Cosmic rays spectrum in fractal-like galactic medium for different particle acceleration mechanism in a source

A.V. Yushkov*, A.A. Lagutin†, A.G. Tyumentsev† and N.V. Volkov†

**INFN Sezione di Napoli, via Cintia, Napoli, Italia 80125*
† Altai State University, Barnaul, 656049 Russia

***Abstract*. The paper is devoted to the investigation of contribution of supernova to observed cosmic ray flux in the solar system assuming two different scenarios of particles acceleration in the supernova remnants: standard shock waves acceleration scenario (Berezhko) and shock waves acceleration with effect of nonlinear amplification of the initial magnetic field by accelerated particles (Ptuskin, Zirakashvili). The propagation of the accelerated particles through the inhomogeneous interstellar medium is described in the framework of generalized nonstationary diffusion model based on the fractional diffusion model developed by the authors.**

It is found that acceleration scenarios of Berezhko and Ptuskin, Zirakashvili allow to describe spectra of different groups of nuclei at experimentally observed energy range with $\delta \geq 0.6$ and $E_{max} \approx 3 \cdot 10^6 Z$ GeV irrespectively of the assumptions on Galactic medium extent of fractality. At the same time nuclei spectra reconstructed from the experimental data in the framework of the above mentioned scenarios reproduce the all-particle spectrum only at $E \leq 10^5$ GeV. Thus the conclusion is drawn that self-consistent description of experimental data on spectra of all particles and different groups of nuclei can not be achieved with generation spectra exponent in supernova $p \leq 2$.

***Keywords*: cosmic rays, anomalous diffusion, supernova**

I. INTRODUCTION

It is commonly believed that observed in solar system cosmic ray flux can be explained in the framework of standard scenario based on the particles acceleration by shock waves in the supernova remnants. To verify this supposition we have made a new calculation of spectra of nuclei assuming two different scenarios of particles generation in the supernova remnants: standard shock waves acceleration scenario [1], [2] and shock waves acceleration with effect of nonlinear amplification of the initial magnetic field by accelerated particles [3], [4]. We demonstrate that self-consistent description of experimental data on spectra of all particles and different groups of nuclei can not be achieved with generation spectra exponent in supernova $p \leq 2$.

II. SPECTRA OF COSMIC RAYS NUCLEI FROM GALACTIC SOURCES

The cosmic ray propagation in the fractal-like interstellar medium without energy losses and nuclear interactions is described by equation for concentration of the cosmic rays $N(\vec{r}, t, R)$ with rigidity R generated by sources $S(\vec{r}, t, R)$ [5]

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

where $D = D_0(\alpha, \beta) R^\delta$ is the fractal diffusivity, D_{0+}^{μ} is the Riemann - Liouville fractal derivative [8], $(-\Delta)^{\alpha/2}$ is the fractional Laplacian (Riss operator) [8]. For a point pulsed source with the density $S(\vec{r}, t, R) = S_0 R^{-\gamma} F(R/R_{\max}) \delta(\vec{r}) \Theta(T - t) \Theta(t)$, which simulates particle generation in supernova shells during the time interval T and the function $F(R/R_{max})$ reflects a form spectrum cutoff at $R > R_{max}$ for a model of source, the solution to this equation has the form

$$N(\vec{r}, t, R) = \frac{S_0 R^{-\gamma} F(R/R_{\max})}{D(R, \alpha, \beta)^{3/\alpha}} \times \\ \times \int\limits_{\max[0, t-T]}^{t} \tau^{-\frac{3\beta}{\alpha}} \Psi_3^{(\alpha,\beta)} \left(|\vec{r}| (D(R, \alpha, \beta) \tau^\beta)^{-\frac{1}{\alpha}} \right) d\tau. \quad (2)$$

Here,

$$\Psi_3^{(\alpha,\beta)}(r) = \int\limits_0^\infty g_3^{(\alpha)} \left(r \tau^{\beta/\alpha} \right) g_1^{(\beta,1)} \left(\tau^{3\beta/\alpha} \right) d\tau \quad (3)$$

is the density of fractional-stable distribution determined by three-dimensional spherically-symmetric stable distribution $g_3^{(\alpha)}(r)$ $(\alpha \leq 2)$ and one-sided stable distribution distribution $g_1^{(\beta,1)}(t)$ with the characteristic parameter $\beta \leq 1$ [9].

The differential flux J_i of the particles of type i due to all sources of Galaxy may be separated into two components

$$J_i = J_i(r \leq 1kpc) + J_i(r > 1kpc). \quad (4)$$

Data of observations [10], [11] and calculations show that the main contribution to the observed flux of cosmic rays in the energy range $1 \div 10$ GeV is from multiple distant $(r \geq 1kpc)$ old $(t \geq 10^6 yr)$ sources. It is accepted to evaluate the contribution from these sources in the stationary approximation [11]. Repeating the

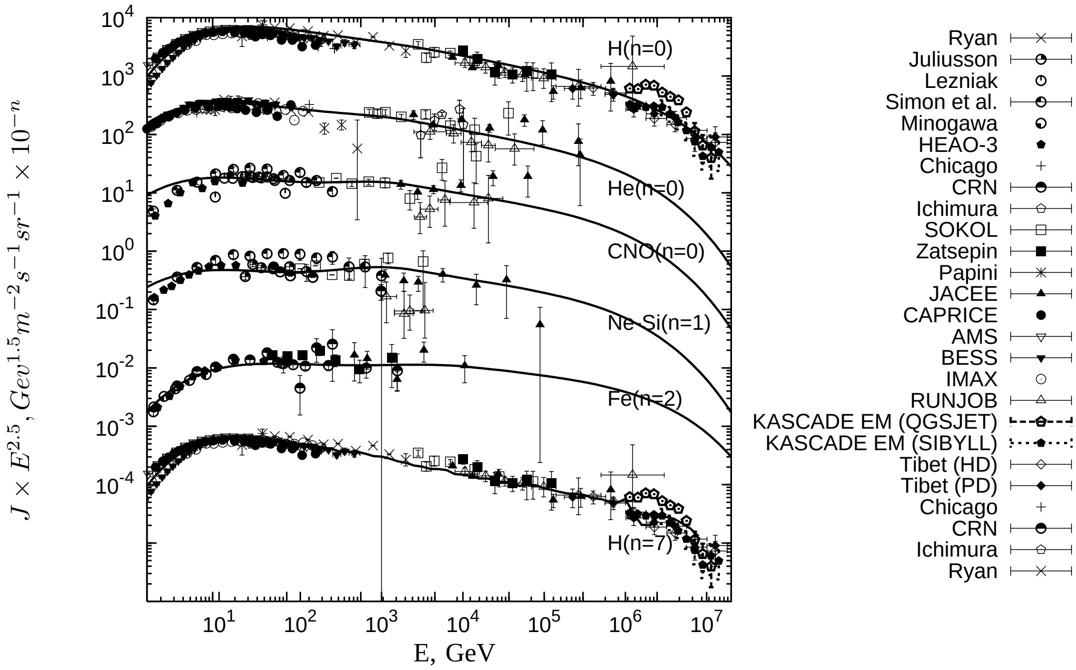

Fig. 1: Comparison of the calculated spectra of nuclei with the experimental data [6]: (bottom line) a proton spectrum for scenario [3] at $T = 10^4$ yr, $\delta = 0.6$ and (other lines) the results of this study, obtained within the scenario [1], [2] at $\gamma = 2$, $T = 10^4$ yr, $E_{\max} = 3 \cdot 10^6 Z$ GeV, $\delta = 0.6$

calculations performed by us in [12], we find that the intensity of i^{th}-type nuclei from a stationary source $S \sim R^{-\gamma} F(R/R_{\max})$ in a fractal-like medium can be presented as $\sim R^{-\gamma-\delta/\beta} F(R/R_{\max})$. Since the contribution of a nearby $(r \leq 1kpc)$, relatively young $(t \leq 10^6 yr)$ source is described by (2), the resultant spectrum of nuclei from all galactic sources in the interstellar medium can be written as

$$J_i(R) = \frac{v_i}{c} \mathrm{C}_{0i} R^{-\gamma-\delta/\beta} F(R/R_{\max}) + \\ + \frac{v_i}{4\pi} \sum_{j(r \leq 1kpc)} N(\vec{r_j}, t_j, R). \quad (5)$$

When analyzing the experimental data obtained in the Solar system, the intensity (5) was corrected to the 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

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

where T is the kinetic energy per nucleon, m_p is the mass of a proton and J_{ISM} is the interstellar flux (5). The potential energy Φ, describing the average energy loss of particle from interstellar space to 1 AU, is determined by solar modulation parameter $\phi: \ \Phi = \phi Z/A$. $\phi = 750MV$ is accepted in this paper.

III. Results and conclusions

In calculation we examined two variants of ejected from supernova spectra. In the standard scenario considered in [1], [2], the spectrum begins to be formed after the shock wave reaches the Sedov stage. In this stage, both the number of accelerated particles and the maximum energy of particles E_{max}, at which sharp exponential cutoff occurs, increase. The function of cutoff of supernova spectrum can be written in this scenario as $F(R) \sim \exp\left(-(R/R_{\max})^{1/2}\right)$, by source parameters $\gamma \leq 2$, $T \sim (10^4 \div 10^5)$ yr, and $E_{\max} = 5 \cdot 10^5 Z (N_H / 3 \cdot 10^{-3} cm^{-3})(B_0/3\mu G)$ GeV [2].

In the scenario [3], [4] of acceleration by shock waves with amplification of the initial magnetic field of the medium due to the nonresonant flux instability formed by accelerated particles [14], cosmic rays with the highest energies are generated in the free expansion stage. Since the amplified field decays with time, the maximum energy of accelerated particles (in contrast to the standard scenario [1], [2]) decreases as well. The resultant spectrum in the range $E < E_{max}$ has the exponent $\gamma = 2$, similar to that in [1], [2], and $S \sim (E^{-3.6} \div E^{-4.0})$ at $E > E_{\max}$. The energy $E_{\max}$ at which the spectrum softens in this acceleration scenario is $2.5 \cdot 10^5 Z$ GeV for II – type supernovae and reaches $3 \cdot 10^6 Z$ GeV for the I – type supernovae.

As a result of calculation we found that acceleration scenarios [1]–[4] allow to describe spectra of different

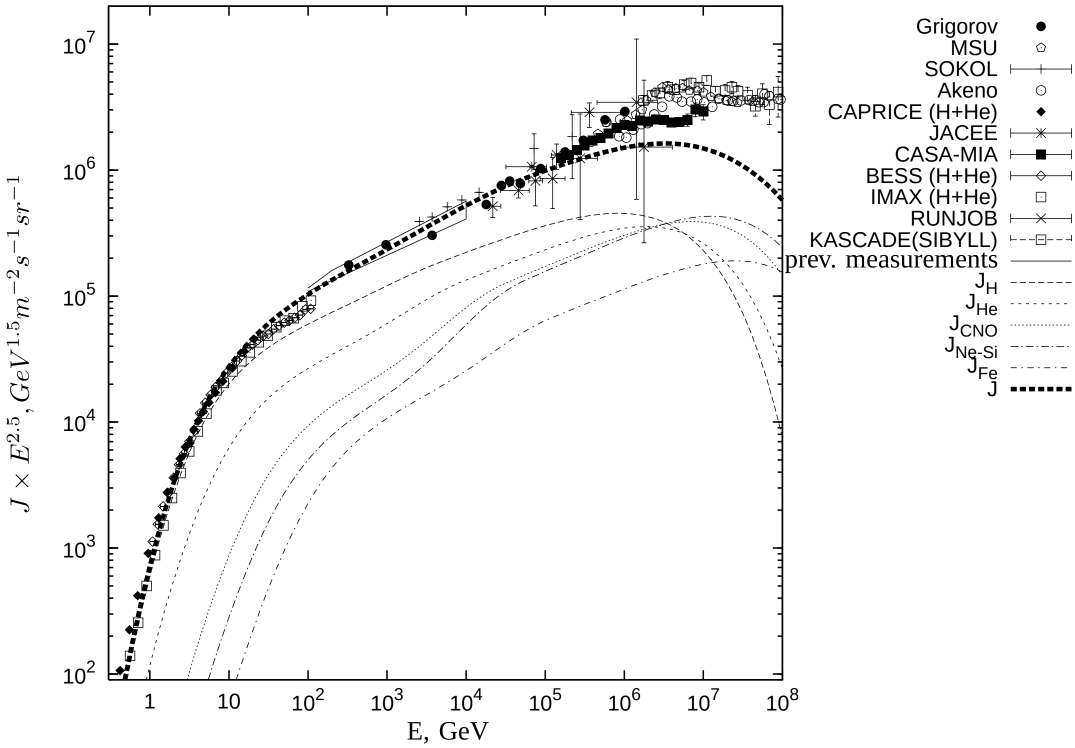

Fig. 2: Comparison of the spectrum of all particles for the scenario [1], [2] with the experimental data [3]

groups of nuclei at experimentally observed energy range with $\delta \geq 0.6$ and $E_{max} \approx 3 \cdot 10^6 Z$ GeV irrespectively of the assumptions on Galactic medium extent of fractality (Fig.1). At the same time nuclei spectra reconstructed from the experimental data in the framework of the above mentioned scenarios reproduce the all-particle spectrum only at $E \leq 10^5$ GeV (Fig.2).

Thus the conclusion is drawn that self-consistent description of experimental data on spectra of all particles and different groups of nuclei can not be achieved with generation spectra exponent in supernova $p \leq 2$.

A. Acknowledgments

This study was supported by the Russian Foundation for Basic Research, project no. 09-02- 01183.

REFERENCES

[1] Berezhko E.G., Elshin V.K., Ksenofontov L.T. // JETP, 1996, vol. 109, p. 1.
[2] Berezhko E.G., Ksenofontov L.T. // JETP, 1999, vol. 116, p. 391.
[3] Ptuskin V.S., Zirakashvili V.N. // Astron. Astrophys., 2005, vol. 429, p. 755. (arXiv: astro-ph/0408025).
[4] Zirakashvili V.N., Ptuskin V.S., Rogovaya S.I. // Bulletin of the Russian Academy of Sciences, 2007, vol. 71, no. 4, p. 464.
[5] Lagutin A.A., Uchaikin V.V. // NIM Phys. Res., 2003, **B**201, p. 212.
[6] Lagutin A.A., Tyumentsev A.G. // Izv. RAN, Ser. Fiz., 2003, vol. 67, no. 4, p. 439.
[7] Lagutin A.A., Tyumentsev A.G. // Izv. AGU, 2004, no.5(35), p.4.
[8] Samko S.G., Kilbas A.A., Marichev O.I., *Fractional integrals and derivatives — Theory and Applications*, Gordon and Breach, New York, 1993.
[9] Uchaikin V.V. // Phys. Usp., 2003, vol. 46, p. 821.
[10] Ginzburg V.L., Syrovatskii S.I., *Origin of cosmic rays*, Pergamon Press, 1964.
[11] Berezinskii V.S., Bulanov S.V., Ginzburg V.L. et al., *Astrophysics of Cosmic Rays*, Amsterdam: North-Holland, 1990.
[12] Lagutin A.A., Makarov V.V., Tyumentsev A.G. // Proc. 27th ICRC, Hamburg, 2001, vol. 5, p. 1889 (arXiv:astro-ph/0107253).
[13] Gleeson L.J., Axford W.I. // Ap. J., 1968, vol. 154, p. 1011.
[14] Bell A.R. // MNRAS, 2005, vol. 358, p. 181.