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Cosmic Rays below $Z = 30$ in a diffusion model: new constraints on propagation parameters.

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Abstract. We studied cosmic ray propagation with semi-analytical solutions of a diffusion model, including convection, reacceleration and the standard energy losses. We use cosmic ray nuclei data to give constraints on the diffusion parameters *i.e.* the diffusion coefficient normalisation K_0 and its spectral index δ, the halo thickness L, the Alfvén velocity V_a, and the convection velocity V_c. A very good agreement with B/C data arises for a number of configurations, all of which are compatible with sub–Fe/Fe data. We find that (i) models without convection or without reacceleration are excluded and (2) the above-mentionned parameters are strongly correlated. We obtain limits on the spectral index δ of the diffusion coefficient, and in particular we exclude a Kolmogorov spectrum ($\delta = 1/3$). These results are used in another contribution to study the secondary antiproton flux.

1 Introduction

Composition and spectra of cosmic rays arise from the nuclear interaction of an initial distribution of energetic particles with interstellar matter (*spallations*) and their electromagnetic interactions with galactic magnetic fields (*acceleration* and *diffusive reacceleration*). The modelling of these effects suffer from some uncertainties. First, the nuclear cross sections to be used were not very well known until recently. Second, our knowledge of the galactic magnetic field is far from complete. Cosmic rays are sensitive to its small scale inhomogeneities (*diffusion*) which are not well observed. They are also sensitive to the presence of plasma shock–waves (acceleration in localized sources and diffusive reacceleration). Third, composition and spectra are altered as the cosmic rays enter the solar magnetic field, so that some more modelling has to be done in order to infer interstellar spectra from observations.

However, despite these sources of uncertainty, some gross features of the cosmic ray properties are well established. First, cosmic rays are produced and destroyed in the galactic disk by spallations. Second, the isotopic ratio of radioactive species shows that they also spend a fraction of time in an empty region, called the *diffusion halo*. Eventually they can escape from the disk-halo structure zone. To have a good modelling of cosmic ray propagation, we should know the geometry and size of the diffusion zone, the characteristics of the galactic magnetic field, and the sources.

We used the existing data on nuclei to put constraints on the parameters describing the propagation of cosmic ray nuclei. One consequence is that many of the large uncertainties affecting the calculation of the antiproton flux could be strongly reduced (Donato & al. , 2001a). This is of utmost relevance for the study of exotic sources of antiprotons and antideuterons.

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2 The diffusion model and the associated parameters

It has been recognized for a long time that the relevant physical propagation model to be used is the diffusion model (Berezinskii et al. , 1990) (Ginzburg & Syrovatskii , 1964), though the so–called leaky box model has been widely preferred for decades because of its simplicity. The equivalence between the two models is only approximate, this is why we prefer the physically better motivated diffusion model (see (Maurin et al. , 2001) for a longer discussion).

The steady–state differential density $N^j(E, \boldsymbol{r})$ of the nucleus j as a function of energy E and position $\boldsymbol{r}$ in the Galaxy, is given by

$$q^j + \sum_{m_k > m_j} \tilde{\Gamma}^{kj} N^k = \nabla.(K^j \nabla N^j - V_c N^j) \tag{1}$$

$$-\frac{\partial}{\partial E}\left(\frac{\nabla.V_c}{3} E_k \left(\frac{2m + E_k}{m + E_k}\right) N^j\right) \tag{2}$$

$$+\frac{\partial}{\partial E}(b^j N^j) - \frac{1}{2}\frac{\partial^2}{\partial E^2}(d^j N^j) + \tilde{\Gamma}^j N^j \tag{3}$$

The first terms represent spatial diffusion (K^j is the diffusion coefficient) and convection (V_c is the convection velocity, perpendicular to the disk and away from it). The presence of a convective wind has two distinct effects on cosmic rays. First, it takes them away from the disk, which leads to the term $\nabla(V_c N_i)$. Second, the associated adiabatic expansion gives rise to an energy loss term, proportional to the divergence of this velocity. The energy dependence of the diffusion coefficient K^j has been assumed to be of the form $K(E) = K_0\,\beta \times \mathcal{R}^\delta$, supported by magnetohydrodynamics considerations (Ptuskin et al. 1997). In this expression, $\mathcal{R}$ stands for the rigidity p/Z. The values of K_0, V_c and δ are not fixed a priori, but will be considered as free parameters of the model.

The last rhs and the second lhs terms are for spallations. Cross sections play a crucial role in propagating the cosmic rays throughout the Galaxy. The total inelastic (or *reaction*) cross section and the spallation cross section are related by $\sigma^{tot}_{inel} = \sigma^{tot} - \sigma^{tot}_{elastic}$. We used the parameterization in (Tripathi et al. , 1999) for σ^{tot}_{inel} throughout this study.

Spallation cross sections were computed with the code of (Webber et al. , 1990) updated with new parameters (table V of (Webber et al. , 1998)). Their precision can be estimated to about 10%. The code is also extended for spallation on He with the parameterization given in (Ferrando & al. , 1988).

The nuclei to be propagated can be separated in stable, ”long-lived” radioactive and ”short-lived” radioactive species. The last kind includes the nuclei whose period is much shorter than the typical propagation time, and they are not explicitly considered as they are implicitly taken into account in the reaction chains. A table of all the disintegration chains can be found in Letaw & al. 1984. The propagation history of stable and radioactive nuclei are different, as the latter can decay in the diffusion halo. Their diffusion equations are different, and explicit solutions can be found in (Maurin et al. , 2001).

The spatial distribution of the sources $q_i(E, \boldsymbol{r})$ (first lhs term) have been assumed to follow distributions given in (Case & Bhattacharya , 1998), but the results presented below are not sensitive to this particular choice. Their elemental composition has been adjusted as to reproduce HEAO–3 data at 10.6 GeV/n, while the relative isotopic abundances were taken from (Anders & Grevesse , 1989) and (Grevesse & Sauval , 1998). Finally, their spectral dependence has been assumed to follow $Q^j(E) \propto p^{-\alpha_j}$ where the index α_j of each element has been adjusted as to reproduce the data at high energy given in (Wiebel-Sooth et al. , 1998). Other functional forms for the diffusion coefficient and the spectral dependence of the sources have been tested, and they all failed to reproduce experimental data.

The remaining terms represent several effects which affect the energy spectrum of cosmic rays. Ionization losses in the ISM neutral matter (90% H and 10% He), and Coulomb energy losses in a completely ionized plasma, dominated by scattering off the thermal electrons ($< n_e > \sim 0.033$ cm^{-3}, $T_e \sim 10^4$ K (Nordgren , 1992)). are taken into account using fomulae given for example in (Strong & Moskalenko , 1998). Interaction of CR with interstellar shocks also leads to the so-called reacceleration, characterized by the Alfvénic speed V_a. It has only been considered in the disk, which is supported by recent complete magnetohydrodynamics simulations (Ptuskin et al. , 1997).

The galaxy is modelled as a cylindrical box whose radial extension is $R = 20$ kpc, with a matter disk of thickness $2h = 200$ pc and a halo of half–height L, which is a free parameter. Sources and interactions with matter are confined to the thin disk and diffusion which occurs throughout disc and halo with the same strength is independent of space coordinates. The solar system is located in the galactic disc ($z = 0$) and at a centrogalactic distance $R_\odot = 8$ kpc.

The set of coupled equations (1) was solved with the shower technique. The flux is first evaluated for the heaviest primary cosmic ray, for which the diffusion equation is simple and does not couple to any other species. Then, the flux of the next nucleus is computed, with a spallation term depending only on the heavier nucleus, whose flux is known from the previous step. This procedure is repeated for all the nuclei down to the lightest one. We started at $Z = 30$, the heaviest non negligeable primary found in cosmic radiation, since $(Z > 30) \leq 10^{-3}$ Fe. For all light nuclei, we checked that it is sufficient to start from $Z = 16$ (S). For the detail of solutions, the reader is referred to (Maurin et al. , 2001).

Finally, solar modulation is taken into account with the force-field approximation (Perko , 1987). We dealt with data taken around period of minimal solar activity, for which the solar modulation parameter has the value $\Phi = 250$ MV.

3 Results

We varied the diffusion model parameters K_0, L, V_c, V_a, and δ in the whole parameter space. The constraints are much simpler to express with the combinations δ, L, K_0/L, V_c and $V_a/\sqrt{K_0}$ (this last expression appears naturally in the description of reacceleration). We first focus on the B/C ratio, B being purely secondary and its main progenitor C being primary.

It is very well suited to determine the value of the diffusion parameters as the spectral shape of this ratio is very sensitive to any changes in the parameters values. Moreover, it is also the quantity measured with the best accuracy, so that it is ideal to test models. Indeed, being the ratio of two nuclei having similar Z, it is less sensitive to systematic errors than single fluxes or other ratios of nuclei with more distant Z. We used the HEAO–3 data (Engelmann et al. , 1990) with quoted errors of 2–3%, as well as ISEE–3 data (Krombel & Wiedenbeck , 1988) and balloons experiments data (Dyers & Meyer , 1987) which have larger error bars. We calculated the χ^2 over a total 26 experimental data points , for each possible combination obtained varying the free parameters in the whole parameter space. The following curves display different representations of the configurations giving a good χ^2, i.e. $\chi^2 < 40$. The best models have $\chi^2 \approx 28$. Some of these configurations have a very small halo size in which case the condition $h \ll L$ is no longer valid. Thus we also

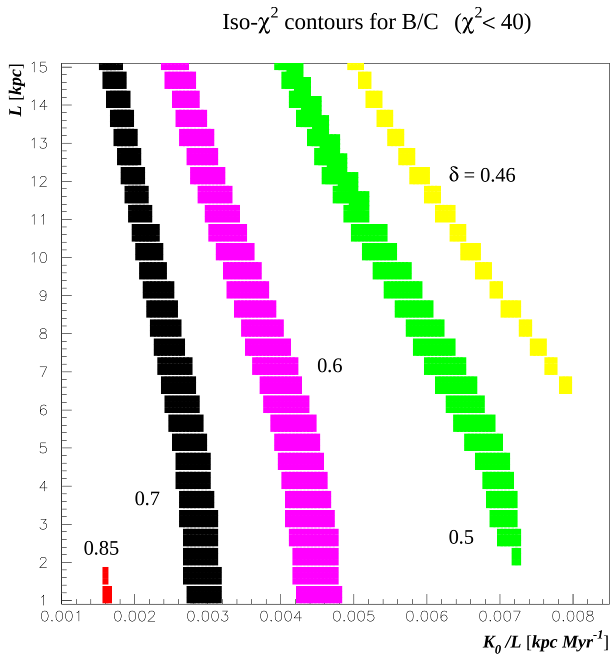

Fig. 1. projection of the subset of parameters giving a good fit to B/C data onto the K_0/L–L plane for different values of δ. On the right panel, the rescaling described in the text has been applied.

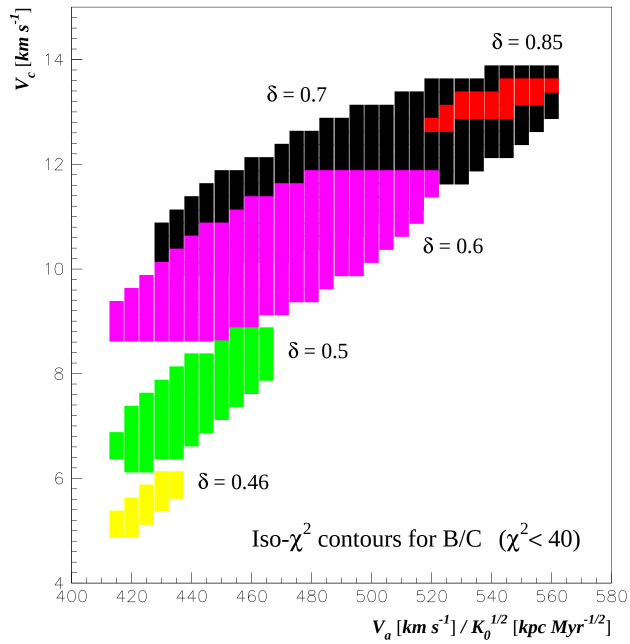

Fig. 2. projection of the subset of parameters giving a good fit to B/C data onto the $V_a/\sqrt{K_0}$–V_c plane for different values of δ.

required $L > 1$ kpc in the whole analysis. The range of δ extends from approximately 0.45 to 0.85. In particular the value $\delta = 0.33$ corresponding to a Kolmogorov–like turbulence spectrum is strongly disfavoured ($\chi^2 > 100$). Fig. 1 shows a projection of the allowed parameters onto the K_0/L – L plane, each value of δ giving a different contour plot. The halo size L is not constrained by this analysis, but it should be by a further specific analysis of radioactive nuclei. The ratio $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ is particularly interesting for this purpose. Since $^{10}\mathrm{Be}$ is a radioactive element, it is very sensitive to the processes which can occur in the halo. Therefore, it can be used to further determine the size of the halo (Donato & al. , 2001c).

In a projection onto the $V_a/\sqrt{K_0}$ – V_c plane, the values of V_c are shifted downward as δ is decreased but the allowed range of $V_a/\sqrt{K_0}$ does not significantly change. Nevertheless, the allowed values for V_c or V_a never reach 0, so that no–wind or no–reacceleration models can be excluded.

The so-called sub-Fe/Fe ratio, i.e. (Sc+V+Ti)/Fe, is another important secondary/primary ratio to consider. It is independent of B/C and its study should give complementary constraints on the diffusion parameters. However, the associated experimental error bars, of the order of 10%, are larger than for B/C and it was not possible to use this ratio to give constraints. We checked that the configurations giving a good fit to B/C data are also compatible with sub-Fe/Fe from HEAO–3 (Engelmann et al. , 1990) and from balloons (Dyers & Meyer , 1987).

4 Discussion and conclusion

We obtain good quantitative constraints on the diffusion parameters from B/C data. In particular, there is a very strong correlation between L, K_0/L, V_c, $V_a/\sqrt{K_0}$ and δ. For $\delta = 0.6$, we find that 8.5 km s^{-1} $< V_c <$ 12 km s^{-1} and $410 < V_a/\sqrt{K_0} < 530$ (where V_a is expressed in km s^{-1} and K in kpc^2 Myr^{-1}). Furthermore, we show that the power law index for the diffusion coefficient is restricted to the interval $[0.45, 0.85]$, the best χ^2 being 25.5 for $\delta = 0.70$. For any δ in this interval, the good parameters in the K_0/L – L and $V_a/\sqrt{K_0}$ – V_c planes can be straightforwardly deduced from the corresponding values for $\delta = 0.6$ by a simple scaling law. We exclude any model without a convective velocity or without reacceleration for any combination of the three other diffusion parameters.

Our conclusions could get more stringent by new measurements in the whole energy spectrum for all nuclei. We emphasize that all our results were obtained using the best data, which are rather scarce and more than 20 year–old; new data are thus strongly needed. The AMS experiment on board the International Space Station will have in principle the ability to provide some of these data.

The next steps of this analysis will be to study radioactive species. In particular, we expect the next generation data (giving the spectral distribution of radioactive isotopes over a large energy range) to provide a new insight on cosmic ray propagation, and thus to constraint further the diffusion parameters. We have also investigated the standard antiproton signal, using the results described in this paper (Donato & al. , 2001a) (Donato & al. , 2001b).

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