Stable and Radioactive Nuclei in a Diffusion Model

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Abstract

We present the results on the source spectrum function for primary nuclei in galactic cosmic rays, where two distinct energy dependences are used for the source spectra. We discuss the evolution of the goodness of fit to B/C data with the propagation parameters and also show that the results are not much affected by a different choice for the diffusion scheme. We apply the constraints on the diffusion scheme as derived from stable nuclei to calculate the propagation of beta-radioactive isotopes. The diffusion model is refined to properly take into account the effect of a local bubble in the interstellar medium. Our calculations are compared to existing data, which prefer the local bubble description instead of the homogeneus scheme.

1. Introduction

Galactic cosmic rays detected with energies from 100 MeV/nuc to 100 GeV/nuc were most probably produced by the acceleration of a low energy galactic population of nuclei and diffused by the turbulent magnetic field. The acceleration and diffusion processes have a magnetic origin, so that they should depend on rigidity. The rigidity function for the diffusion coefficient is given by quasi-linear theory as

$$K(\mathcal{R}) = K_0 \beta \left(\frac{\mathcal{R}}{1 \text{ GV}} \right)^{\delta} \tag{1}$$

where the parameters K_0 and δ should ideally be given by the small-scale structure of the magnetic field responsible for the diffusion. The spectrum just after acceleration and for a species j, $Q^j(\mathcal{R})$, depends on the details of the acceleration process, which are not clearly understood. However, a power–law seems to be preferred [1] and we assumed the following two possible forms:

$$Q^j(\mathcal{R}) = \frac{q_0^j}{\beta} \left(\frac{\mathcal{R}}{1\text{GV}} \right)^{-\alpha} \tag{2}$$

$$Q^j(\mathcal{R}) = q_0^j \left(\frac{\mathcal{R}}{1\text{GV}} \right)^{-\alpha} . \tag{3}$$

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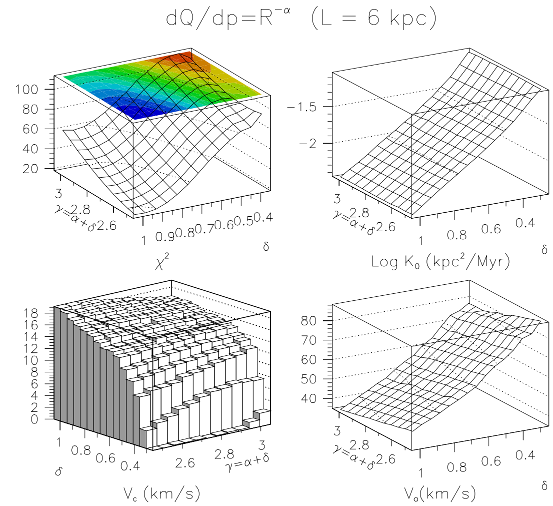

Fig. 1. From top to bottom: for each best χ^2 in the plane $\delta - \gamma$ ($L = 6$ kpc), the corresponding values of $\log(K_0)$, V_c and V_a are plotted for both source spectrum types.

where the value of α is still debated (grossly from about 1.5 to 2.5).
We propagate accelerated particles in a two-zones diffusion models, which has been described at length in [1, 2]. Briefly, our model takes into account spatial diffusion and convection wind (V_c), both acting in the thin matter disc and in the diffusive halo (this last has unknown size L kpc). Spallations over the interstellar matter, second order reacceleration (V_a) and standard energy losses are set in the thin disc. The complete diffusion equation and its solutions may be found in [1] (see Eq. 4).

2. Analysis of stable nuclei

We tested our diffusion model by using data on the B/C ratio. The analysis was performed with six free parameters: $K_0, \delta, V_C, V_a, L, \alpha$ and with the implementation of both the source spectra alternatively. We produced all the chain of primary and secondary nuclei by strating from S. Our aim is to compare predictions for the B/C spectrum with existing measurements, in particular with the 26 data points from HEAO3 [3].
In Fig. 1. we show the preferred values of the three diffusion parameters K_0, V_c and V_a, for each best χ^2 in the $\delta - \gamma$ plane. Here we defined $\gamma = \delta + \alpha$. L has been fixed to 6 kpc but we checked that the behavior does not particulary depend on L. The source spectrum is the pure power law one of Eq. (2). The two upper panels show that the evolution of α does not affect K_0. On the other hand, we clearly see the (anti)correlation between K_0 and δ entering the diffusion coefficient

formula, because they need to give about the same normalization at high energy ($K_0 \times E^{\delta}_{\rm thresh} \approx cte$). The lower left panel shows the values for the convective velocity. Only very few configurations include $V_c = 0$ km s^{-1}, always when $\delta = 0.3$ (for both types of source spectra). Increasing γ and δ at the same time makes V_c change its trend. For small diffusion slope, convection is unfavored, as found in [4]. Finally, the Alfvén velocity (lower right panel) V_a doubles from $\delta = 1.0$ to 0.3, whereas it is almost unchanged by a variation in the parameter γ. We found in [1] that the three parameters K_0, V_c and V_a behave very similarly with respect to a change in the source spectrum from "pure power law" to "modified". In fact, the influence on the primary and secondary fluxes can be factored out if energy changes are discarded. The currently available data on B/C do not allow to discriminate clearly between these two shapes for the acceleration spectrum.

3. Radioactive isotopes in the Local Bubble

We studied the compatibility of our diffusion model with current data on β-radioactive isotopes. These species diffuse on a typical distance $l_{\rm rad} \equiv \sqrt{K\gamma\tau_0}$ before decaying. In this expression, not only the diffusion coefficient K, but also the lifetime $\gamma\tau_0$, depend on energy, due to the relativistic time stretch. In Table 1. we give the values of some distances for ^{10}Be, ^{26}Al and ^{36}Cl. These species

	τ_0 (Myr)	1 GeV/nuc	10 GeV/nuc
^{10}Be	2.17	220 pc	950 pc
^{26}Al	1.31	110 pc	470 pc
^{36}Cl	0.443	56 pc	250 pc

Table 1. Rest frame lifetimes and corresponding values of l_{rad} for some β radioactive nuclei at two different energies ($K_0 = 0.033$ kpc^2 Myr^{-1} and $\delta = 0.6$).

are therefore very sensitive to the characteristics of the local interstellar medium (LISM). The Solar System is embedded in an underdense region, usually called the Local Bubble (see [5] for references). The bubble leads substantially to a decrease in the spallation source term of the radioactive species. We modelled the bubble as a hole in the thin disc approximation and the radius of this hole is considered as an unknown parameter in the analysis. In [5] we provided the theoretical tools to treat the presence of the hole in the galactic disc in our two-zone diffusion model. The major result we found is that at the center of the bubble, the radioactive fluxes are decreased as

$$\frac{N^{r_{\rm hole}}}{N^{r_{\rm hole}=0}} \propto \exp(-r_{\rm hole}/l_{\rm rad}) \ .$$

Using the diffusion parameters allowed by the B/C data [2] to compute the

^{10}Be/^{9}Be and ^{36}Cl/Cl ratios, we find that each of the radioactive nuclei points towards a bubble of radius $\lesssim$ 100 pc, in relatively good agreement with direct observations. If these nuclei are considered simultaneously, only models with a bubble radius $r_{\rm hole} \sim 60 - 100$ pc are consistent with the data and the case for $r_{\rm hole} = 0$ pc is disfavored. This is shown in Fig. 2., which is a projection of the parameter subspace allowed by B/C, ^{10}Be/^{9}Be and ^{36}Cl/Cl on the $L - \delta$ plane (left panel, no hole) or $r_{\rm hole} - \delta$ plane (right panel, hole $r_{\rm hole}$). When the ratio ^{26}Al/^{27}Al is added to the analysis, the results become less clear [5], and it is suspected that the data (nuclear or astrophysical) on which they rely should not be trusted.

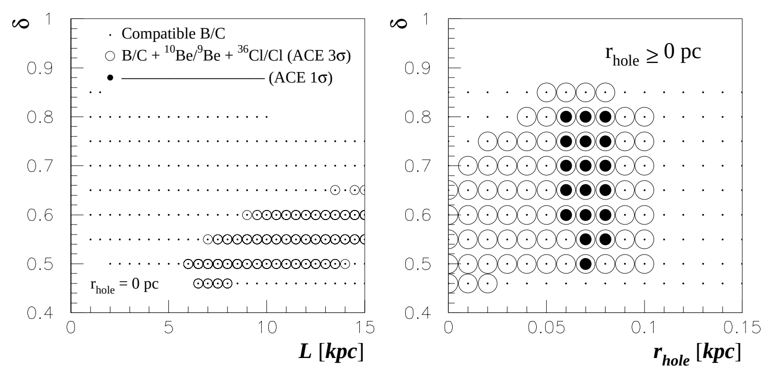

Fig. 2. Representation of the models compatible with B/C plus both ^{10}Be/^{9}Be and ^{36}Cl/Cl ACE 3-σ (open circles) and 1-σ (filled circles) [7]. Left panel displays homogeneous models ($r_{\rm hole} = 0$) in the plane $L - \delta$. Right panel displays inhomogeneous models ($r_{\rm hole} \geq 0$) in the plane $r_{\rm hole} - \delta$.

4. References

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