Energy spectrum and mass composition of primary cosmic rays around the ‘knee’ in the framework of the model with two types of sources

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Analysis of the experimental data on cosmic ray spectra in the framework of the proposed model with two types of sources leads to conclusion, that sources with particle generation spectral exponent $p \sim 2.85$ give the major contribution to the all-particle spectrum in the energy range $10^5 - 10^7$ GeV. ‘Fine structure’ of spectrum around the ‘knee’ may arise due to presence of nearby supernova type source, accelerating particles up to the energies $\sim 3 \cdot 10^4 Z$ GeV, if the energy output of such source is $\sim 2 \cdot 10^{48}$ erg/source.

1. Introduction

Behaviour of primary cosmic ray nuclei spectra in the vicinity of the ‘knee’ is, undoubtedly, one of the key elements for solution of problem of high energy cosmic rays sources and for establishment of acceleration mechanisms. So, for example, non-monotonous behaviour of mass composition and additional breaks in all-particle spectrum in the energy range $10^5 - 10^7$ GeV would support scenario with supernovae as the major cosmic ray sources and acceleration on shock-waves fronts up to the energies $E_{\text{max}} \sim 10^5 Z$ GeV. Particle spectrum produced by this mechanism may be represented as $S_{\text{SN}} \sim E^{-2}\Theta(E_{\text{max}} - E)$, where Heaviside step function $\Theta(x)$ qualitatively reflects a sharp cut-off of the spectrum for $E > E_{\text{max}} [1,2]$.

The recent results on the proton spectrum of Tibet collaboration [3] with no indications on cut-off in the spectrum up to $\sim 10^7$ GeV allow to affirm, that proton spectrum in the considered energy range is formed by sources with generation spectrum being different from $S_{\text{SN}}$. On the other hand, in papers [4,5] it is shown, that all-particle spectrum in this energy range has several breaks.

Reconciliation of experimental results [3] and deductions [4], based on the analysis of EAS size spectra and data on Cherenkov radiation of showers, is possible, in our opinion, only within the framework of the following scenario: 1) particle generation spectrum for energies $10^5 - 10^7$ GeV in the principal cosmic ray sources is different from that of $S_{\text{SN}}$; 2) contribution of young nearby supernova determines ‘fine structure’ of the spectrum and non-monotonous character of mass composition behavior in the ‘knee’ region.

In this paper we present new calculations of energy spectra and mass composition of cosmic rays, performed for the above formulated scenario of particles generation in two distinct types of sources under assumption of anomalous diffusion of particles in inhomogeneous galactic medium. The main purpose of the calculations is to determine conditions under which the proposed model (two types of sources with different acceleration mechanisms + anomalous diffusion) reproduces results of [4,6].

2. Diffusion model

Following to [7,8], cosmic ray transport in fractal interstellar galactic medium with ‘traps’ and without energy losses and nuclear interactions is given by anomalous diffusion equation

$$\frac{\partial N}{\partial t} = -D(R, \alpha, \beta)D_0^{-\beta}(\Delta)^{\alpha/2}N(r, t, R) + S(r, t, R). \quad (1)$$

Here $D = D_0 R^\delta$ – anomalous diffusion coefficient, $R$ — particle rigidity, $D_0^{\alpha}$ — the Riemann-
Liouville fractional derivative [9]:

$$D_0^\mu f(t) = \frac{1}{\Gamma(1-\mu)} \frac{d}{dt} \int_0^t (t-\tau)^{-\mu} f(\tau) d\tau, \quad \mu < 1,$$

$$(-\Delta)^{\alpha/2}$$ — fractional Laplacian (‘Riss’ operator) [9]:

$$(-\Delta)^{\alpha/2} f(x) = \frac{1}{d_{m,l}(\alpha)} \int_{R^m} \Delta_y^l f(x) \frac{dy}{|y|^{m+\alpha}},$$

where $l > \alpha$, $x \in R^m$, $y \in R^m$,

$$\Delta_y^l f(x) = \sum_{k=0}^{l} (-1)^k \binom{l}{k} f(x - ky)$$

$$d_{m,l}(\alpha) = \int_{R^m} (1 - e^{iy})^{l} |y|^{-m-\alpha} dy.$$ 

If $\alpha = 2$ and $\beta = 1$, the equation (1) is just the normal diffusion equation.

For punctual impulse source with power energy spectrum $S(\vec{r}, t, R) = S_0 R^{-p} \delta(\vec{r}) \Theta(T - t) \Theta(t)$, corresponding to particle generation processes in astrophysical objects, the solution of equation (1) has the form

$$N(\vec{r}, t, R) = \frac{S_0 R^{-p}}{D(R, \alpha, \beta)^{3/\alpha}} \int_{\max[0,t-T]}^t \tau^{-3\beta/\alpha} \times \Psi_3^{(\alpha, \beta)} \left(|\vec{r}|(D(R, \alpha, \beta)\tau)^{-1/\alpha}\right) d\tau,$$

where function $\Psi_3^{(\alpha, \beta)}(r)$ — density of fractional stable distribution [10].

Analysis of the obtained solution and its comparison with the available experimental data for energies below and above the ‘knee’ allowed to determine the basic model parameters [11]. It is shown, that for $p \approx 2.85, \delta \approx 0.27$, anomalous diffusion model satisfactorily describes the basic observable features of cosmic ray spectrum and mass composition in the wide energy range $10^2 - 10^{10}$ (see, e.g., [8, 11]). The obtained all-particle spectrum for sources with $S(E) \sim E^{-2.85}$ practically coincides with ‘background’ spectrum from paper [4] (Figure 1). At the same time the calculations demonstrated that for purely power-like spectrum $S \sim E^{-2.85}$ the model is unable to reproduce additional breaks in the region $10^5 - 10^7$ GeV.

3. Results and conclusions

To find conditions when the model, formulated in Introduction, is able to reproduce results of [4, 6], spectra of nuclei, all-particle spectrum and $\langle \ln A \rangle$ were calculated with the use of (2) and particle generation spectrum in the source of the form $S(E) = S_0 E^{-2.85} + S_1 E^{-2} \Theta(E_{\text{max}} - E)$. As a criterion for determination of particle maximum energy, accelerated by supernova type source, we used conclusion on the considerable increase of $\langle \ln A \rangle$ in the region $10^7 - 10^8$ GeV, obtained in [6]. Results of our calculations, given in Figures 2 and 3 and in Table 1, show, that inclusion into system of sources with $S(E) \sim E^{-2.85}$ adopted in [11], of the additional supernova-type source ($r \approx 100$ pc, $t \approx 10^6$ yr), accelerating particles up to $E_{\text{max}} \approx 3 \cdot 10^8 Z$ GeV with output to proton component $\sim 2 \cdot 10^{48}$ erg/source, allows to describe complicated structure of cosmic ray spectrum and mass composition in the vicinity of...
Energy spectrum and mass composition

Figure 2. Comparison of nuclei spectra obtained in the model with two types of sources with experimental data (experimental data from [11]).

Table 1
Mean logarithmic cosmic ray mass $\langle \ln A \rangle$ vs. primary particle energy in the framework of the anomalous diffusion model with two types of sources.

| $E$, GeV | $\langle \ln A \rangle$ | $E$, GeV | $\langle \ln A \rangle$ |
|----------|----------------|----------|----------------|
| $10^1$   | 0.32           | $6.3 \cdot 10^6$ | 2.05           |
| $2.5 \cdot 10^1$ | 0.49   | $10^6$ | 2.13           |
| $6.3 \cdot 10^1$ | 0.74   | $2.5 \cdot 10^6$ | 2.33           |
| $10^2$   | 0.90           | $6.3 \cdot 10^6$ | 2.39           |
| $2.5 \cdot 10^2$ | 1.23   | $10^7$ | 2.53           |
| $6.3 \cdot 10^2$ | 1.48   | $1.3 \cdot 10^7$ | 2.39           |
| $10^3$   | 1.56           | $2.0 \cdot 10^7$ | 2.45           |
| $2.5 \cdot 10^3$ | 1.65   | $2.5 \cdot 10^7$ | 2.52           |
| $6.3 \cdot 10^3$ | 1.65   | $3.2 \cdot 10^7$ | 2.60           |
| $10^4$   | 1.63           | $4.0 \cdot 10^7$ | 2.69           |
| $2.5 \cdot 10^4$ | 1.52   | $5.0 \cdot 10^7$ | 2.79           |
| $6.3 \cdot 10^4$ | 1.78   | $6.3 \cdot 10^7$ | 2.51           |
| $10^5$   | 1.80           | $7.9 \cdot 10^7$ | 2.44           |
| $2.5 \cdot 10^5$ | 1.81   | $10^8$ | 2.45           |

the ‘knee’. As mentioned above, the all-particle spectrum for sources with $S(E) \sim E^{-2.85}$ practically coincides with ‘background’ spectrum from paper [4].

In conclusion, also, let us note, that verification of the hypothesis [4] about contribution of nearby supernova to the presently observed in the Solar system cosmic ray spectrum may be accomplished via execution of additional measurements (or complementary analysis), e.g., of H, He and CNO nuclei spectra in some energy regions. As follows from our calculations, presented in Figure 2, nearby supernova could give rise to inhomogeneities in the spectra of these nuclei in the regions of $3 \cdot 10^3$ GeV/nucleon (H), $6 \cdot 10^4$ GeV/nucleon (He), $3 \cdot 10^5$ GeV/nucleon (CNO). Indications on the presence of such inhomogeneities in the spectra of He and CNO in these energy regions are present in the data of JACEE collaboration [13].
Figure 3. Cosmic ray spectrum in the ‘knee’ region. Comparison of the data [4] with the present paper results for the model with two types of sources. Dotted line – ‘background’ spectrum [4], dashed line – spectrum [4] with account for young nearby supernova, solid line – all-particle spectrum, obtained in the present paper within the model with two types of sources.

Figure 4. Mean logarithmic cosmic ray mass vs. primary particle energy. Dashed areas — experimental data from [6,12], solid line — our calculation in the framework of the anomalous diffusion model with two types of sources.

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