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Propagation of galactic cosmic rays and antiprotons in a diffusion model

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ABSTRACT

Cosmic ray nuclei fluxes are expected to be measured with high precision in the near future. High quality data on the antiproton component could give important clues about the nature of the astronomical dark matter. A very good understanding of the different aspects of cosmic ray propagation is therefore necessary.
In this lecture, we will briefly describe a two–zones diffusion model where all the physical effects known to be of some relevance in propagation and diffusion are included. We use cosmic ray nuclei data to give constraints on the diffusion parameters. These results are applied to a new evaluation of the interstellar cosmic antiproton flux. We also study and conservatively quantify all possible sources of uncertainty that may affect that antiproton flux. In particular, uncertainties related to propagation are shown to be underdominant with respect the ones coming from nuclear physics.

1 Introduction

Understanding the composition and spectral features of cosmic rays has always been an astrophysical challenge. On one hand, the observational data have long been scarce and suffered from large uncertainties. On the other hand, the theoretical predictions to which these data should be compared to have also suffered from several drawbacks. Composition and spectra 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*). First, the nuclear cross sections to be used were not very well known until recently. Second, cosmic rays are sensitive to magnetic field scale inhomogeneities (*diffusion*), which are not well observed. 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.
In the next Sections, we will outline a diffusion model able to take into account simultaneously all the physical effects considered of some relevance for the propagation of cosmic–rays in the Galaxy and will apply it to calculate the spectra of stable nuclei and antiprotons.

2 The diffusion model

It has been recognized for a long time that the relevant physical propagation model to be used is the diffusion model (Berezinskii & al. 1990, Maurin et al., 2001), though the so–called leaky box model has been widely preferred for decades because of its simplicity. The geometry of the problem used here is a classical cylindrical box whose radial extension is R=20 kpc, with a disk of thickness $2h$ (h=100 pc) where all the sources are located, and a diffusion halo whose half–height L is an unknown parameter. 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 ($z = 0$) at a centrogalactic distance $R_\odot = 8$ kpc.
The steady–state differential density $N^j(E, \vec{r})$ of the nucleus j as a function of energy E and position $\vec{r}$ in the Galaxy, is given by the diffusion equation:

$$\nabla.(K^j \nabla N^j - V_c N^j) - \frac{\partial}{\partial E}\left(\frac{\nabla.V_c}{3} E_k \left(\frac{2m + E_k}{m + E_k}\right) N^j\right) \qquad (1)$$

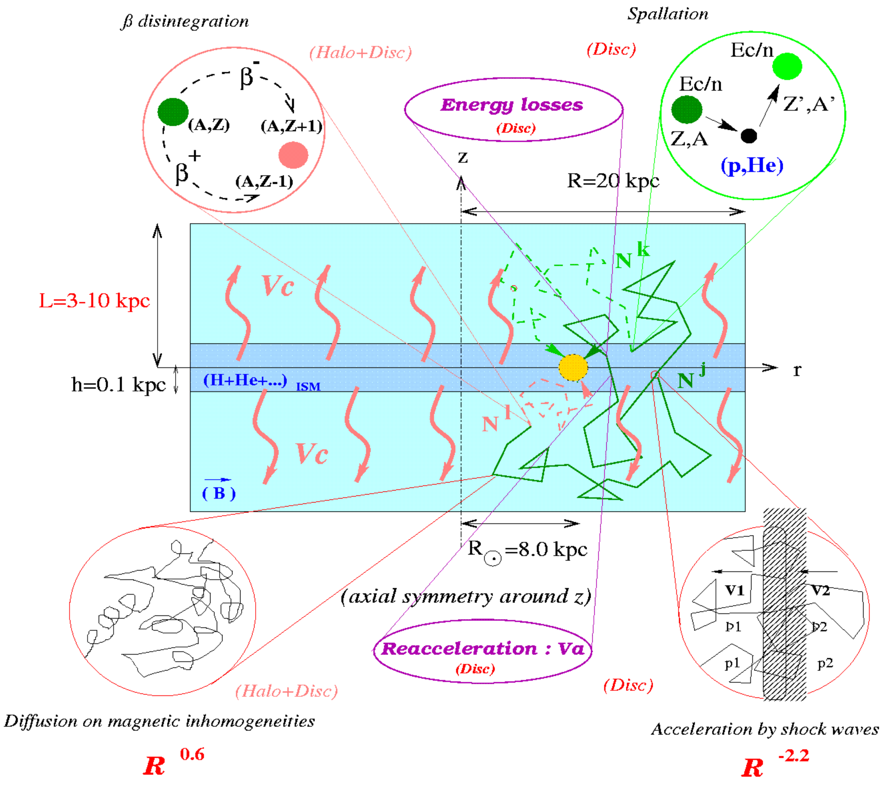
$$+ \quad \frac{\partial}{\partial E}(b^j N^j) - \frac{1}{2}\frac{\partial^2}{\partial E^2}(d^j N^j) + \tilde{\Gamma}^j N^j = q^j + \sum_{m_k > m_j} \tilde{\Gamma}^{kj} N^k$$

The first terms represent diffusion (K^j is the spatial diffusion coefficient; we assume $K = K_0 \mathcal{R}^\delta$, where $\mathcal{R}$ is the particle rigidity) and convection (V_c is the convection velocity). The divergence of this velocity, expressed in the next term gives rise to an energy loss term connected with the adiabatic expansion of cosmic rays. Further, we have to take into account ionization and coulombian losses, plus a reacceleration term in first order derivative (all included in b^j) and finally a second order derivative in E for the associated second order term in reacceleration (d^j is the energy diffusion coefficient). The last term of the l.h.s. takes care of the disappearance of the nucleus j ($\tilde{\Gamma}^j$ for short) due to its collisions with interstellar matter (ISM). In the r.h.s., the source term q^j takes into account the *primary* production and acceleration of nuclei described by an injection spectrum (for the sake of clarity, we have not written down the terms describing the contribution of radioactive species). Finally, the last term is for the *secondary* j sources, namely spallation contribution $\tilde{\Gamma}^{kj}$ from all other heavier nuclei. All the details about the assumptions on the varius terms in the diffusion equation may be found in Maurin et al., 2001.

Fig.1 represents a schematic view of the geometry of the Galaxy and the physical effects acting on a cosmic ray.

This equation may be solved analytically using a development over the base of Bessel functions. The solutions must then be treated numerically for the inclusion of energetic losses, effective at low energies: ionization losses over the neutral interstellar matter, Coulomb interactions over completely ionized plasma, dominated by scattering off thermal electrons, and reacceleration (parameterized by means of the Alfvén velocity V_A). With this semi–analytical approach, we obtain the interstellar spectrum for each nuclear species. To compare calculations with observations, one has to take into account the effects of the solar wind on the particles entering the heliosphere. To this aim, usually people employ the so–called force field approximation (Perko 1987).

Figure 1: *Schematical picture of the diffusion model.*



3 Analysis on stable nuclei

We have compared predictions from our model with the ratio the most sensitive to diffusion parametres: a secondary over a primary nucleus. Up to now, the best measured ratio is B/C (Engelmann et al. 1990). We performed a systematic analysis – indeed the first ever done – varying the relevant parameters K_0, L, V_c, V_a, and δ of our diffusion model. We obtain a lot of configurations giving a good χ^2 and hence able to reproduce the data, as shown in Fig.2.

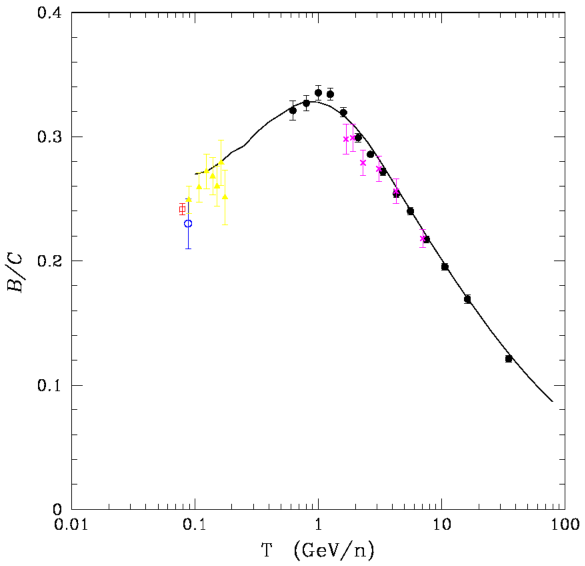


Figure 2: *Computed ratio of* $(^{10}B+^{11}B)/(^{12}C+^{13}C+^{14}C)$ *for a configuration giving a reduced* $\chi^2_r \approx 1.2$.

We tested the values for δ permitted by B/C data. As an example, for a halo thickness of 3 kpc, we find that δ is allowed to vary between 0.5 and 0.84. In the whole parameter space, 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 ($\chi^2 > 100$). For intermediate values of δ, good models are obtained for the full range in L; for low values of δ, models with a small halo size L are excluded; in particular for $\delta < 0.40$, there is no good model with $L < 25$ kpc. Finally, for high values of δ, models with a large halo L are excluded.

For each $V_a/\sqrt{K_0}$ and V_c we varied L and K_0/L and the best values for the χ^2 are depicted in Fig. 3. The very remarkable result is that we find no model having a good χ^2 without convection ($V_c = 0$) or without reacceleration ($V_a = 0$).

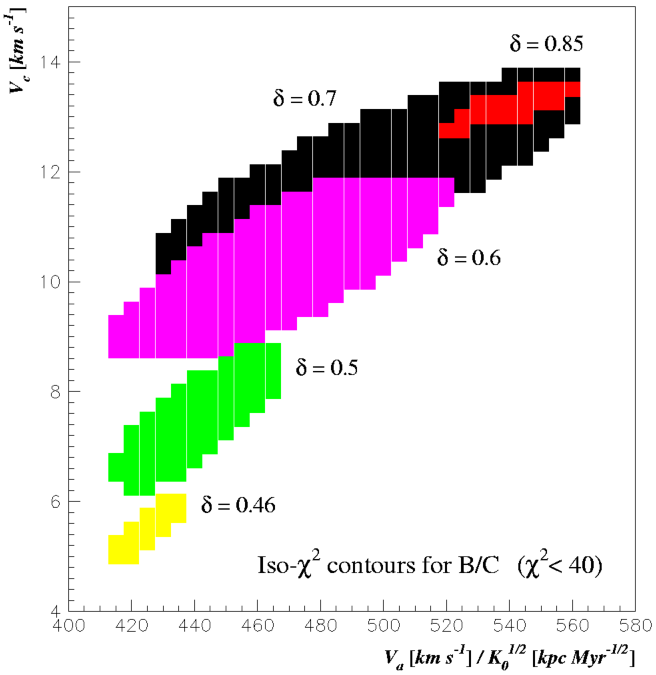


Figure 3: *Models with different values of δ are shown. For each value of V_c and $V_a/\sqrt{K_0}$, only the best χ^2 value is retained when the other parameters L and K_0/L are varied. The figure displays the contour levels for $\chi^2 < 40$.*

4 Secondary antiproton flux

The study of the cosmic ray antiproton spectrum has been a great challenge since the first measurements made at the end of the seventies. Various primary antiproton sources have been proposed (Silk & Srednicki 1984; Mitsui, Maki, & Orito 1996). The case of supersymmetric sources – relic neutralinos in the dark galactic halo – has received a particular attention and constraints on SUSY parameters have been investigated by comparing experimental data to theoretical predictions (Bottino et al. 1998; Bergström, Edsjö, & Ullio 1999). A major problem with this comparison is an accurate estimation of the background secondary antiproton flux. We will consider it as "background" flux, having in mind the possibility of using it to determine whether one of the primary components (such as from supersymmetric relic particles or evaporating primordial black holes) could be seen against it or not.

The secondary antiprotons are yielded by the spallation of cosmic ray nuclei (proton and helium) over the interstellar medium. Recent measurements made by the balloon–borne spectrometer BESS and by the AMS detector during the space shuttle flight dramatically reduced the uncertainties both on primary proton and helium spectra. Consequently, the uncertainties on the calculated secondary $\bar{p}$ spectrum due to incoming primaries are negligible.

Whereas p–p interactions are clearly the dominant process for secondary antiproton production in the Galaxy, p–nucleus and nucleus–nucleus collisions should also be taken into account. They not only enhance the antiproton flux as a whole but can change its low energy tail, mostly for kinematical reasons. So we calculated the total antiproton yield considering p–p, p–He, He–p and He–He interactions. Unfortunately, very few experimental data are available on antiproton production cross-sections in nuclear collisions. A model-based evaluation is therefore necessary. Antiproton production *via* the proton–proton interaction was parameterized according to Tan and Ng (1982, 1983). The Monte Carlo program DTUNUC[1] version 2.3 was used to evaluate the cross-sections for p–He, He–p and He-He antiproton production reactions. The resulting cross-sections have been compared with experimental data on proton–nucleus collisions.

Once they have been created, antiprotons may annihilate on interstellar protons. This process dominates at low energy, and its cross-section has been taken from Tan and Ng (1983). Also, antiprotons may survive inelastic scatterings where the target proton is excited to a resonance: these so–called tertiary antiprotons do not annihilate but lose a significant amount of their kinetic energy. We then propagate and solar–modulate the antiproton rate exactly as for stable nuclei. For a complete discussion on the above–discussed interactions and on the treatment of the tertiary component, we refer to Donato et al., 2001.

Fig. 4 displays this computed antiproton flux along with experimental data collected by the BESS experiment (Orito et al. 2000, Maeno et al. 2000) for a reference set of parameters (see Donato et al., 2001). The dotted lines represent the contribution to the total flux coming from the various nuclear reactions.

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[1] http://sroesler.home.cern.ch/sroesler/

First of all, we notice that the calculated spectrum agrees very well with the BESS data points. This strong result gives confidence in our consistent treatment of nuclei and antiproton propagation. Second, even if the main production channel is the spallation of cosmic ray protons over interstellar hydrogen, we see that the contribution of protons over helium is very important, particularly at low energies (where a hypothetical primary signature would be expected).

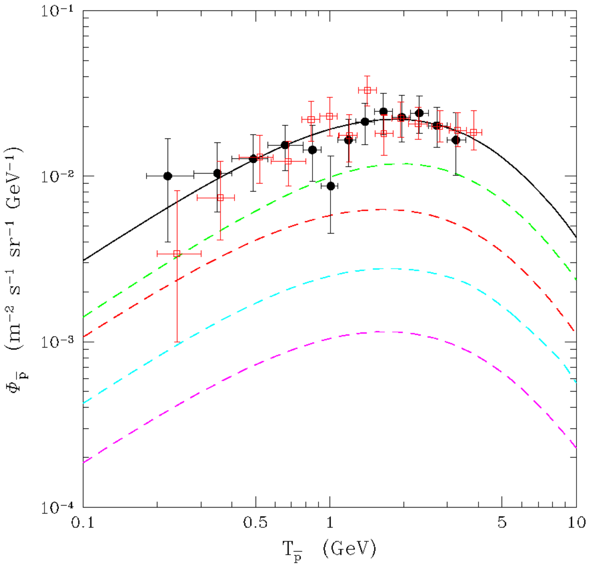

Figure 4: *Solid line shows the total secondary antiproton spectrum for the reference set of diffusion parameters (see text for details). Dashed lines are the contributions to this total flux from various nuclear reactions (from top to bottom: p–p, p–He, He–p and He–He). Data points are taken from* BESS 95+97 *(filled circles) and from* BESS 98 *(empty squares).*

Since the propagation parameters are not perfectly known, some uncertainty must affect the antiproton spectrum. To estimate it, we calculated the antiproton spectra corresponding to all the combinations of the free parameters (δ, K_0, L, V_c and V_a) giving a good fit to B/C. The result is presented in Fig. 5. The two curves represent the minimal and the maximal flux obtained with this set of parameters. The undeterminacy is 9% from 100 MeV to 1 GeV, reaches

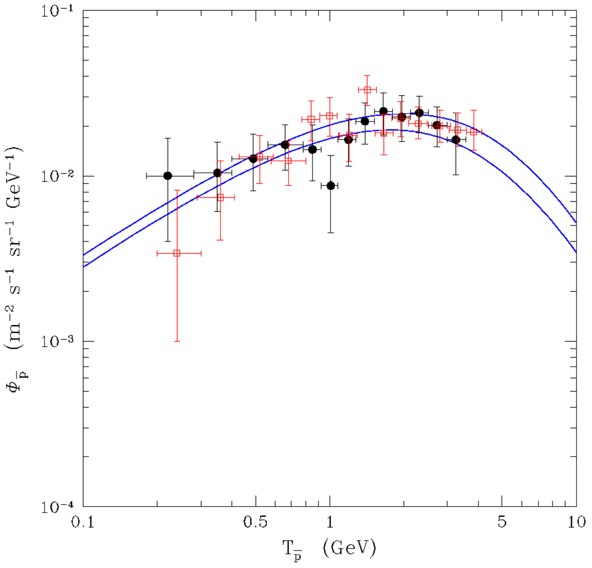

Figure 5: *Antiproton spectra generated with the whole region of parameter space consistent with B/C (Fig. 7 of Paper I). The resulting bounds give an estimation of the uncertainty due to the undeterminacy of the diffusion parameters (data as in the previous figure).*

a maximum of 24% at 10 GeV and decreases to 10% at 100 GeV. It may be considered quite conservative
The uncertainties on the antiproton production cross-sections from p-He, He-p and He-He reactions have been evaluated using the most extensive set of experimental data available (see Donato et al. 2001 for details). All those measurements have been compared with DTUNUC computations. Results on the secondary antiproton spectrum are presented in Fig. 6. The shift of the upper and the lower curve with respect to the central one is of the order of 22–25 % over the whole energy range, dominating uncertainties due to propagation. Many other minor sources of uncertainties have been estimated and discussed in Donato et al.,2001, and they do not add more than few % to the undeterminacy of the flux.

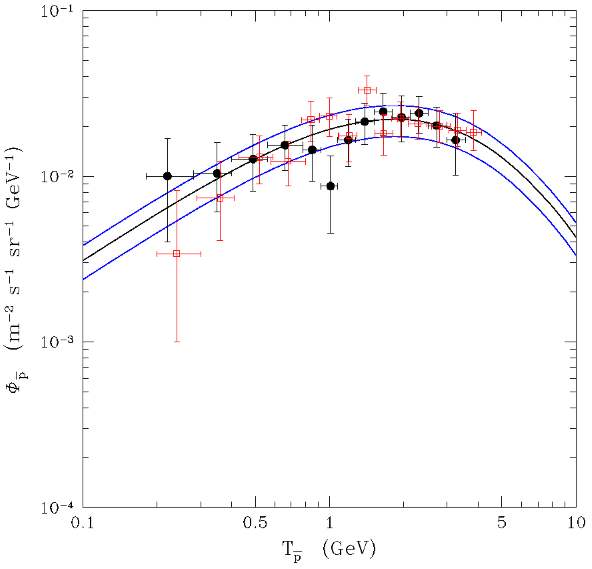

Figure 6: *The antiproton spectrum has been computed with extreme values of* DTUNUC *nuclear parameters. The central line is the reference curve showed in Fig. 4, while upper and lower curves correspond respectively to the maximum and minimum of the antiproton production rate. These two bounds give an estimation of the uncertainty due to the undeterminacy of the nuclear parameters (data as in the previous figure).*

5 Conclusions and perspectives

We have discussed the propagation of stable nuclei and antiprotons in a two–zone diffusion model, which is shown to reproduce data quite well without any further adjustement. A deep understanding of the physical processes leading to acceleration and propagation of galactic cosmic rays, and more severe constraints on the diffusion parameters, might be got thanks to the several promising space experiments planned for the next decade.

6 Acknowledgements

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