Mass Composition of the Primary Cosmic Rays in the Energy Region $10^{14} \div 10^{20}$ eV in Anomalous Diffusion Model

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Abstract

We discuss the problem of cosmic ray mass composition variation in wide energy region $10^{14} \div 10^{20}$ eV. The mass composition predicted in the framework of recently developed anomalous diffusion model is tested using the results of COR-SIKA calculations and experimental data on the depth of maximum of extensive air showers. We show that the model predictions for the mass composition are consistent with observations of different experiments.

1. Introduction

The measurement of the mass composition of the primary cosmic rays (PCR), especially with energies $\geq 10^{19}$ eV, is known to be one of the most actual problems of modern astrophysics. The reliable data about composition of the PCR are necessary for solving the problems of the origin of ultrahig energy cosmic ray and also mechanisms of their acceleration and propagation through the interstellar medium.

In recent works [1-5] the new interpretation of experimental data in the framework of galactic approach were offered under assumption that cosmic-ray particles propagate through the fractal interstellar medium (the anomalous diffusion model). It was shown that the "knee" ($E_0 \approx 3 \times 10^{15}$ eV) and the "ankle" ($E_0 \approx 8 \times 10^{18}$ eV) in PCR energy spectrum and also phenomenon of absence of Greisen-Zatsepin-Kuzmin cutoff [6,7] could be explained in natural way in the anomalous diffusion model.

At present stage, analysis and comparison of the experimental data on extensive air showers (EAS) with results of EAS simulations is the only single effective method for the estimation of a PCR energy spectrum, composition and also for the test of hadronic interaction models at ultrahigh energies. One of the basic EAS characteristics, which can be used to determine the cosmic ray mass composition, is the depth of shower maximum t_{max}.

In this paper the results of calculations of t_{max} of EAS, simulated by COR-

Fig. 1. Cascade curves for proton and iron induced vertical showers at primary energies of 10^{18} and 10^{19} eV.

Fig. 2. Comparison of the weighted depth of shower maximum in anomalous diffusion model with experimental data [9-14].

SIKA(v.6.0) [8] in wide energy region for different primaries are presented. The mass composition in energy region $10^{14} \div 10^{20}$ eV, predicted in the framework of anomalous diffusion model, is compared with experimental data of different arrays, which use various detection techniques: Casa-Blanca [9], Space-Vulcan [10], Hegra-Airobicc [11], Fly's Eye [12], HiRes-MIA [13] and Yakutsk [14].

2. Calculation and results

We used the quark-gluon string model with jets (QGSjet) which provides the best overall description of the experimental data about EAS [15]. The calculations have been made for five groups of nuclei (p, He, CNO, Ne-Si, Fe), in the standard atmosphere. For each primary particle from 500 ($E_0 = 10^{14}$ eV) to 50 ($E_0 = 10^{20}$ eV) events were simulated with thinning level 10^{-6}.

In figure 1 we show cascade curves of electrons for vertical showers induced by proton and iron of 10^{19} eV. The depths of EAS maximum were approximated by quadratic expression of the form

$$t_{max} = a + b \cdot lgE + c \cdot (lgE)^2. \tag{1}$$

In table 1 we show the approximation coefficients a, b, c for different groups of

Table 1. Approximation coefficients of $t_{max}(E)$ (see (1)) for different primaries.

type of nuclei	a	b	c
p	-801.55	119.84	-1.97
He	-878.11	120.68	-1.86
CNO	-1131.84	142.84	-2.38
Ne-Si	-1164.74	141.26	-2.26
Fe	-1149.86	135.01	-2.01

Table 2. The mass composition of primary cosmic rays in anomalous diffusion model.

E, eV	p_p	p_{He}	p_{CNO}	p_{Ne-Si}	p_{Fe}	$\langle A \rangle$
10^{14}	0.43	0.25	0.12	0.11	0.09	10.91
$3 \cdot 10^{14}$	0.46	0.24	0.11	0.10	0.09	10.59
10^{15}	0.51	0.23	0.09	0.09	0.08	9.49
$3 \cdot 10^{15}$	0.50	0.26	0.08	0.08	0.08	9.01
10^{16}	0.41	0.26	0.11	0.11	0.11	11.55
$3 \cdot 10^{16}$	0.35	0.25	0.13	0.13	0.14	14.09
10^{17}	0.31	0.23	0.15	0.15	0.16	15.84
$3 \cdot 10^{17}$	0.30	0.22	0.15	0.16	0.17	16.73
10^{18}	0.30	0.21	0.15	0.16	0.18	17.04
$3 \cdot 10^{18}$	0.39	0.18	0.13	0.14	0.16	15.25
10^{19}	0.81	0.14	0.03	0.01	0.01	2.71
$3 \cdot 10^{19}$	0.81	0.14	0.03	0.01	0.01	2.59
10^{20}	0.81	0.14	0.03	0.01	0.01	2.59

nuclei.

For the mass composition, predicted in the framework of anomalous diffusion model (table 2), the weighted depths of shower maximum $t_{max}^{AD}(E) = \sum_i p_i \cdot t_{max}^i$, where i denotes the group of nuclei, were obtained according to CORSIKA calculations for five types of nuclei. In figure 2 we present our results for the depth of maximum in proton- and iron-induced showers and also $t_{max}^{AD}(E)$ in comparision with experimental data in the energy range $10^{14} \div 10^{20}$ eV.

It must be emphasized that experimental data, which consistently demonstrate the remarkable lightening of the primary composition around the main features in energy spectrum ($E_0 \approx 3 \times 10^{15}$ eV and $E_0 \approx 8 \times 10^{18}$ eV), and our results obtained in the framwork of anomalous diffusion model are in satisfactory agreement in the whole considered energy range.

3. Conclusions

We have considered the mass composition variation of primary cosmic rays at energy $10^{14} \div 10^{20}$ eV. CORSIKA/QGSjet simulations of extensive air showers for primary p, He, CNO, Ne-Si, Fe in a wide energy range were performed. The depths of shower maximum were estimated for mass composition predicted in the framework of anomalous diffusion model. It was shown that the experimentally observed lightening of primary composition in the "knee" and the "ankle" regions is the consequence of anomalous diffusion of cosmic rays in fractal interstellar medium.

4. References

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