{18}$ eV and $2{\cdot}10^{19}$ eV, respectively. Solid lines correspond to Eq. (1) and (2) with the best parameters b_μ and b_s found using the standard least squares method. Dashed lines are calculations in which charged particle densities

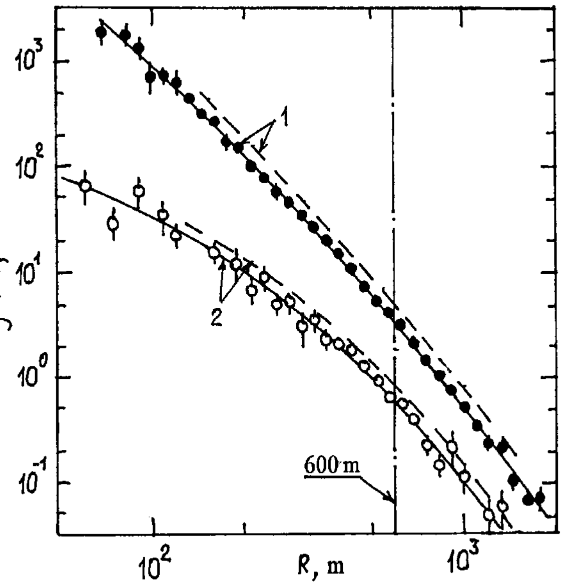

Figure 1. Lateral distributions of charged particles (•) and muons (o) with threshold energy $E_{\mu} \approx 1.0 \cdot \sec\theta$ GeV in EAS with $\langle\cos\theta\rangle = 0.98$ at $E_o = 2 \cdot 10^{18}$ eV. Lines 1 and 2 - Eq. (1) and (2) of experimental data (full) and obtained by the QGSJET model for primary protons (dashed)

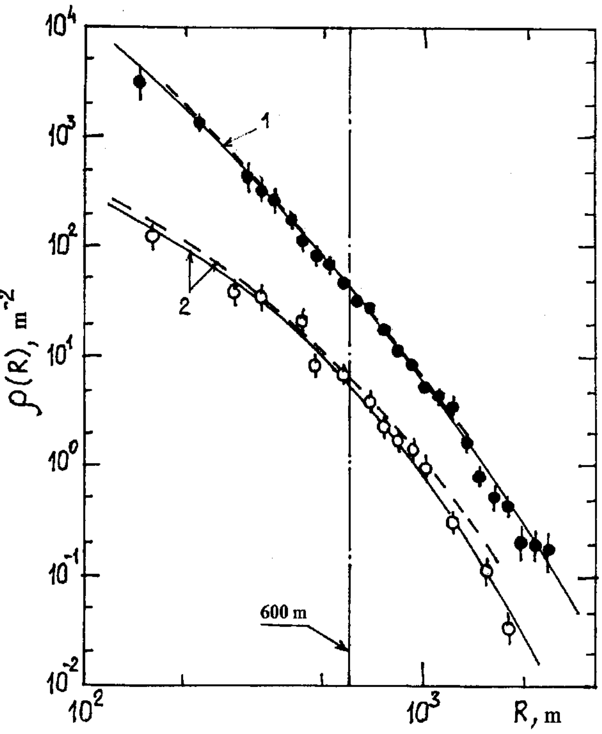

Figure 2. Same as in Fig.1 but at $E_o = 2 \cdot 10^{19}$ eV

were found as $\rho_{ch} = \rho_e(\geq 0.5 \text{ MeV}) + \rho_{\mu}(\geq 0.3 \text{ GeV})$. Main parameters of LDF are given in Table, where $\rho_{s,600}$ and $\rho_{\mu,600}$ are densities at a distance R = 600 m from the shower core, N_s and N_{μ} are the total number of charged particles and muons, respectively.

Table

E_o, eV	$2 \cdot 10^{18}$		$2 \cdot 10^{19}$	
	Experiment	QGSJET	Experiment	QGSJET
$\langle b_s \rangle$	3.50 ± 0.03	3.63 ± 0.01	3.19 ± 0.04	3.76 ± 0.01
g_s	1.0	1.0	3.5	1.0
$\log\langle\rho_{s,600}\rangle$	0.53 ± 0.03	0.64 ± 0.01	1.63 ± 0.02	1.63 ± 0.01
$\log\langle N_s \rangle$	8.51 ± 0.01	8.73 ± 0.01	9.62 ± 0.03	9.82 ± 0.01
$\langle b_{\mu} \rangle$	2.21 ± 0.04	2.08 ± 0.01	1.92 ± 0.06	2.12 ± 0.01
g_{μ}	6.5	6.5	8.0	6.5
$\log\langle\rho_{\mu,600}\rangle$	-0.19 ± 0.02	-0.07 ± 0.01	0.74 ± 0.05	0.84 ± 0.01
$\log\langle N_{\mu} \rangle$	6.86 ± 0.04	6.95 ± 0.01	7.82 ± 0.04	7.87 ± 0.01

The data analysis showed the measured LDFs for both components at $E_o \approx (5\text{-}20) \cdot 10^{17}$ eV and $\theta \leq 45°$ were in agreement with theoretical values by a form within the limits of experimental errors and by an absolute meaning they were smaller by a factor ~ 1.4. This is good seen in Figures 3 and 4 where zenith-angle dependences of $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ are presented. For convenience of comparison all theoretical values of $\rho_{s,600}(\theta)$ and $\rho_{\mu,600}(\theta)$ were reduced by 1.4 times.

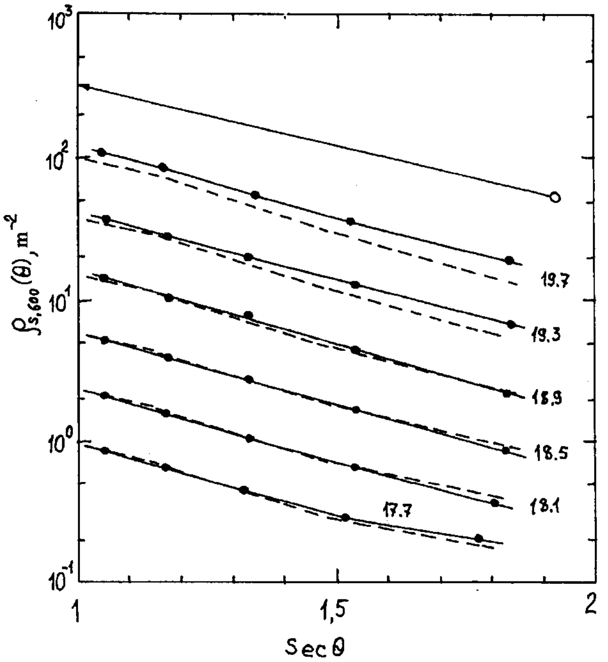

Figure 3: $\rho_{s,600}(\theta)$ vs secθ for different E_0: ● - our experiment, o - $\rho_{s,600}(58.7°) = 54$ m^{-2} of the largest of showers registered at the Yakutsk array ($E_0 \approx 1.5 \cdot 10^{20}$ eV). Dashed lines are the QGSJET model for primary protons (calculated $\rho_{ch,600}(\theta)$ were reduced by 1.4 times)

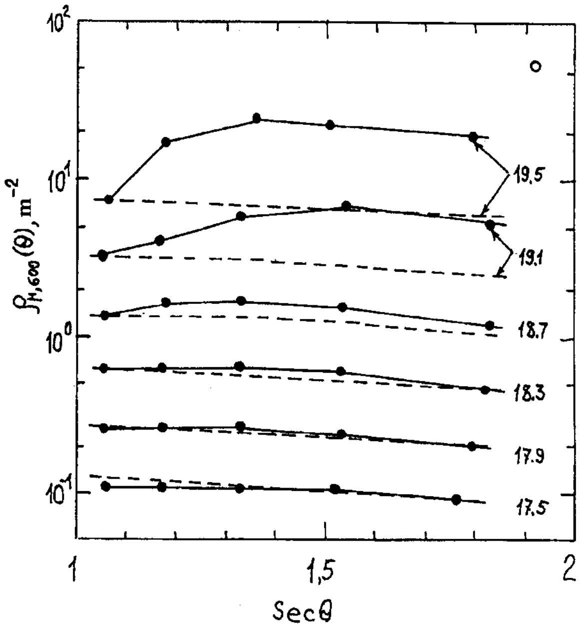

Figure 4: $\rho_{\mu,600}(\theta)$ vs secθ for different E_0: ● - our experiment, o - $\rho_{s,600}(58.7°) = 54$ m^{-2} of the largest of showers registered at the Yakutsk array ($E_0 \approx 1.5 \cdot 10^{20}$ eV). Dashed lines are the QGSJET model for primary protons (calculated $\rho_{\mu,600}(\theta)$ were reduced by 1.4 times)

Experimental data at $E_0 \leq 5 \cdot 10^{18}$ eV satisfy the following important relations which we used to estimate E_0 at $\theta = 0°$:

$$E_0 = (4.8 \pm 1.6) \cdot 10^{17} \cdot (\rho_{s,600}(0°))^{1.0 \pm 0.03} \quad \text{[eV]} \qquad (3)$$

and

$$E_0 = (3.4 \pm 1.3) \cdot 10^{18} \cdot (\rho_{\mu,600}(0°))^{1.06 \pm 0.02} \quad \text{[eV]}. \qquad (4)$$

Similarly, from the QGSJET model for primary protons we have:

$$E_0 = 4.17 \cdot 10^{17} \cdot (\rho_{ch,600}(0°))^{1.0 \pm 0.01} \quad \text{[eV]} \qquad (5)$$

and

$$E_0 = 2.4 \cdot 10^{18} \cdot (\rho_{\mu,600}(0°))^{1.08 \pm 0.01} \quad \text{[eV]}. \qquad (6)$$

In showers with $E_0 \geq 5 \cdot 10^{18}$ eV there is no such an agreement. In the most inclined EAS the experimental $\rho_{s,600}(\theta)$ are slightly above than theoretical values. As E_0 further increases this tendency intenses and shifts to the side of the less inclened showers and, at last, at $E_0 \geq (4\text{-}5) \cdot 10^{19}$ eV it manifests itself in vertical EAS.

LDF of muons (Fig.4) at $E_0 \geq 5 \cdot 10^{18}$ eV is more significantly changed. Thereby, the experiment testifies about the preferential increase of a relative portion of muons in the total charged particle flux (Fig.5). This essentially influences the measurement of particle densities with ground-based detectors (e.g., water Cerenkov tanks at the Haverah Park array).

Open circles in Fig.3 are $\rho_{s,600}(58.7°) = 54$ m^{-2} for the largest of showers registered at the Yakutsk array (Efimov et al., 1990). The arrow is the recounting of this density to a vertical with the absorption path length of 530 g/cm^2. The energy of this shower is $E_0 = 1.5 \cdot 10^{20}$ eV as it follows from (3) and $E_0 = 2.2 \cdot 10^{20}$ eV according to the QGSJET model.

Actually the energy of this shower can be lower, as (3) was found at $E_0 \leq 10^{19}$ eV and FDFs of charged particles, on the whole, (Fig.2 and Table) and $\rho_{s,600}(\theta)$, in particular, (Fig.3) exhibit the noticeable increases. Any extrapolations not only of experimental but also calculated dependences can lead to large errors, among them, in the estimation of primary particle energy. In this case the additional investigations of LDF of charged particles at the arrays with detectors of not more than 500 m separation should be carried out.

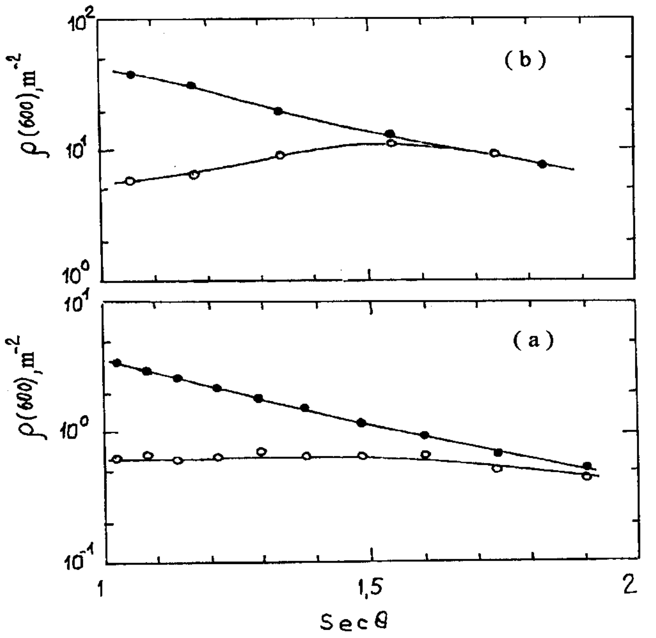

Figure 5. Zenith-angle dependence of ρ_{600} for charged partcles (●) and muons (O) at $E_0 = 2 \cdot 10^{18}$ (a) and $E_0 = 2 \cdot 10^{19}$ eV (b) by Yakutsk EAS array data

3. Conclusion:

The above analysis showed that in the region of $E_0 \approx (5\text{-}20) \cdot 10^{17}$ eV the Yakutsk EAS array data do not contradict the QGSJET model for primary protons. The noncoincidence of E_0 by ~ 1.4 times requires the additional correction of some parameters of this model and calculations up to the response of the scintillation detector.

At $E_0 \geq 5 \cdot 10^{18}$ eV a shower develops in another way. Firstly, the LDF form of the two components changes (parameters g_s and g_μ in Table). Secondly, in inclined events ($\theta > 35\text{-}40°$) a portion of muons noticeably increases (Fig.5). Thereby, the muon component changes more strongly (Fig.4).

These changes do not find the explanation in the framework of the QGSJET model and require other concepts concerning the EAS development in the ultrahigh energy region. Many data obtained at the Yakutsk EAS array point to this fact (e.g. Glushkov et al., 1999).

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