Proton to helium ratio in cosmic rays: analysis of the PAMELA data

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Abstract. In our previous papers we proposed an anomalous diffusion model for solution of the knee problem in the primary cosmic-rays spectrum and explanation of different values of spectral exponent of protons and other nuclei at wide energy region. The anomaly results from large free paths (Levy flights) of particles between magnetic domains. The physical arguments and the calculations indicate that the bulk of observed cosmic rays with energy $10^8 - 10^{10}$ 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 ($J_G$). The contribution of the nearby ($r < 1$ kpc) relatively young ($t < 10^5$ yrs) sources defines the spectrum in the high energy region and provides the knee ($J_L$). Consequently the cosmic rays intensity from all galactic sources for some group of nuclei consists of local $J_L$ and global $J_G$ components.

We show that in the framework of our anomalous diffusion model with two-component representation of CR intensity the behavior of proton to helium ratio observed by PAMELA can be reproduced.

Introduction
Experimental data of PAMELA [1] have shown that proton and helium spectra have different spectral indexes depending on rigidity. The result comes into conflict with predicted by the shock diffusion acceleration model and diffusive propagation in the Galaxy. It is interpreted as an indication of existence of different populations of cosmic ray sources.

The study is performed in frameworks of anomalous diffusion (AD) model of cosmic rays in fractal-like galactic medium, developed by the authors [2, 3, 4]. The AD model was shown to provide a description of the main feature of cosmic ray spectrum, ”knee”, at $\sim 3 \cdot 10^6$ GeV.

Possibility to explain of observable dependence proton to helium ratio by means of our model is investigated.

1. AD model
Following [2, 3], cosmic ray transport in fractal interstellar galactic medium with ‘traps’ and without energy losses and nuclear interactions is given by anomalous diffusion equation

$$\frac{\partial N}{\partial t} = -D(R, \alpha, \beta)D_{0+}^{1-\beta}(-\Delta)^{\alpha/2}N(\vec{r}, t, R) + S(\vec{r}, t, R).$$

(1)

Here $D = D_0 R^\delta$ — anomalous diffusion coefficient, $R$ — particle rigidity, $D_{0+}^{\mu}$ — the Riemann-Liouville fractional derivative [5], $(-\Delta)^{\alpha/2}$ — fractional Laplacian (‘Riss’ operator) [5]
Our calculation
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Figure 1. Ratio of protons to helium nuclei as a function of energy in GeV per nucleon. Proton/helium ratio, obtained in this paper, is compared with experimental measurements (experimental data are taken from [6]).

In case $\alpha = 2$ and $\beta = 1$, equation (1) is 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

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

where function $\Psi_{3}^{(\alpha, \beta)}(r)$ — is a density of fractional stable distribution [7]. $\Psi_{3}^{(\alpha, \beta)}(r)$ is determined by three-dimensional spherically-symmetrical stable distribution $q_{3}^{(\alpha)}(r)$ ($\alpha \leq 2$) [8] and one-sided stable distribution $q_{1}^{(\beta, 1)}(t)$ with characteristic exponent $\beta$ [8].

2. Proton to helium ratio
Determination of the key parameter of the model, exponents $\alpha$ and $\beta$, is based on the results of the investigation of particles diffusion in the cosmic and laboratory plasma and on interpretation of the data for magnetosphere [9, 10].

The main parameters of the model ($p, \delta, \alpha, \beta, D_0$) were evaluated from experimental data. It has been shown that under condition $p \approx 2.85$, $\delta \approx 0.27$, $D_0 \approx 1 \cdot 10^{-4} pe^{1.1}y^{-0.8}$ in the case $\alpha = 1.1$, $\beta = 0.8$ the model can explain the different values of spectral exponent of protons and
Figure 2. Ratio of protons to helium nuclei as a function of rigidity. Proton/helium ratio, obtained in this paper, is compared with experimental measurements [1].

other nuclei, mass composition variations, the steepening of the all-particle spectrum in wide energy range [11].

In this paper the cosmic rays intensity from all galactic sources is presented as [3]

\[ J(\vec{r}, t, E) = J_L(\vec{r}, t, E) + J_G(\vec{r}, E) = \frac{v}{4\pi} N(\vec{r}, t, E). \]  

(3)

Here \( J_L \) is the contribution of nearby \( (r \leq 1 \text{ kpc}) \) young \( (t \leq 10^6 \text{ yr}) \) sources with \( p \approx 2.85 \) calculated with (2) \( (T \sim 10^4 \text{ yr}) \) [3], and \( J_G \) is the component determined by the multiple old \( (t \geq 10^6 \text{ yr}) \) distant \( (r \geq 1 \text{ kpc}) \) sources, calculated in stationary variant of theoretical AD spectrum (2) [12].

For analysis of the experimental data obtained in the Solar system, the intensity (3) was corrected for modulation effects. We use the spherically symmetric force model of [13] to describe the solar modulation. The influence of solar modulation on the particle flux is

\[ J_{\text{mod}}(T) = \frac{(T^2 + 2m_p c^2 T) J_{\text{ISM}}(T + \Phi)}{(T + \Phi)^2 + 2m_p c^2 (T + \Phi)}, \]  

(4)

where \( T \) is the kinetic energy per nucleon, \( m_p \) is the mass of a proton and \( J_{\text{ISM}} \) is the interstellar flux (3). The potential energy \( \Phi \), describing the average energy loss of particle from interstellar space to 1 AU, is determined by solar modulation parameter \( \phi : \Phi = \phi Z/A \), we use \( \phi = 750 \text{ MV} \) in this paper.
The division of CR intensity into two components \( J_L(\vec{r},t,E) \) and \( J_G(\vec{r},E) \) allows to describe the ratio of protons to helium nuclei as a function of energy in good agreement with experimental data (Fig.1). Moreover, new experimental result of PAMELA [1] demonstrating power-law dependence of the ratio of fluxes between proton and helium versus rigidity is in good agreement with our calculations too (Fig.2).

Therefore two-component representation of CR intensity with local \( J_L(\vec{r},t,E) \) and global \( J_G(\vec{r},E) \) components allows to describe ratio of protons to helium nuclei as a function of energy or rigidity in the framework of our anomalous diffusion model.

References

[1] Adriani O et al 2011 Science 332 69
[2] Lagutin A A and Uchaikin V V 2003 Nucl. Instrum. Methods Phys. Res., Sect. B 201 212
[3] Lagutin A A and Tyumentsev A G 2004 Izv. Altai. Gos. Univ. 35 4 (in Russian)
[4] Lagutin A A, Yushkov A V and Tyumentsev A G 2005 IJMP A 6834
[5] Samco S G, Kilbas A A and Marichev O I 1993 Fractional integrals and derivatives Theory and Applications (New York: Gordon and Breach) p 976
[6] Yoon Y S and et al 2011 ApJ 728 122
[7] Uchaikin V V 2003 Physics-Uspekhi 46 821.
[8] Uchaikin V V and Zolotarev V M 1999 Chance and Stability (Netherlands, Utrecht: VSP) p 594
[9] Greco A and et al 2003 J. Geophys. Res. 108 1
[10] Perri S and Zimbardo G 2008 J. Geophys. Res. 113 A03107
[11] Lagutin A A and et al 2011 Proc. of the 32th ICRC, Beijing OG 1.2 icrc1014
[12] Lagutin A A, Tyumentsev A G and Makarov V V 2001 Proc. of the 27th ICRC, Hamburg 5 1889
[13] Gleeson L J and Axford W I 1968 ApJ 154 1011