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The shape of EAS lateral distribution and primary composition of the UHE cosmic rays

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Abstract. Theoretical predictions for lateral distribution function of electrons in extensive air showers based on scaling formalism are presented. Our results are tested by comparison with AGASA experimental data taking into account the contribution of low-energy muons and simultaneously the effect of scintillation detectors response, according to recent simulation results. The possibility for ultrahigh energy cosmic ray primary composition deduction from the shape of LDF is discussed in detail.

1 Introduction

One of the basic characteristics of extensive air showers (EAS) of superhigh energies, that can be measured quite accurately by large ground-based air shower arrays is charged particle local density at various distances from the core location. Reliable theoretical predictions on the lateral distribution function (LDF) of different EAS components in wide radial distance range are therefore of great importance in cosmic ray research for both physical interpretation of existing experimental data and new experiments design studies. Unfortunately, the problem of fast, proper and at the same time adequate to numerous specific experimental conditions calculations of LDF at large distances from the shower core ($r \geq 1$ km) is not solved yet.

Direct Monte-Carlo technique is of course preferable but takes unreasonably much computation time. One of widely used approaches implements an analytical description of electromagnetic subshowers, usually based on different well known modifications of NKG formula (L. G. Dedenko et al., 1975; A. A. Lagutin et al., 1979; A. V. Plyasheshnikov et al., 1988) obtained for distances up to several hundreds meters from the core position. In this case formal extrapolation to $r \sim 1$ km and farther is a source of mistakes. The weak point of hybrid methods is the necessity of complete recalculation of prerecorded libraries of subshowers in case of any changes in input assumptions. Established thinning algorithms seem very promising, but still not sufficiently effective in case of very large radial distances, because small fraction of distant particles is tracked with very large weights (A. M. Hillas, 1997). There are evidences [see, for example, A. Filipcic et al. (2000)], that it is possible to improve statistical significance of thinning at large distances by artificial limiting the weight, which particle can obtain, but such technics are still in the stage of development.

On the other hand, present situation concerning comparisons of lateral distributions measured by scintillation counters at Akeno and Yakutsk with each other as well as with theoretical predictions at ultrahigh energies ($E_0 \geq 10^{18}$ eV) remains mostly unsatisfactory. Though in several recent publications [see, for example, A. V. Glushkov et al. (1999); M. Nagano et al. (2000)] reasonable agreement between the shapes of experimental and calculational charged particle LDFs was achieved, the absolute values demonstrate significant discrepancies. As a consequence shifting theoretical densities vertically with a factor ~ 1.5 is now widespread technique utilized during comparisons of lateral distributions. Furthermore latest theoretical studies (T. Kutter, 1998; A. A. Lagutin et al., 1999; A. I. Goncharov et al., 2000; M. Nagano et al., 2000) indicate strong influence of the effect of scintillation detector response on the shape of LDF. It is also worth to mention peculiarities of lateral distributions of charged particles and muons at $E_0 \geq 5 \cdot 10^{18}$ eV founded by Yakutsk group, that have not been confirmed by other experiments at this moment and can not be explained by simulations without exotic physical assumptions (A. V. Glushkov et al., 1997, 1999).

In this paper we check the validity of one-parametric scaling representation of lateral distribution of electrons established in our earlier works by comparison with AGASA experimental data. In order to perform adequate comparisons with experiment recent CORSIKA simulation results about contribution of low-energy muons and energy deposition in scintillation counters are used. We also examine here the possibility of utilizing the experimental data about the shape

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of charged particle LDF for cosmic ray primary composition deduction.

2 Scaling formalism for LDF in cascade showers

According to scaling formalism (A. A. Lagutin et al., 1997, 1998, 1999), the lateral distribution of electrons in both gamma- and hadron-induced cascade showers can be represented in a form:

$$\rho_e(r; E_0, t) = \frac{N_e(E_0,t)}{R^2_{\text{m.s.}}(E_0,t)}\, F\left(\frac{r}{R_{\text{m.s.}}(E_0,t)}\right). \quad (1)$$

Here $\rho_e(r; E_0, t)$ – electron density at radial distance r from the core in showers of primary energy E_0 at depth t from primary particle injection point, N_e – total number of electrons at observation level, $R_{\text{m.s.}}$ – mean square radius (the second moment of normalized electron LDF), which is defined as

$$R_{\text{m.s.}}(E_0,t) = \left[\frac{2\pi}{N_e(E_0,t)}\int_0^\infty r^2 \rho_e(r; E_0, t)\, r\, dr\right]^{1/2}. \quad (2)$$

Function $F(X)$ in formula (1) (*scaling function*) is normalized LDF with respect to variable $X = r/R_{\text{m.s.}}$. It does not depend practically on primary particle type, shower energy and age. Besides it is not sensitive to variations of basic parameters of hadronic interaction model. Finally we obtain the following formula for electron density (A. A. Lagutin, R. I. Raikin, 2001):

$$\rho_e(r) = N_e\, \frac{0.28}{R^2_{\text{m.s.}}} \left(\frac{r}{R_{\text{m.s.}}}\right)^{-1.2} \left(1+\frac{r}{R_{\text{m.s.}}}\right)^{-3.33} \times$$
$$\times \left(1+\left(\frac{r}{10\, R_{\text{m.s.}}}\right)^2\right)^{-0.6}. \quad (3)$$

Though the structure of function (3) is similar to modified Linsley function, which is traditionally used for fitting experimental LDF of charged particles measured by scintillation counters, the important difference is that function (3) is one-parametric and scale-invariant.

Our latest results obtained for the mean square radius of electrons can be approximated as follows (A. A. Lagutin et al., 2001; R. I. Raikin et al., this proccedings):

$$R_{\text{m.s.}}(E_0,t) = \frac{\rho_0}{\rho(t)}\, 173.0 \times$$
$$\times \left[0.546 + \frac{2}{\pi}\, \text{arctg}\left(\frac{t}{t_{\max} + 100\ \text{g/cm}^2} - 1\right)\right],\ \text{m}. \quad (4)$$

Here $\rho(t)$ is air density at depth t, $\rho_0 = 1.225\ \text{g/cm}^3$, $t_{\max}$ – depth of maximum of average cascade curve. Approximation (4) gives one-valued relation between $t_{\max}$ and normalized average lateral distribution function of electrons. It is important that relation (4) is stable to variation of hadron-air inelastic cross section and inclusive spectra of secondaries remaining valid within the limits defined by widespread hadronic interaction models (A. A. Lagutin et al., 2001; R. I. Raikin et al., this proccedings).

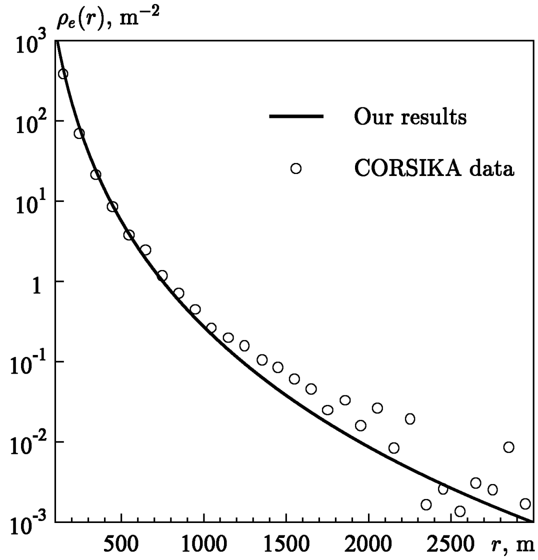

Fig. 1. Average lateral distribution of electrons for 10^{18} eV proton-induced extensive air showers. Function (3) is shown in comparison with CORSIKA/QGSJET data (M. Nagano et al., 2000)

On Fig. 1 we compare our scaling LDF of electrons with CORSIKA/QGSJET predictions (M. Nagano et al., 2000) for 10^{18} eV proton-initiated extensive air showers. Our results are presented by function (3) with $N_e = 4.37 \cdot 10^8$ and $R_{\text{m.s.}} = 118$ m ($t_{\max} = 722\ \text{g/cm}^2$) as QGSJET predicts for proton-induced showers of considered energy. It is seen, that function (3) is steeper than CORSIKA data. The difference becomes essential at $r \geq 1$ km and increases considerably when irregularities appear in CORSIKA data due to the lack of distant particles caused by thin sampling.

3 Comparison of electron LDF with AGASA data

Adequate comparisons of theoretical results with experimental lateral distributions of charged particles require to take into account the contribution of low-energy muons and also detector response effect.

According to CORSIKA simulations (M. Nagano et al., 2000) lateral distribution of muons changes its form sharply, when muon threshold energy decrease from 1 GeV to 0.25 GeV. About 10-15% additional increasing in muon densities without disturbing the shape of LDF was pointed out for threshold energy 10 MeV. As a result coefficient $k_\mu(r) = \rho_\mu(r; \geq 10\,\text{MeV})/\rho_\mu(r; \geq 1\,\text{GeV})$ in vertical showers increases from ~ 1.8 at 600 m to ~ 2.7 at 2000 m from the core making muon lateral distribution much flatter in comparison with LDF measured experimentally by muon detectors with high threshold energy.

In several recent papers (T. Kutter, 1998; A. A. Lagutin et al., 1999; A. I. Goncharov et al., 2000; M. Nagano et al., 2000) theoretical study of the influence of scintillation detector re-

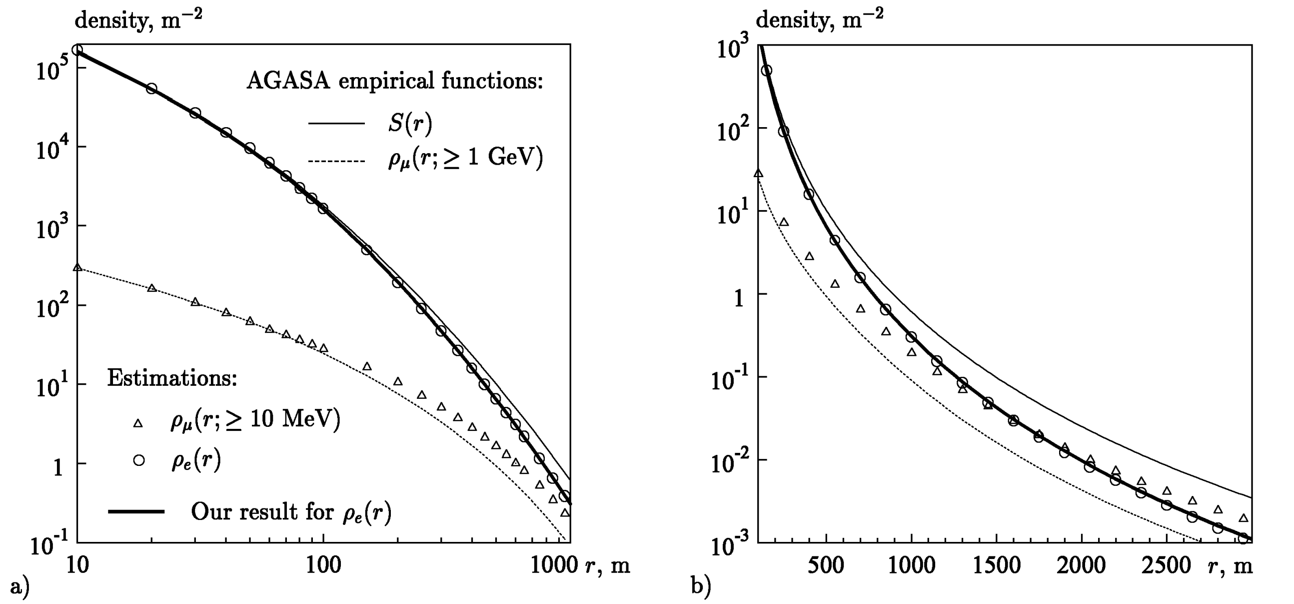

Fig. 2. Comparison of our prediction for lateral distribution of electrons in 10^{18} eV proton-induced EAS with result of $\rho_e(r)$ estimation from AGASA data. Same data is plotted with logarithmic (a) and linear (b) radial distance scale

sponse on the shape of charged particle LDF has been made. The correction factor $k_{\rm sc}(r) = S(r)/\rho_{\rm ch}(r)$, where $S(r)$ is scintillation yield in units of minimum ionizing particle (*scintillator density*) and $\rho_{\rm ch}(r)$ is charged particle density itself, was investigated. While absolute values of $k_{\rm sc}$ calculated using different methods and simulation codes are different from each other, the main tendency in radial dependence is same. Function $k_{\rm sc}(r)$ increases distinctly from several tens to at least several hundreds meters from the core position. It means that utilizing a factor 1.1 of scintillator density to spark chamber density, which has been determined experimentally by AGASA group within 100 m from the core (M. Teshima et al., 1986), is not quite accurate for large distances. For our comparisons we implemented data T. Kutter (1998), calculated by CORSIKA for 5 cm plastic scintillator, according to which $k_{\rm sc} \sim 1.1$ at $r = 50$ m and $k_{\rm sc} \sim 1.4$ at $r = 600 - 1000$ m. For very large distances ($r \geq 1$ km) no changes in the shape of LDF due to scintillation detector response were assumed.

Formally, the relation between two experimentally observable characteristics $S(r)$ and $\rho_\mu(r;\geq 1\ {\rm GeV})$ can be presented as follows:

$$S(r) = \frac{[\rho_e(r) + \rho_\mu(r;\geq 1\ {\rm GeV})k_\mu(r)]\, k_{\rm sc}(r)}{K_{\rm array}}. \quad (5)$$

Here $K_{\rm array}$ is coefficient, which depends on single particle definition used in concrete experiment [in case of AGASA $K_{\rm array} = 1.1$ (M. Nagano et al., 2000)].

Since $k_\mu(r)$ and $k_{\rm sc}(r)$ are determined basically by low energetic part of a cascade, it is reasonable to expect that radial behaviour of both correction factors will not depend critically on features of hadronic interactions at very high energies, primary energy (at least in a limited energy range) and composition. This conclusion has been partially confirmed by theoretical studies T. Kutter (1998); A. I. Goncharov et al. (2000); M. Nagano et al. (2000). Therefore we can use relation (5) to estimate electron LDF from the experimental data. On Fig. 2 we show the result of such estimation of $\rho_e(r)$ for vertical 10^{18} eV showers obtained from AGASA data in comparison with our scaling distribution for proton primaries (same as on Fig. 1, except of normalizing constant). AGASA empirical functions for $S(r)$ and $\rho_\mu(r;\geq 1\ {\rm GeV})$ together with estimated $\rho_\mu(r;\geq 10\ {\rm MeV})$ are also shown. We utilized both logarithmic (a) and linear (b) radial distance scales to emphasize that our result is in very good agreement with the one estimated from AGASA experimental data in whole radial distance range.

4 Cosmic ray primary composition from the shape of LDF

The chemical composition of primary cosmic rays with $E_0 \geq 10^{18}$ eV is not measured well for today. The basic method used to deduce primary composition from experimental data of large ground-based air shower arrays is muon component analysis. Though muon local density at fixed distance from the core position is rather sensitive to the type of primary particle (including γ-rays), the observable muons with $E_{\rm th} = (0.5 - 1)$ GeV $\cos\theta$ are mostly derived from high energy interactions. Thus the interpretation of experimental data on the basis of comparisons with theoretical results depends on hadronic interaction model used in calculations. This problem is still unsolved.

A key result, which allows us to consider the shape of lateral distribution function measured by scintillation counters as a source of information about primary composition of ultrahigh energy cosmic rays, is rather strong energy (and

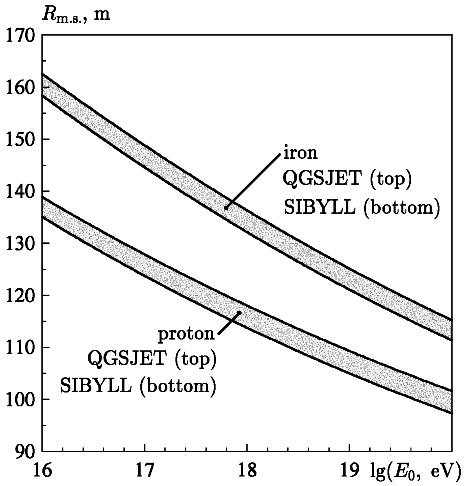

Fig. 3. The energy dependence of the mean square radius of EAS electrons for proton- and iron- initiated showers at AGASA observation depth as predicted by approximation (4) with CORSIKA and SIBYLL results for $t_{\rm max}$. See text for details

consequently composition) dependence of the shape of electron LDF. It is important that, as scaling property (1) shows, this dependence can be completely described by the variation of single parameter – mean square radius of electrons. According to our results (A. A. Lagutin et al., 2001; R. I. Raikin et al., this proccedings) the narrowing of electron LDF with energy is likely to be conserved at least up to 10^{20} eV, while the dependence on basic parameters of hadronic interaction model is relatively weak. On Fig. 3 we show mean square radius of electrons vs. primary energy for proton- and iron-initiated showers at AGASA observation level ($t_{\rm obs} = 920\ {\rm g/cm^2}$). The shaded areas represent uncertainties of the result among QGSJET (top) and SIBYLL (bottom) interaction models [here we used approximation (4) with these models predictions for $t_{\rm max}$ as reported in A. M. Hillas (1997)].

Unfortunately, the mean square radius itself can not be estimated directly from experimental data so far as it demands high precision measurements of lateral distribution of electron component in wide radial distance range (from several meters to several thousands meters from the core). Nevertheless, the change of slope of charged particle LDF around 600 m from the shower core reflects well the changes in electron lateral distribution, as experimental uncertainties in this region are relatively small and the contribution of muons with $E_{\rm th} = 1\ {\rm GeV}$ in vertical showers is about 10% at $5 \cdot 10^{18}$ eV, decreasing with energy (N. Hayashida et al., 1995).

We should point out that theoretical studies of both $k_\mu(r)$ and $k_{\rm sc}(r)$ are far from being complete up to now and also it is still difficult to finally exclude some exotic processes or new particles in EAS of ultrahigh energies. Furthermore, it is impossible to confirm or deny the presence of small fraction of γ-induced showers from such kind of analysis. But the main disadvantage for making some conclusions about composition is controversial character of existing experimental data, obtained by AGASA and Yakutsk array. While energy independence of the shape of $S(r)$ from $\sim 10^{17.5}$ eV up to highest observed energies reported by AGASA group repeatedly [see, for example, N. Hayashida et al. (1999)] is an evidence for changing primary composition from relatively light to relatively heavy in this energy region, Yakutsk data shows extremely sharp steepening of LDF around $5 \cdot 10^{18}$ eV (A. V. Glushkov et al., 1997, 1999), which (refusing extraordinary explanations) leads to converse conclusion. Nevertheless the weak sensitivity of the result to hadronic interaction model makes such kind of analysis interesting as another one source of information about primary composition, hopefully in nearest future with further accumulation of experimental data.

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