

# Propagation model for cosmic ray species in the Galaxy

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## Abstract

In a recent paper [Astrophys. J. 565 (2002) 280], it has been shown that the flux of secondary cosmic ray (CR) antiprotons appears to be contradictory to measurements of secondary to primary nuclei ratios in cosmic rays when calculated in the same Galactic propagation model. The contradiction appears as a value of the diffusion coefficient necessary to match the secondary ratios  $\bar{p}/p$  and B/C. In particular, it was shown that the reacceleration models designed to match secondary to primary nuclei ratios produce too few antiprotons. It is, however, clear that some reacceleration is unavoidable in the turbulent interstellar medium. Here we discuss an idea of how to improve reacceleration model by allowing for the damping of interstellar turbulences on the small scale by cosmic rays, mostly protons. This would lead to increase in the mean free path lengths at low energies, the well-known phenomena empirically discovered in the Leaky-Box models, thus producing less secondary nuclei. The effect on secondary antiprotons will be discussed elsewhere.

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## 1. Introduction

The spectrum and origin of antiprotons in CR has been a matter of active debate since the first reported detections in balloon flights (Golden et al., 1979; Bogomolov et al., 1979). There is a consensus that most of the CR antiprotons observed near the Earth are “secondaries” produced in collisions of energetic CR particles with interstellar gas (e.g., Mitchell et al., 1996).

The spectrum of secondary antiprotons has a peak at about 2 GeV decreasing sharply towards lower energies. This unique shape distinguishes antiprotons from other CR species. Over the last few years the accuracy has

been improved sufficiently (BESS flights of 1995–2000: Orito et al., 2000; Sanuki et al., 2000; Asaoka et al., 2002) that we can restrict the spectrum of the secondary component accurately enough to test Galactic CR propagation models, and the heliospheric modulation.

It has been recently shown (Moskalenko et al., 2001, 2002; see also Molnar and Simon, 2001; Sina et al., 2004) that accurate antiproton measurements by BESS instrument during the last solar minimum 1995–1997 (Orito et al., 2000) are inconsistent with existing propagation models at the  $\sim 40\%$  level at about 2 GeV while the stated measurement uncertainties in this energy range are now  $\sim 20\%$ . The conventional models based on local CR measurements, simple energy dependence of the diffusion coefficient, and uniform CR source spectra throughout the Galaxy fail to reproduce simultaneously both the secondary to primary nuclei ratio and antiproton flux.

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The reacceleration model designed to match secondary to primary nuclei ratios, e.g., boron/carbon (Simon et al., 1986; Seo and Ptuskin, 1994) produce too few antiprotons because, e.g., matching the B/C ratio at all energies requires the diffusion coefficient to be too large. The models without reacceleration can reproduce the antiproton flux, however they fall short of explaining the low-energy decrease in the secondary to primary nuclei ratio. To be consistent with both, the introduction of breaks in the diffusion coefficient and the injection spectrum is required, which would suggest new phenomena in particle acceleration and propagation.

This forces us to developing a more sophisticated treatment of wave-particle interaction in a course of CR propagation in the turbulent interstellar medium. (An alternative idea of a local “unprocessed” nuclei component in low-energy CR is evaluated in (Moskalenko et al., 2003a, 2004)). In particular, we suggest a new approach which includes the interaction of particles with waves in the interstellar medium in a self-consistent way and take into account the wave damping on energetic particles. This requires numerical methods and iterative procedure to derive the diffusion coefficient at arbitrary energy. Secondary-to-primary elements ratios and antiproton flux should be used as final indicators of the consistency. In our calculations we use CR propagation code GALPROP. More details are given in Ptuskin et al. (2003) and Moskalenko et al. (2003b).

## 2. Basic features of the GALPROP models

The cylindrically symmetric GALPROP models have been described in detail elsewhere (Strong and Moskalenko, 1998); here we summarize their basic features.

The models are three-dimensional with cylindrical symmetry in the Galaxy, and the basic coordinates are  $(R, z, p)$  where  $R$  is Galactocentric radius,  $z$  is the distance from the Galactic plane and  $p$  is the total particle momentum. In the models the propagation region is bounded by  $R = R_h$ ,  $z = \pm Z_h$  beyond which free escape is assumed.

The propagation equation we use for all CR species is written in the form:

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi, \quad (1)$$

where  $\psi = \psi(\mathbf{r}, p, t)$  is the density per unit of total particle momentum,  $\psi(p) dp = 4\pi p^2 f(\mathbf{p}) d\mathbf{p}$  in terms of phase-space density  $f(\mathbf{p})$ ,  $q(\mathbf{r}, p)$  is the source term,  $D_{xx}$  is the spatial diffusion coefficient,  $\mathbf{V}$  is the convection velocity, reacceleration is described as diffusion in momentum space and is determined by the coefficient  $D_{pp}$ ,  $\dot{p} \equiv dp/dt$  is the momentum loss rate,  $\tau_f$  is the time scale for fragmenta-

tion, and  $\tau_r$  is the time scale for radioactive decay. The numerical solution of the transport equation is based on a Crank–Nicholson (Press et al., 1992) implicit second-order scheme. The three spatial boundary conditions  $\psi(R_h, z, p) = \psi(R, \pm z_h, p) = 0$  are imposed on each iteration, where we take  $R_h = 30$  kpc.

For a given  $z_h$  the diffusion coefficient as a function of momentum and the reacceleration or convection parameters is determined by boron-to-carbon (B/C) ratio data. The spatial diffusion coefficient is taken as  $D_{xx} = \beta D_0 (\rho/\rho_0)^\delta$  if necessary with a break ( $\delta = \delta_1$  below rigidity  $\rho_0$ ,  $\delta = \delta_2$  above rigidity  $\rho_0$ ). The injection spectrum of nucleons is assumed to be a power law in momentum,  $dq(p)/dp \propto p^{-\gamma}$  for the injected particle density. For the case of reacceleration the momentum-space diffusion coefficient  $D_{pp}$  is related to the spatial coefficient  $D_{xx}$  (Berezinskii et al., 1990; Seo and Ptuskin, 1994) via the Alfvén speed  $v_A$ . The convection velocity (in  $z$ -direction only)  $V(z)$  is assumed to increase linearly with distance from the plane ( $dV/dz > 0$  for all  $z$ ). This implies a constant adiabatic energy loss.

The interstellar hydrogen distribution uses HI and CO surveys and information on the ionized component; the helium fraction of the gas is taken as 0.11 by number. The  $H_2$  and HI gas number densities in the Galactic plane are defined in the form of tables, which are interpolated linearly. The extension of the gas distribution to an arbitrary height above the plane is made using analytical approximations.

The distribution of CR sources is chosen to reproduce the CR distribution determined by analysis of EGRET  $\gamma$ -ray data (Strong and Mattox, 1996) and was described in Strong and Moskalenko (1998).

Energy losses for nucleons by ionization and Coulomb interactions are included, and for electrons by ionization, Coulomb interactions, bremsstrahlung, inverse Compton, and synchrotron.

Positrons and electrons (including secondary electrons) are propagated in the same model. Positron production is computed as described in Moskalenko and Strong (1998), that paper includes a critical reevaluation of the secondary  $\pi^\pm$ - and  $K^\pm$ -meson decay calculations.

Gas-related  $\gamma$ -ray intensities are computed from the emissivities as a function of  $(R, z, E_\gamma)$  using the column densities of HI and  $H_2$ . The interstellar radiation field, used for calculation of the inverse Compton emission and electron energy losses, is calculated based on stellar population models and COBE results, plus the cosmic microwave background.

## 3. New developments

The experience gained from the original fortran-90 code allowed us to design a new version of the model, entirely rewritten in C++, that is much more flexible.

It allows essential optimizations in comparison to the older model and a full three-dimensional spatial grid. It is now possible to explicitly solve the full nuclear reaction network on a spatially resolved grid. The code can thus serve as a complete substitute for the conventional “leaky-box” or “weighted-slab” propagation models usually employed, giving many advantages such as the correct treatment of radioactive nuclei, realistic gas and source distributions etc. It also allows stochastic SNR sources to be included. It still contains an option to switch to the fast running cylindrically symmetrical model which is sufficient for many applications such as the present one.

In the new version, we have updated the cross-section code to include the latest measurements and energy dependent fitting functions. The nuclear reaction network is built using the Nuclear Data Sheets. The isotopic cross-section database consists of thousands of points collected from the literature. This includes a critical re-evaluation of some data and cross checks. The isotopic cross-sections are calculated using the author’s fits to major beryllium and boron production cross sections  $p + C, N, O \rightarrow Be, B$  (Moskalenko and Mashnik, 2003). Other cross-sections are calculated using phenomenological approximations by Webber et al. (1990) and/or Silberberg et al. (1998) renormalized to the data where it exists. The cross-sections on the He target are calculated using a parametrization by Ferrando et al. (1988).

The reaction network is solved starting at the heaviest nuclei (i.e.,  $^{64}\text{Ni}$ ). The propagation equation Eq. (1) is solved, computing all the resulting secondary source functions, and then proceeds to the nuclei with  $A - 1$ . The procedure is repeated down to  $A = 1$ . In this way all secondary, tertiary etc. reactions are automatically accounted for. To be completely accurate for all isotopes, e.g., for some rare cases of  $\beta^\pm$ -decay, the whole loop is repeated twice. Our preliminary results for all CR species  $Z \leq 28$  are given in Strong and Moskalenko (2001).

#### 4. Cosmic rays in interstellar turbulence: a self-consistent approach

It is known that galactic CR have relatively high energy density and they can not always be treated as test particles moving in given interstellar magnetic fields, see Berezhinskii et al. (1990). In particular, when the stochastic reacceleration of CR is considered, one has to take into account the damping of waves, which loose energy on particle acceleration. The damping causes the change of the wave spectrum that in its turn affects the particle transport. Thus in principle the study of CR propagation may need a self-consistent consideration. We shall see from the numerical estimates below that the back reaction of CR on interstellar turbulence

should be taken into account at particle energies below 10 GeV/nucleon.

It is assumed that the wave-particle interaction in the interstellar plasma has a resonant character (the cyclotron resonance). The scattering of energetic particles by random hydromagnetic waves leads to the spatial diffusion of CR in the Galaxy. The CR diffusion coefficient is determined by the following approximate equation (Berezhinskii et al., 1990):

$$D(p) = \frac{vr_g B^2}{12\pi k_{\text{res}} W(k_{\text{res}})}, \quad (2)$$

where  $v$  is the particle velocity,  $r_g = pc/(ZeB)$  is the particle Larmor radius in the average magnetic field  $B$  ( $Ze$  is the particle charge),  $k_{\text{res}} = 1/r_g$  is the resonant wave number, and  $W(k)$  is the spectral energy density of waves defined as  $\int dk W(k) = \delta B^2/4\pi$  ( $\delta B$  is the random magnetic field,  $\delta B \ll B$ ).

In its simplified form, the steady state equation for hydromagnetic waves with a nonlinear energy transfer in  $k$ -space can be written as

$$\frac{\partial}{\partial k} \left( C_A k^2 W(k) \sqrt{\frac{kW(k)}{4\pi\rho_H}} \right) = -2\Gamma_{\text{cr}}(k)W(k) + S\delta(k - k_L), \quad (3)$$

$k \geq k_L$  (e.g., Landau and Lifschitz, 1987; Norman and Ferrara, 1996). Here the left-hand side of equation describes the Kolmogorov type nonlinear cascade from small  $k$  to large  $k$ ,  $C_A$  is a constant and according to the numerical simulations of magnetohydrodynamical turbulence by Verma et al. (1996) the magnitude of  $C_A$  is very roughly equal to 0.3,  $\rho_H$  is the interstellar gas density. The right-hand side of Eq. (3) includes the wave damping on CR and the source term which works on a large scale  $\sim 1/k_L$ , and describes the generation of turbulence by supernova bursts, powerful stellar winds, and superbubbles expansion. In the limit of negligible damping,  $\Gamma_{\text{cr}} = 0$ , the solution of Eq. (3) gives the Kolmogorov spectrum  $W(k) \propto k^{-5/3}$  at  $k > k_L$ . The latter leads to the diffusion coefficient  $D(p) \propto v(p/Z)^{1/3}$ .

The expression for wave amplitude attenuation is given by (Berezhinskii et al., 1990):

$$\Gamma_{\text{cr}} = \frac{\pi e^2 V_a^2}{2kc^2} \int_{p_{\text{res}}(k)}^{\infty} \frac{dp}{p} \Psi(p), \quad (4)$$

where  $V_a = B/\sqrt{4\pi\rho_H}$  is the Alfvén velocity,  $p_{\text{res}} = ZeB/cck$  is the resonant momentum.

The solution of Eqs. (3), (4) at  $k > k_L$ , gives

$$\frac{kW(k)}{B^2} = \left[ \left( \frac{k_L}{k} \right)^{1/3} \left( \frac{k_L W(k_L)}{B^2} \right)^{1/2} - \frac{\pi e^2 V_a}{3C_A c^2 k^{1/3}} \right]^2 \times \int_{k_0}^k dk_1 k_1^{-8/3} \int_{p_{\text{res}}(k_1)}^{\infty} \frac{dp}{p} \Psi(p). \quad (5)$$

The wave damping on CR is essential only at relatively small scales  $k^{-1} < k_d^{-1}$ ,  $k_d \ll k_L^{-1}$  (in fact,  $k_d^{-1} \sim 10^{12}$  cm,  $k_L^{-1} \sim 10^{20}$  cm). The turbulence at  $k_d^{-1} \ll k^{-1} < k_L^{-1}$  obeys the Kolmogorov scaling  $W(k) \propto k^{-5/3}$ . It is clear from Eq. (5) that the dissipation of waves on CR described by the second term in square brackets makes the wave spectrum at large wave numbers steeper than the Kolmogorov spectrum.

The diffusion mean free path  $l(p)$ , as defined by  $D(p) = vl(p)/3$ , is now given by:

$$l(p) = r_g^{2/3}(p_L) r_g^{1/3}(p) \left[ \left( \frac{r_g(p_L)}{l(p_L)} \right)^{1/2} - \frac{2\pi^{3/2} V_a p_L^2}{3C_A B^2} \times \int_{p/p_L}^1 dt t^{2/3} \int_{t_{pL}}^{\infty} \frac{dp_1}{p_1} \Psi(p_1) \right]^{-2}, \quad (6)$$

where we use the resonant conditions  $p = p_{\text{res}}(k)$  and introduce  $p_L = p_{\text{res}}(k_L)$ . Eq. (6) is formally valid at  $p < p_L \sim 10^{17}$  eV/c. The second term in square brackets reflects the modification of diffusion mean free path due to the wave dissipation on CR. It increases with decreasing the particle energy. It is easy to estimate that the second term in square brackets is small at high energies but it is comparable with the first term in square brackets at  $p \sim 1$  GeV/c (at  $l = 3$  pc,  $V_a = 30$  km s $^{-1}$ ,  $B = 3$   $\mu$ G). So, the nonlinear modification of CR diffusion is expected at  $E < 10$  GeV/nucleon.

As the most abundant species, the CR protons mainly determine the wave dissipation. Their distribution function  $\Psi(p)$  should be used to calculate  $W(k)$  and  $l(p)$ . The self-consistent treatment of CR propagation implies the solution of transport Eq. (1) for  $\Psi(p)$  with the diffusion mean free path Eq. (6), which is a function of  $\Psi(p)$ .

To demonstrate the effect of wave damping, let us consider a simple case of one-dimensional diffusion model of CR propagation with the source distribution  $q(r, p) = q_0(p)\delta(z)$  (that corresponds to the infinitely thin disk of CR sources located at  $z = 0$ ) and the flat CR halo of height  $H$ , see Berezhinskii et al. (1990), Jones et al. (2001). The CR source spectrum is of the form  $q_0(p) \propto p^{-\gamma}$  and the index is estimated as  $\gamma = 2.0$ – $2.4$ .

Let us assume that stochastic reacceleration does not essentially change the CR spectrum on the characteristic time of CR leakage from the Galaxy. We also ignore ionization energy losses and losses for nuclear fragmentation and assume that the equilibrium density of CR protons is determined by the balance between their production in the sources and the free diffusion leakage from the Galaxy. The solution of the diffusion equation for the relativistic protons in the galactic disk is then

$$\Psi(p) = \frac{3q_0(p)H}{2vl(p)}. \quad (7)$$

We simplify Eq. (6) by using the approximation  $\int_{t_{pL}}^{\infty} \frac{dp_1}{p_1} \Psi(p_1) \approx (\gamma + \frac{1}{3})^{-1} \Psi(t_{pL})$  and write it down as

$$l(p) \approx l_K(p) \left[ 1 - \frac{2\pi^{3/2} V_a p^{1/3}}{3C_A B^2 (\gamma + \frac{1}{3})} \left( \frac{l_K(p)}{r_g(p)} \right)^{1/2} \times \int_p^{p_L} dp_1 p_1^{2/3} \Psi(p_1) \right]^{-2}, \quad (8)$$

where  $l_K(p)$  is the diffusion mean free path in the turbulence with Kolmogorov spectrum, which is not modified by the wave damping on CR.

Now one can obtain the following solution of Eqs. (7) and (8) for the diffusion mean free path in the case of a power law source spectrum:

$$l(p) = l_K(p) \left[ 1 + \frac{\pi^{3/2} V_a H p^{1/3}}{C_A B^2 (\gamma + \frac{1}{3})} \left( \frac{l_K(p)}{r_g(p)} \right)^{1/2} \times \int_p^{p_L} dp_1 p_1^{2/3} \frac{q_0(p_1)}{v(p_1) l_K(p_1)} \right]^2. \quad (9)$$

The last expression together with Eq. (7) presents the self-consistent solution of the considered simple problem.

The low-energy asymptotic mean free path Eq. (9) is  $l(p) \propto v^{-2} p^{3-2\gamma}$ . The high-energy asymptotic mean free path Eq. (9) is  $l(p) \approx l_K(p) \propto p^{1/3}$  that corresponds to a Kolmogorov spectrum of waves. One can check that the wave spectrum preserves the Kolmogorov scaling  $W(k) \propto k^{-5/3}$  at small  $k$  and it is modified as  $W(k) \propto k^{1-2\gamma}$  at large wave numbers.

## 5. Conclusion

The back reaction of energetic particles on interstellar turbulence may change the spectrum of hydromagnetic waves at large wave numbers that leads to the change of CR diffusion coefficient. In particular, the modification of Kolmogorov type spectrum of turbulence leads to the CR diffusion coefficient which goes through a minimum at particle magnetic rigidity about a few GV, so that the diffusion coefficient has the power law asymptotics  $D(p) \propto vp^{1/3}$  and  $D(p) \propto v^{-1} p^{3-2\gamma}$  at large and small  $p$ , respectively. (The exponent of CR source spectrum  $\gamma \sim 2.2$ .) Such a behaviour reduces the rate of stochastic reacceleration of CR in the interstellar medium that is needed to reproduce the observed peaks in the secondary-to-primary elements ratios in CR at these rigidities. The reduced rate of reacceleration may help to explain the antiproton data.

In a future work, we plan to undertake a full scale self-consistent modeling of CR transport in the turbulent interstellar medium in the frameworks of the realistic galactic model described here and with the damping of waves on energetic particles included.

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