Energy-Dependent Abundance of Secondary Nuclei in Cosmic Rays: an Indication of Altitude-Dependent Convection above the Galactic Plane?

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Abstract

Based on accurate calculations of abundance of secondary nuclei in low energy cosmic rays we suggest a new parametrization for the energy dependent escape time of energetic particles from the Galaxy. The interpretation of this parametrization is suggested in the frameworks of the diffusion convection model with non monotone dependence of cosmic ray convection velocity as a function of the distance from the galactic plane

1 Introduction:Cosmic ray escape length.

Energetic secondary nuclei result from the spallation of more heavy primary nuclei in a course of cosmic ray diffusion in the interstellar gas. The observed ratios of fluxes of secondary to primary nuclei (e.g., B/C, ^{3}He/^{4}He, and sub-Fe/Fe) allow to determine the escape length $X_e = \rho v T_e$ of cosmic rays from the Galaxy (here ρ is the mean gas density averaged over the volume filled by cosmic rays in the Galaxy, v is the particle velocity, T_e is the escape time from the Galaxy). Different parametrization for dependence of the escape length on particle energy were suggested by different authors and all of them show a characteristic maximum of $X_e(E)$ at about 2 GeV/nucleon, see e.g. Engelmann et al. (1990), Webber et al. (1996), Stephens and Streitmatter (1998).

There is no universally accepted theoretical explanation of the peak in the $X_e(E)$ dependence. The interplay between the particle diffusion in random magnetic field with energy dependant diffusion coefficient $D(E)$ and the convective transport with some convection (wind) velocity $u(\mathbf{r})$ could provide the explanation, see Jones (1979), Ptuskin et al. (1997). Other possible explanations include effect of turbulent diffusion (random convective motions) and effect of distributed reacceleration of cosmic rays after their exit from the sources, see papers by Jones et al. at this Conference.

The scaling of the escape length at low energies in models mentioned above is $X_e \propto v$ that seemingly was supported by observations. However, we made new accurate calculations of the escape length using the best available set of spallation cross sections. The escape length found in this new calculations may be presented by the following equation (assuming that it is described as $X_e = \beta F(\beta R)$ where R is the particle magnetic rigidity, F is an arbitrary function; this special presentation is actually inferred by the diffusion convection model which will be discussed in the next section):

$$X_e = \frac{37.5\beta}{(\beta R)^{0.62} + (\beta R/2.4GV)^{-\delta}} g/cm^2 \quad (1)$$

Where $\delta \geq 1.4$. In the following $\delta = 1.4$ is adopted. The characteristic feature of Eq. (1) is its rather strong energy dependence at small energies: $X_e(E) \propto \beta(\beta R)^{1.4}$ at $R < 2$ GV. This dependence is evidently not compatible with the models discussed above. (Although, the situation may be not so unfavorable for reacceleration model after its modification. We intend to study this issue in a future work.)

2 Diffusion-convection model of cosmic ray transport:

In search for explanation of empirical relation (1) we consider cosmic ray diffusion and convection in a one-dimensional model with varying on distance convection velocity $u(z)$.The basic equation for distribution function of fast particles on rigidity R reads as follows (see e.g. Berezinskii et al. 1990):

$$-\frac{\partial}{\partial z}D(z,R)\frac{\partial f}{\partial R}+u(z)\frac{\partial f}{\partial z}-\frac{du(z)}{dz}\frac{R}{3}\frac{\partial f}{\partial R}+\frac{\mu}{m}v\sigma\delta(z)f=\eta(R)\delta(z) \tag{2}$$

The distribution function on rigidity is normalized to the total number density of cosmic ray particles as $N_{cr}(z)=\int dRR^2f(z,R)$; σ is the total cross section of nuclear fragmentation; $\mu\approx 1$ mg/cm^{-2} is the surface gas density of the galactic disk; m is the average mass of the interstellar atom. Cosmic ray sources and interstellar gas are concentrated in a thin galactic disk and their spatial distributions are described by $\delta(z)-$ functions; $\eta(R)$ is the surface density of cosmic ray sources in the disk. We shall consider the specific form of the diffusion coefficient $D(z,R)$ inspired by the work of Ptuskin et al. (1997). It is assumed that the streaming instability of cosmic rays moving from the Galaxy along the average spiral magnetic field sustains the steady state MHD turbulence in the galactic wind. The resulting cosmic ray diffusion coefficient depends on energy as $D\propto vR^{\gamma_s-1}$ (here γ_s is the power law index of the source spectrum) and only weakly depends on distance along the given flux tube. Thus we accept $D=D(R)=\kappa\beta R^{\gamma_s-1}$, where $\gamma_s=2.1$ and $\kappa=2\cdot 10^{27}$ cm^2/s for R measured in GV.

Our goal is to find a profile of convection velocity $u(z)$ that would provide the observed escape length and, in particular, to present $u(z)$ as an analytical functional of $X_e(R)$. The last can be done only approximately.

Let us consider Eq. (2) without regards for fragmentation, i.e. set $\sigma=0$. By its meaning the escape length X_e is determined then for an observer at the galactic disk from the expression

$$X_e(R)=v\mu\frac{f_0(R)}{\eta(R)} \tag{3}$$

where $f_0(R)=f(z=0,R)$.

In the "boundary layer" approximation we assume that diffusion dominates over convection in the region $|z|\le z_c$, $z_c=D/u(z_c)$ and we omit the second and the third terms in Eq. (2) as small compared with the first term. On the other hand we omit the first (diffusion) term in Eq. (2) compared with the second and the third term at $|z|>z_c$. Using this approximation and the conditions of continuity of the distribution function f and the diffusion-convection flux $j=-D\frac{\partial}{\partial z}f-u\frac{R}{3}\frac{\partial}{\partial R}f$ at $z=z_c(R)$, we solved Eq. (2) at $\sigma=0$, found $f_0(R)$ and with the use of Eq. (3) obtained the following approximate equation:

$$X_e=\frac{v\mu}{2}\left[\frac{1}{u_c(R)}+\frac{1}{\eta(R)}\int_R^\infty dR_1\frac{\eta(R_1)}{R_1u_c(R)}\left(1+\frac{R_1}{u_c(R_1)}\frac{du_c(R_1)}{dR_1}\right)\right] \tag{4}$$

This equation may be solved with respect to $u_c(R)$:

$$u_c(R)=\left[\frac{X_e(R)}{\mu v}+\sqrt{\frac{R}{\eta(R)}}\int_R^\infty dR_1\frac{\eta(R_1)X_e(R_1)}{\mu v(R_1)}\frac{d}{dR_1}\left(\frac{1}{\sqrt{\eta(R_1)R_1}}\right)\right]^{-1} \tag{5}$$

Eq. (5) together with equation $z_c=D(R)/u(z_c)$ determines the convection velocity u as implicit function of distance z for any given escape length $X_e(R)$ and source spectrum $\eta(R)$. This solves the problem.

The source term for secondary nuclei is determined by the fragmentation of primary nuclei so that $\eta^{(2)}=\frac{\mu}{m}v\sigma_{21}f_0^{(1)}$ (here σ_{21} is the corresponding production cross section, the superscripts (1) and (2) correspond to primary and secondary nuclei respectively). Figure 1 shows the convection velocity as a function of distance from the galactic midplane for the escape length (1). The equilibrium spectrum of primary nuclei was taken in the form $I^{(1)}\propto\beta(E+E_0)^{-2.7}$. A distinguishing characteristic of the convection velocity $u(z)$ on Figure 1 is its decrease with distance from the value $u(40\text{pc})\approx 35$ km/s to $u(1\text{kpc})\approx 12$ km/s following by the increase to $u(3\text{kpc})\approx 20$ km/s. The found solution for $u(z)$ merges with the galactic wind solution by Ptuskin et al. (1997) at about $z\approx 3$ kpc and further out from the galactic plane. Notice that the cosmic ray convection is provided both by the real gas motion with a frozen magnetic field and by a possible flux of hydromagnetic waves that propagates in the medium.

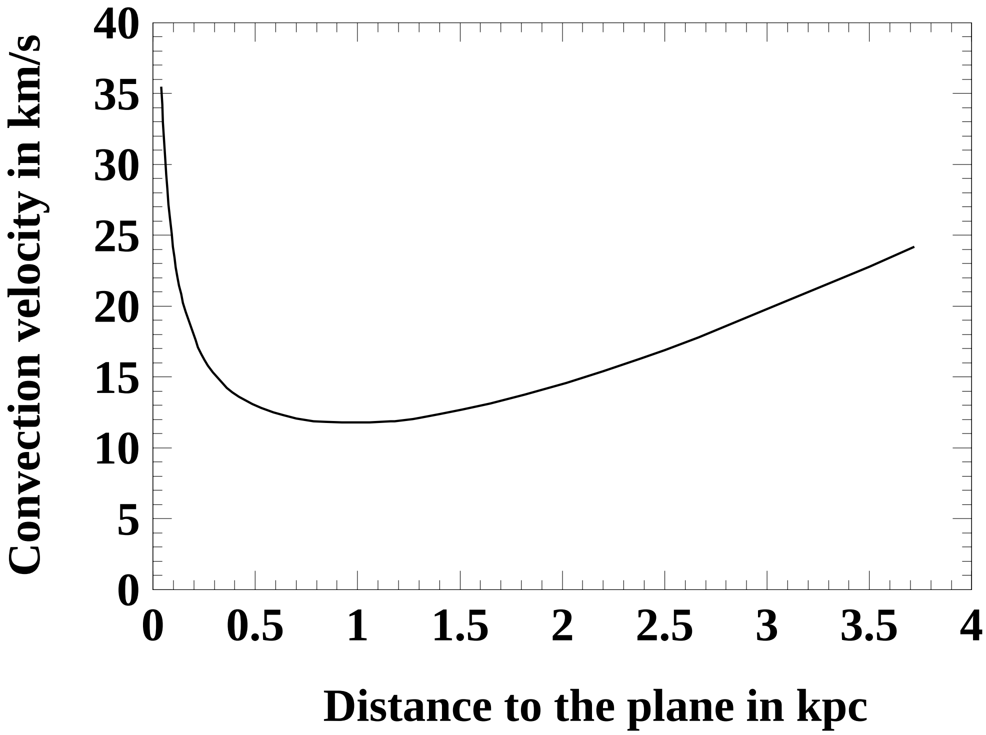

Figure 1: Convection velocity as a function of the distance to the galactic plane

References

Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., Ginzburg, V. L., Ptuskin, V. S. 1990, Astrophysics of Cosmic rays, North-Holland

Engelmann, J. J., et al. 1990, A&A 233, 96

Jones, F.C. 1979, ApJ 229,747

Ptuskin, V.S., Volk, H.J., Zirakashvili, V.N., Breitschwerdt, D. 1997 A&A 321, 434

Stephens, S. A., Streitmatter, R. E. 1998, ApJ

Webber, W. R., Lukasiak, A., McDonald, F. B., Ferrando, P. 1996, ApJ 457, 435