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Average mass composition of primary cosmic rays in the superhigh energy region by Yakutsk complex EAS array data

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Abstract: The characteristics relating to the lateral and longitudinal development of EAS in the energy region of $10^{15} - 10^{19}$ eV have been analyzed in the framework of the QGSJET model and of mass composition of primary cosmic rays. It is found that at $E_0 \geq 5 \times 10^{15}$ eV the mean mass composition of primary cosmic rays begins to vary as indicated by a rise of $\langle \ln A \rangle$ with increasing energy. The maximum value of $\langle \ln A \rangle$ is observed at $E_0 \sim (5 - 50) \times 10^{16}$ eV. It is confirmed by data of many compact EAS arrays and does not contradict an anomalous diffusion model of cosmic ray propagation in our Galaxy. In the superhigh energy region ($\geq 10^{18}$ eV) the value $\langle \ln A \rangle$ begins to decrease, i.e. the mass composition becomes lighter and consists of protons and nuclei of He and C. It does not contradict our earlier estimations for the mass composition and points to a growing role of the metagalactic component of cosmic rays in the superhigh energy region.

Introduction

An investigation of superhigh energy cosmic rays in the 1950s - 1960s and 1970s - 1990s has led to the discovery of irregularities in the energy spectrum at the energy $\sim 3 \times 10^{15}$ eV and $\sim 10^{19}$ eV [1, 2]. The problem of origin of breaks in the energy spectrum requires reliable knowledge about the mass composition of primary cosmic rays (PCR) from high energies $\sim 10^{12} - 10^{14}$ eV up to ultra-high energies $10^{18} - 10^{21}$ eV.

The study of PCR mass composition at $E_0 \geq 10^{15}$ eV is possible only with the arrays registering extensive air showers (EAS) and by indirect way only using the EAS characteristics maximum sensitive to the mass composition. For these purposes, at the Yakutsk complex array the characteristics of both longitudinal and radial development of EAS are taken. The longitudinal development of showers is reconstructed measuring the EAS Cherenkov light, and the radial development measuring the structural functions of electron and muons with $E_{thr} \geq 1$ GeV.

In this paper PCR mass composition data obtained at the Yakutsk EAS array in recent year are summarized.

Method

The estimation of PCR mass composition was determined by the formula:

$$\langle \ln A \rangle \equiv \sum_i a_i \cdot \ln A_i, \qquad (1)$$

where a_i is the relative portion of nuclei to the mass number A_i. In each case the experimental data were compared with calculations by the QGSJET model for the primary proton and iron nucleus in the framework of a superposition model:

$$\langle \ln A \rangle = \frac{P^{\exp} - P^{\mathrm{p}}}{P^{\mathrm{Fe}} - P^{\mathrm{p}}} \times \ln A_{\mathrm{Fe}}, \qquad (2)$$

where P is a parameter characterizing the longitudinal or radial development of EAS, for example, $X_{\max}$ — a maximum depth of a shower development, $\rho_\mu / \rho_{\mathrm{s}}$ — a portion of muons at the fixed distance from a core, $N_\mu - N_{\mathrm{s}}$ — a correlation between the total number of muon and electrons at sea level etc. The energy region of $10^{15} - 10^{19}$ eV, where there are "knee" and "ankle" irregularities in the CR energy spectrum, has been considered specially.
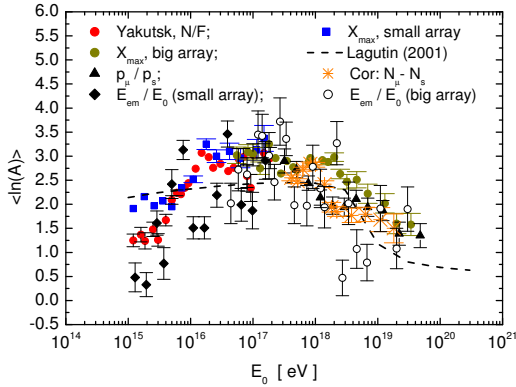
Figure 1: Mass composition of CR obtained by different characteristics of EAS in the region of ultrahigh energies.
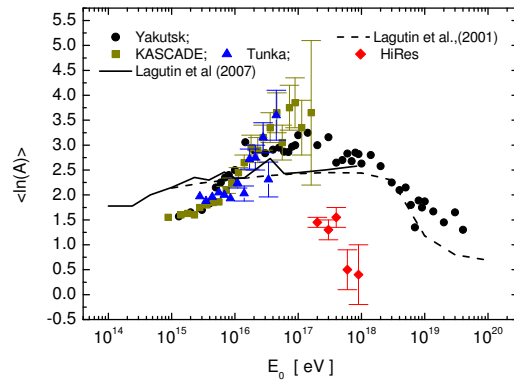

Figure 2: Mass composition of cosmic rays at superhigh and ultrahigh energies. The curve is a calculation by Lagutin et al (2001) and (2007) according to the anomalous diffusion model for cosmic ray propogation.

Results and discussion

Fig. 1 and Fig. 2 present results on the PCR mass composition of the Yakutsk EAS array. Data were obtained in the framework of the QGSJET model and two-component mass composition (proton-iron nucleus). A few characteristics corresponding to the radial and longitudinal development of EAS [3–6] are used in this analysis. In each case, the value $\langle \ln A \rangle$ was determined by an interpolation method according to (2). From Fig. 1, Fig. 2 it follows that the mass composition changes reaching the heavier in the energy region of $(2 - 5) \times 10^{17}$ eV and then, beginning from 3×10^{18} eV it becomes lighter.

The curves are calculations according to the anomalous diffusion model of cosmic ray propagation in the Galaxy (dashed line in Fig. 1) [7] and the two-source model (solid line in Fig. 2) [8]. The calculations have been carried out separately for each of following groups of nuclei: p, He, CNO, N-Si, Fe. The summary values of $\langle \ln A \rangle$ are shown in Fig. 1 and Fig. 2 and for the first case in the Table 1. Data in the Table 1 point to the change of mass composition. In the energy region of $5 \times 10^{15} - 5 \times 10^{18}$ eV the mass composition is heavier than at $E_0 \simeq 10^{19}$ eV. It contradicts the experimental data (Fig. 2). The calculations [8] according to a scenario for the particle generation in the sources of two different types, assuming the analogous model for the CR propagation, showed

the presence of a fine structure in the dependence of $\langle \ln A \rangle$ on energy (see Fig. 2). There are also the sharp peaks in our experimental data. In this connection, the investigation of the PCR mass composition with using a great numbers of EAS characteristics and statistical data as possible is of particular interest.

It should be noted that in the region after a "knee" the estimations of the CR mass composition obtained at the compact arrays agree well with each other. The same cannot be said of the energy region of $\sim 10^{18}$ eV (see Fig. 2), where HiRes data point to the faster enriching of the primary radiation by light nuclei and protons in comparison with the Yakutsk array data, which point to the gradual change of the mass composition from heavier to light (proton and He nuclei, on the whole) at $E_0 \sim 10^{19}$ eV. In both cases, the data point to the existence of tendency to the "protonization" of PCRs at $E_0 > 3 \times 10^{18}$ eV.

Summary

A character of energy-dependence of $\langle \ln A \rangle$ (see Fig. 2) by the Yakutsk array data points to the change of primary particle mass composition at the singular points of CR energy spectrum. The $\langle \ln A \rangle$ rises with energy after the "knee", riching the maximum value $\langle \ln A \rangle = 3.5$ in the energy interval of

Table 1: Calculation results for $\langle \ln A \rangle$.

E_0, eV	A H, %	He, %	CNO, %	Ni-Si, %	Fe, %	$\langle \ln A \rangle$	$\langle \ln A \rangle$ experiment
1×10^{15}	22	21	20	17	19	2.14	1.55 ± 0.25
1×10^{16}	19	19	20	18	23	2.32	2.15 ± 0.24
1×10^{17}	17	17	20	19	26	2.43	3.16 ± 0.23
1×10^{18}	18	16	19	19	27	2.44	2.61 ± 0.21
1×10^{19}	55	17	9	8	11	1.18	1.66 ± 0.18
1×10^{20}	68	18	6	4	3	0.69	-

$(2 - 5) \times 10^{17}$ eV, and then it begins to decrease. Such a behavior does not contradict a hypothesis for the propagation of CR by the anomalous diffusion laws in fractal interstellar medium (Lagutin et al, 2001) and according to which the mass composition of primary particles varies similar to experimental data. At $E_0 > 10^{18}$ eV the value $\langle \ln A \rangle$ decreases gradually and at $E_0 \sim 10^{19}$ eV the mass composition is practically represented by He nuclei and protons. This does not contradict calculations by Berezinsky et al. [9] for the metagalactic model, in which the "ankle" observed in the experiments on registration of ultrahigh energy cosmic rays can only be formed by the proton component arriving from the Extragalaxy. Thereby, details of experimental spectrum form, for example, "dip", i.e. the decrease of intensity at $E_0 \sim 10^{19}$ eV, are most likely caused by the interaction of the extragalactic protons with relic photons ($p + \gamma \rightarrow p + e^- + e^+$). As a direct evidence of this hypothesis, an anisotropy can be used which is associated with the origin and sources of cosmic rays. According to [10–12], at $E_0 > 8 \times 10^{18}$ eV the weak correlation in the arrival directions of EAS with the Galaxy plane and the strong correlation with the Extragalaxy plane are observed. The pulsars can be possible sources of cosmic rays.

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