УДК 537.591.15

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Energy spectra and mass composition of cosmic rays in the fractal-like galactic medium

We consider the problem of the cosmic ray spectrum formation assuming that cosmic rays are produced by galactic sources. The fractional diffusion equation proposed in our recent papers is used to describe the cosmic rays propagation in interstellar medium. We show that in the framework of this approach it is possible to explain the locally observed basic features of the cosmic rays in the energy region $10^{10}\div 10^{20}$ eV: difference between spectral exponents of protons and other nuclei , mass composition variation, "knee" problem, flattening of the primary spectrum for $E\geq 10^{18}\div 10^{19}$ eV.

The main goal of the present paper is to formulate a new mechanism of cosmic ray spectrum formation that explains the locally observed basic features of the cosmic rays in the energy region $10^{10} \div 10^{20}$ eV. Our research was motivated by recent advances in the field of the fractional diffusion of cosmic rays [1, 2]. In these papers the authors made an important discovery related to the nature of the "knee", namely, that the "knee" in primary cosmic rays spectrum is due to fractal structure of the interstellar medium. In other words, under natural physical assumption about the diffusivity $D(E)\sim E^{\delta}$ and the source function $S(E)\sim E^{-p}$, with δ, p being the constants, the "knee" appears when the free paths of particles between galactic inhomogeneties may be anomalously large. These paths (the so-called "Lévy flights") are distributed according to inverse power law $p(r)\propto Ar^{-1-\alpha}$, $r\to\infty$, $\alpha<1$ being an intrinsic property of the fractal-like medium.

The physical arguments and the calculations indicate that the bulk of observed cosmic rays with energy $10^8\div 10^{10}$ eV is formed by numerous distant ($r>1$ kpc) sources. It means that the contribution of these sources to the observed flux may be evaluated in the framework of the steady-state approach. Using our results [3] we present the flux of the particles of type i from all distant sources in the form $J_G^i(r>1\text{ kpc}) = \upsilon_i C_{0i} E^{-p-\delta/\beta}$, where υ_i is a particle velocity, C_{0i} is a constant evaluated via fitting of experimental data.

The contribution of the nearby ($r\leq 1$ kpc) relatively young ($t\leq 10^5$ y) sources defines the spectrum in the high energy region and, as it was shown in previous papers [2, 4], provides the "knee". We present this component in the form

$$J_L^i = \frac{\upsilon_i}{4\pi}\sum_j N(\vec{r}_j, t_j, E), \tag{1}$$

where $(\vec{r}_j, t_j)$ are the coordinate and the age of the source (j), $N_i(\vec{r}_j, t_j, E)$ is the concentration found in Ref. [2] in the framework of the anomalous diffusion approach. List of the supernova remnants, used in our calculations, is given in Ref. [5].

The similar separation of the flux into two components with significantly different properties is frequently used in the studies of cosmic rays. However, the presence of the large free paths of the particles (the "Lévy flights") in our model leads us to the introduction of the third component. This third component is formed by the particles which pass a distance between an acceleration site of a source and solar system without scattering. The flux of non-scattered particles J_{NS}^i is determined by the injected flux ($\propto S_{0i}E^{-p}$) and the "Lévy flight" probability $p(>r)$. Taking into account that for the particle with energy E the probability $p(>r)\sim A(E,\alpha)\sim E^{\delta_L}$, we have $J_{NS}^i = C_{1i}^0 E^{-p+\delta_L}$.

We assume that this component defines the spectrum in the ultrahigh energy region $E\geq 10^{18}$ eV and provides the flattening of the spectrum. In other words, in our model the "ankle" in primary cosmic ray spectrum is also due to the "Lévy flights" of the cosmic ray particles.

Thus, the differential flux J_i of the particles of the type i from all Galactic sources may be presented in the form $J_i(E) = J_G^i(E) + J_L^i(E) + J_{NS}^i(E)$.

The main parameters of the model (p, δ, β, D_0, α) were evaluated from experimental data. Fig.1 and Tabl.1 demonstrate, that under condition $p\approx 2.9$, $\delta\approx 0.3$, $D_0\approx 5\cdot 10^{-7}\text{pc}^{0.5}\text{y}^{-1}$ in the case α=0.5, β=1.0 the model explains well the locally observed basic features of the cosmic rays in the energy region $10^{10}\div 10^{20}$ eV. Mass composition of

Расширенная версия доклада, представленного на 19-ом Европейском симпозиуме по космическим лучам (Флоренция, 2004)

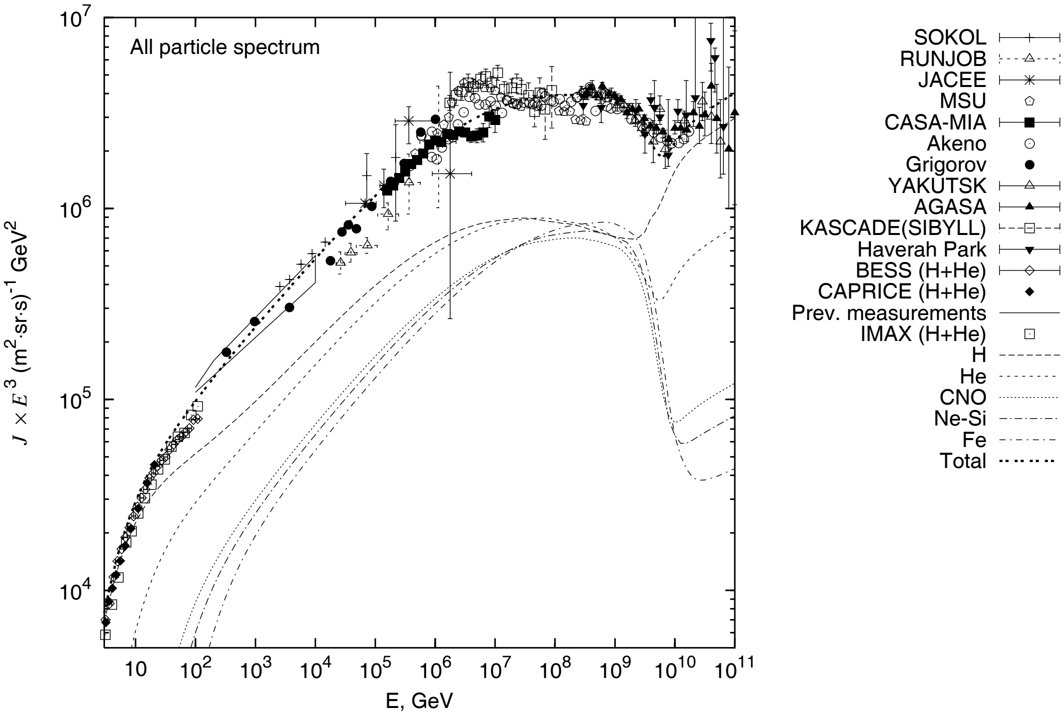

Figure 1. Comparison of our elemental and all-particle spectra calculations with experimental data

Table 1

Mass composition of cosmic rays in anomalous diffusion model

E, GeV/part.	H	He	CNO	Ne-Si	Fe	$\langle lnA \rangle$	$\langle A \rangle$
10^2	0.54	0.31	0.08	0.05	0.02	0.88	5.28
$3 \cdot 10^2$	0.46	0.29	0.11	0.08	0.06	1.17	8.18
10^3	0.41	0.28	0.13	0.09	0.08	1.36	10.11
$3 \cdot 10^3$	0.37	0.27	0.15	0.11	0.09	1.50	11.39
10^4	0.34	0.27	0.17	0.12	0.11	1.63	12.67
$3 \cdot 10^4$	0.31	0.25	0.18	0.13	0.13	1.76	14.14
10^5	0.27	0.24	0.19	0.15	0.15	1.90	15.71
$3 \cdot 10^5$	0.25	0.23	0.20	0.16	0.17	2.03	17.28
10^6	0.22	0.21	0.20	0.17	0.19	2.14	18.76
$3 \cdot 10^6$	0.20	0.20	0.20	0.18	0.21	2.24	20.08
10^7	0.19	0.19	0.20	0.18	0.23	2.32	21.21
$3 \cdot 10^7$	0.18	0.18	0.20	0.19	0.25	2.38	22.15
10^8	0.17	0.17	0.20	0.19	0.26	2.43	22.86
$3 \cdot 10^8$	0.17	0.16	0.20	0.19	0.27	2.45	23.31
10^9	0.18	0.16	0.19	0.19	0.27	2.44	23.46
$3 \cdot 10^9$	0.23	0.15	0.18	0.18	0.26	2.30	22.35
10^{10}	0.55	0.17	0.09	0.08	0.11	1.18	10.71
$3 \cdot 10^{10}$	0.65	0.17	0.07	0.05	0.06	0.80	6.63
10^{11}	0.68	0.18	0.06	0.04	0.04	0.69	5.41
$3 \cdot 10^{11}$	0.70	0.18	0.05	0.04	0.03	0.63	4.77

the particles in a source, obtained from our calculations, is p ≈74%, He≈20%, CNO≈3%, (Ne-Si) ≈2%, Fe≈1%.

This work is supported in part by the grants of the program UR No 02.01.001 and RFFI No 04–02–16724.

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