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The depth of maximum shower development and its fluctuations: cosmic ray mass composition at $E_0 \geq 10^{17}$ eV

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Abstract. We present new data on Cherenkov light observations obtained during 1994–2009 period, after a modernization of the Yakutsk EAS array. A complex analysis of $x_{\max}$ and its fluctuations $\sigma(x_{\max})$ was performed in a wide energy range. With the new data, according to QGSJet II model, an estimation was made of cosmic rays mass composition for $E_0 \sim 10^{17} - 3\times10^{19}$ eV. The result points towards a mixed composition with a large portion of heavy nuclei at $E_0 \sim 10^{17}$ eV and the dominance of light nuclei at $E_0 \sim 10^{19}$ eV. The analysis of $\sigma(x_{\max})$ energy dependence for the same energies qualitatively confirms this result. A shape of $x_{\max}$ distribution at fixed energy 10^{18} eV is analysed to make more precise conclusion on cosmic ray mass composition.

1 Introduction

The Yakutsk array is for detection of extensive air showers (EAS) from ultra-high energy cosmic rays (UHECR) and effectively controls energy domain from 10^{15} eV to 5×10^{20} eV by measuring charged particles, muons with $\varepsilon_{\text{thr}} \geq 1\,\text{GeV}\cdot\sec\theta$ and Cherenkov light emission. In the same energy region two irregularities of cosmic ray (CR) energy spectrum are observed – the knee (3×10^{15} eV) and the ankle (8×10^{18} eV). The nature of these irregularities is yet to be explained. From the work by Berezinsky et al. (2006) it follows that such spectrum shape could be a consequence of transition between galactic and extragalactic components in total CR flux, i.e. there must be some region in CR spectrum where intensities of these fluxes become equal to each other and then decrease. The boundaries of such a transition region is yet unknown and represents a subject of research at many large EAS arrays. The physics of this phenomenon is tightly connected with particle drift in magnetic fields of our Galaxy and outer space. And since nuclei of different masses behave differently in magnetic field, the CR composition in different points of space will differ. Therefore, it is possible solve the problem of transitional region by measuring CR mass composition in EAS related experiments.

It is a known fact that the depth of shower maximum ($x_{\max}$) and fluctuations in EAS development are sensitive to atomic number of primary particle and for this reason they are used to estimate the CR mass composition (Dedenko et al., 1987; Dyakonov et al., 1989; Knurenko et al., 2005). It's especially important for ultra-high energy region where direct measurements of mass composition are impracticable. For example, works by Dyakonov et al. (1986, 1987, 1988) utilized single characteristics and their combinations: $\langle x_{\max}\rangle$, $\sigma(x_{\max})$ and $dx_{\max}/d\lg E_0$. These works provided initial estimation of inelastic interaction cross-sections at ultra-high energies.

In this paper we present the data on longitudinal EAS development reconstructed from Cherenkov emission data. These data were obtained after modernization of the Yakutsk array when the accuracy of main EAS characteristics increased as compared to previous series of observations. Precise knowledge of the mass composition together with energy spectrum plays a major role in understanding of CR astrophysics (Knurenko et al., 2008). In this sense, engaging the maximal possible number of composition-sensitive EAS characteristics increases the reliability of CR chemical composition estimation. It is important to consider not only mean EAS parameters, e.g. $x_{\max}$, muon content $\rho_\mu/\rho_{\text{ch}}$ but also their fluctuations in given energy intervals (Knurenko et al., 2006, 2007). In order to minimize the latter, it is also a good idea to analyze them at fixed energies.

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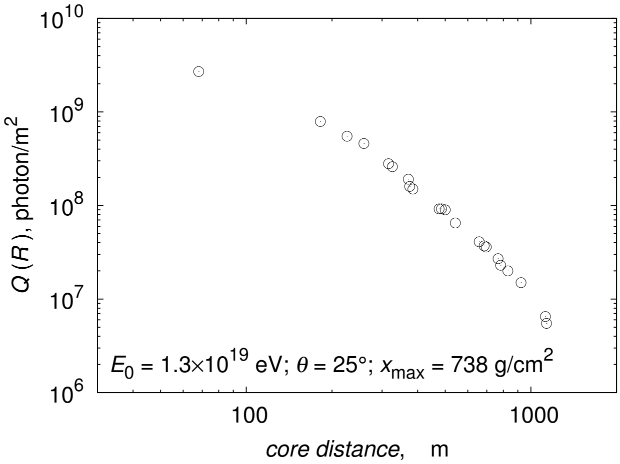

Fig. 1. Measurement of the parameter $p = \lg Q_{200}/Q_{550}$

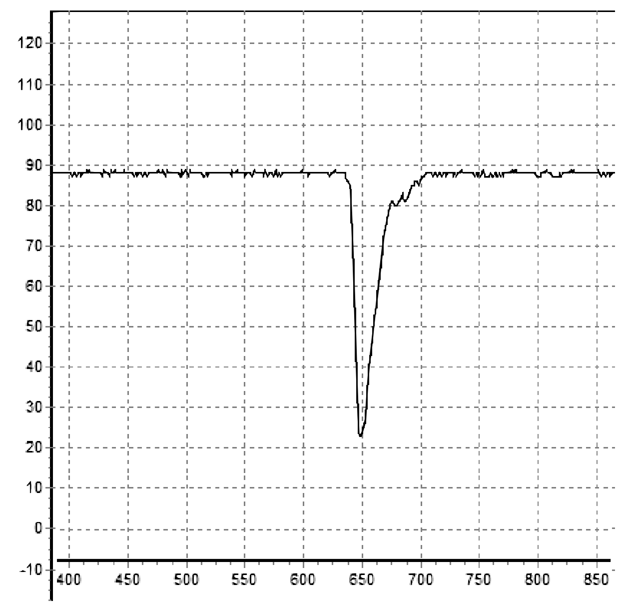

Fig. 2. Analysis of the shape of Cherenkov light pulse $\tau_{1/2}$

2 Technical aspects of the estimation of the longitudinal EAS development characteristics

The determination of $x_{\max}$ in individual showers is based on methods developed at the Yakutsk array and utilize the measurements of EAS Cherenkov light emission at different core distances. In the first one, $x_{\max}$ is determined by the parameter $p = \lg Q_{200}/Q_{550}$ (a relation of Cherenkov light fluxes at 200 and 550 m from the core); the second one involves the reconstruction of EAS development cascade curve, using Cherenkov light lateral distribution function and a reverse solving (Knurenko et al., 2001); the third is based on half-width and half-height of Cherenkov light pulse recorded at 200 m from the core (Khristiansen et al., 1975); the fourth

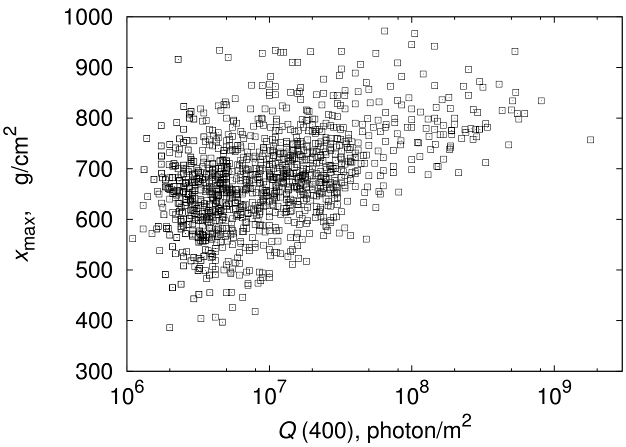

Fig. 3. Individual EAS events detected in Yakutsk experiment during 1994 – 2009. Here $Q(400)$ is the energy estimator, Cherenkov light flux at 400 m

method includes recording of Cherenkov track with several detectors based on camera-obscura located at $300-500$ m from the array center (Petrov et al., 2008). Examples demonstrating these techniques for $x_{\max}$ estimation are shown in Figs. 1 and 2. The sensitivity of these techniques is described in works (Dyakonov et al., 1991; Belyaev et al., 1980; Dyakonov, 1981; Hillas and Patterson, 1983).

There are various factors affecting the methods mentioned above: the way the showers are selected, precision of core location, atmosphere transparency, mathematical methods used to calculate parameters of approximated functions, hardware-related fluctuations and so on. The influence from single and composite factors on physical results of Yakutsk array operation was calculated either with full simulation of measurement procedure or empirically estimated during special methodical experiments. For instance, estimation of hardware-related errors was performed by the analysis of two nearby detectors that measure charged particles, muons and Cherenkov light emission (Dyakonov et al., 1987, 1981). The accuracy of $x_{\max}$ determination in individual showers was estimated in simulation of EAS characteristics measurements at the array involving Monte-Carlo methods and amounted to $30-45\,\mathrm{g\,cm^{-2}}$, $35-55\,\mathrm{g\,cm^{-2}}$, $15-25\,\mathrm{g\,cm^{-2}}$, $35-55\,\mathrm{g\,cm^{-2}}$ respectively for the first, second, third and fourth methods. The total error of $x_{\max}$ estimation included errors associated with core location, atmospheric transparency during observational period, hardware fluctuations and mathematical methods used to calculate main parameters.

3 Mean depth of maximal shower development

A scatter plot of the reconstructed $x_{\max}$ as a function of detected Cherenkov light flux is shown on Fig. 3 for showers

Table 1. New data from the Yakutsk array

E_0, eV	1.5×10^{17}	2.0×10^{17}	3.0×10^{17}	4.5×10^{17}	5.8×10^{17}	8.6×10^{17}	1.2×10^{18}	1.7×10^{18}	2.4×10^{18}
x_{max}	632	648	655	670	687	685	700	719	723
$\sigma(x_{max})$	5	5	6	6	7	7	7	7	8
E_0, eV	3.5×10^{18}	5.0×10^{18}	8.0×10^{18}	1.1×10^{19}	1.6×10^{19}	2.4×10^{19}	3.5×10^{19}	5.1×10^{19}	–
x_{max}	738	765	761	786	780	778	785	808	–
$\sigma(x_{max})$	8	9	11	13	18	21	26	25	–

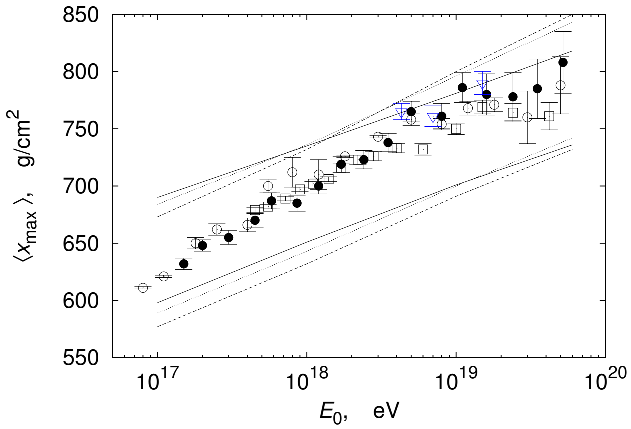

Fig. 4. Energy dependence of x_{max}. Filled circles represent Yakutsk data (see also Table 1), open circles – CASA-MIA (Abu-Zayyad et al., 2001), squares – AUGER data (Abraham et al., 2010), blue triangles – preliminary results of the Telescope Array (Tameda et al., 2010) experiment. Solid lines – results obtained with QGSJet II, dashed – EPOS 1.6, point line – SIBYLL 1.62

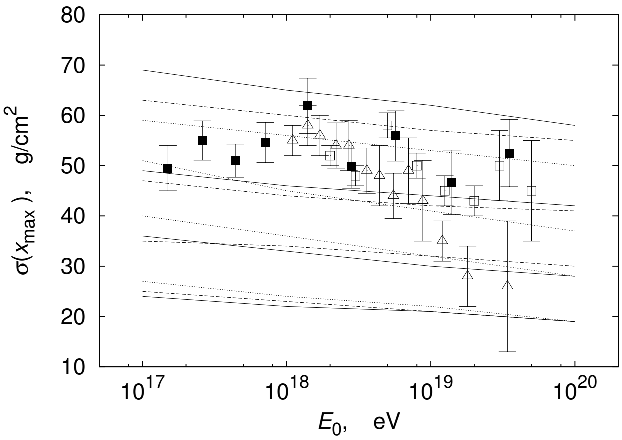

Fig. 5. Fluctuations of the depth of maximum EAS development: filled squares – Yakutsk data, open squares – HiRes data (Abbasi et al., 2010), open triangles – data from Pierre Auger Observatory (Abraham et al., 2010). Straight line – results obtained with QGSJet01, dashed line – QGSJet II, dotted line – SIBYLL 1.62 for various primary nuclei (see Abbasi et al., 2010)

wit an energy above 10^{17} eV. These data were obtained using all four methods and reflect an alteration of x_{max} towards lower atmosphere depths with increasing energy. Figure 4 shows x_{max} values averaged over energy intervals together with the data from other experiments. Numerical values for Yakutsk experiment are supplied in Table 1. On the same picture results of different hadron models calculations are shown. All experimental data coincide within experimental errors and demonstrate irregular shift with energy. Up to 3×10^{18} eV the elongation rate (E.R.) has value $60-80\,\mathrm{g\,cm^{-2}}$ and within the interval of $3\times10^{18}-5\times10^{19}$ eV it equals to $40-60\,\mathrm{g\,cm^{-2}}$. This might be interpreted as a possible change in mass composition at very high energies. A comparison with calculations reveals the tendency of light nuclei abundance starting from 5×10^{17} eV to 2×10^{19} eV and some heavier abundance above 2×10^{19} eV.

4 Fluctuations of x_{max}

Fluctuations of x_{max} play a huge role in EAS longitudinal development as they are associated with the point of first interaction (and, hence, with cross-section of inelastic interaction, σ_{A-air}), energy transfer to secondary hadron particle (inelasticity coefficient K_{inel}) and, to a great extent, depend on the kind of primary particle initiating a shower. So, the amount of fluctuations measured in different energy intervals could characterize CR mass composition at given energy and on the whole determine the dynamics of its change with the energy of primary particle. Figure 5 demonstrates energy dependence of $\sigma(x_{max})$ obtained at the Yakutsk array. To compare with, the same figure shows HiRes data (Abbasi et al., 2010). The data from HiRes experiment virtually reproduce Yakutsk data but have a slight tendency of $\sigma(x_{max})$ change: a small increase in the region of $10^{17}-10^{18}$ eV and decrease at $2\times10^{18}-5\times10^{19}$ eV. The curves representing simulation results, obtained with QGSJet01, QGSJet II and SIBYLL

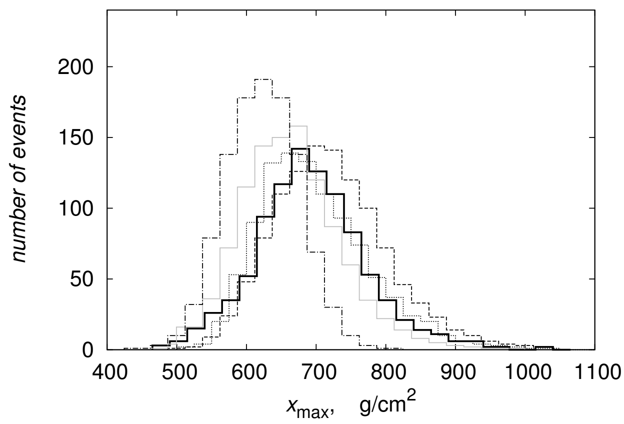

Fig. 6. x_{max} distribution at fixed energy 10^{18} eV. Solid line represents Yakutsk data ($8\times10^{17} < E_0 < 2\times10^{18}$ eV, $\langle E_0\rangle = 1.0\times10^{18}$ eV, 857 events); dotted line – QGSJet01 for mixed composition (70 % p, 30 % Fe); dashed line – QGSJet01 for primary protons, solid grey line – QGSJet01 for CNO group nuclei, dash-dotted line – QGSJet01 for iron nuclei (see Knurenko et al., 2005)

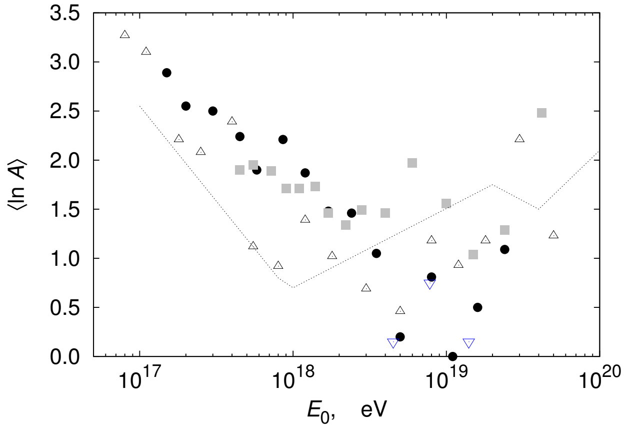

Fig. 7. Mean mass number of primary particle as a function of energy. Circles represent Yakutsk data, triangles – HiRes data (Abbasi et al., 2010), squares – results obtained at Auger observatory (Abraham et al., 2010), blue empty triangles – preliminary data from the Telescope Array experiment (Tameda et al., 2010), dotted line – computational results by Berezhko (2008)

models, are also shown on this figure. Calculations were performed for proton, helium nuclei, CNO group and iron nuclei. Comparison with experimental data has shown that CR composition in this energy region is mixed with domination of protons and helium nuclei. It should be pointed out that according to Fig. 5, the portion of heavy nuclei in the CR flux above 2×10^{18} eV is small and helium and CNO-group nuclei might play a significant role. We came to the same conclusion (Knurenko et al., 2005) where the shape of x_{max} distribution was analyzed within the framework of QGSJet01 model at fixed energies 10^{18} eV and $\sim10^{19}$ eV (see Fig. 6).

5 Cosmic ray mass composition

Figure 7 displays the mean natural logarithm of the CR atomic number $\langle\ln A\rangle$ determined from the x_{max} data from four experiments – Yakutsk, HiRes (Abbasi et al., 2010), Auger (Abraham et al., 2010) and Telescope Array (Tameda et al., 2010). For the derivation of $\langle\ln A\rangle$, x_{max} values were utilized, obtained in simulations within the framework of the QGSJet II models for proton and iron nuclei. The $\langle\ln A\rangle$ value was calculated according to the relation proposed by Hörandel (2005):

$$\langle\ln A\rangle = \frac{x_{max} - x_{max}^{H}}{x_{max}^{Fe} - x_{max}^{H}}\cdot\ln 56 \qquad (1)$$

At first glance, all data reveal a tendency to alter $\langle\ln A\rangle$ with the energy. For instance, in energy interval $2\times10^{17} - 3\times10^{18}$ eV, the value of $\langle\ln A\rangle$ drops from 3 to 1.3 and above 10^{18} eV a slight increase is noted. Such a behaviour is close to the "dip"-scenario from the work by Berezhko (2008), where two peaks are observed in the energy dependence of $\langle\ln A\rangle$. The first one, at $\sim10^{17}$ eV, corresponds to the end of the galactic component, the second, at 10^{19} eV, to the start of CR intensity change due to GZK-cutoff.

However, there is still a significant data dispersion in this energy region due to poor event statistics. Thus, the reliability of our statement is quite limited. For a more precise conclusion on ultra-high cosmic rays origin, a few conditions must be fulfilled: improved statistics, improvement of x_{max} estimation precision, adaptation of a single hadron interaction model that well describes experimental data and involving several alternative methods for x_{max} evaluation.

6 Conclusions

Thus, according to all the data reviewed above, within the framework of QGSJet hadron interaction model it is reasonable to speculate that primary cosmic ray mass composition changes during energy transition from 10^{17} eV to 5×10^{18} eV. At $E_0 \geq 5\times10^{18}$ eV cosmic rays by ~70 % consists of protons and helium nuclei. The content of other nuclei in the region of ankle of the spectrum does not exceed ~30 %. A large portion of protons and helium nuclei in primary CR near the ankle is most likely associated with a significant contribution from particles arriving outside our Galaxy. In such a case the region of transition from galactic to extragalactic component might be the energy interval $10^{17} - 10^{19}$ eV. The problem of mass composition changing above 10^{19} eV remains unresolved due to poor event statistics.

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