Proceedings of ICRC 2001: 1877 © Copernicus Gesellschaft 2001

ICRC 2001

A new calculation of the interstellar secondary cosmic ray antiprotons

A. Molnar and M. Simon

Fachbereich Physik, Universitaet Siegen, 57068 Siegen, Germany

Abstract. The interstellar antiproton flux produced in cosmic ray interactions with the interstellar gas is calculated within the framework of the Leaky Box Model (LBM) and the Diffusion Halo Model (DHM) including stochastic reacceleration and energy changing due to the nonannihilation process. Results of this calculation will be presented and a comparison with recent measurements of the antiproton flux show a good agreement, thus indicating that the antiprotons are of secondary origin. At low energies there is however a hint of an overabundance of measured antiprotons.

1 Introduction

The existing data on the antiproton flux in the cosmic radiation appear to be within the conservatively estimated bounds of theoretical work in which antiprotons are produced as secondary particles of cosmic ray interaction with the interstellar gas (Simon, Molnar and Roesler 1998). In recent years more improvements on the inputs of such a calculation have been implemented, such as new measurements on the cosmic ray spectra, the consideration of contributions of heavy particles, the use of new cross sections and the consideration of nonannihilation processes (see Simon, Molnar and Roesler 1998 and references therein).

We here present results from a calculation which makes use of these improvements and which provides the expected antiproton flux in the presence of reacceleration. We perform this calculation in the framework of two existing and competing propagation models, namely the Leaky Box Model and the Diffusion Halo Model (Molnar and Simon 2001) and compare these results with data.

Correspondence to: A. Molnar
(Molnar@ida.physik.uni-siegen.de)

2 The transport equations for the Leaky Box Model and the Diffusion Halo Model

In order to obtain the equilibrium spectra of cosmic ray antiprotons one has to solve the following equations for the different models. For the LBM we solved:

$$\begin{aligned} \frac{N_{\bar{p}}(E)}{\tau_{esc}(E)} + \frac{N_{\bar{p}}(E)}{{}_{\bar{p}}\tau_{int}(E)} &= Q_{\bar{p}}(E) + Q_{\bar{p}}^{non}(E) \\ &- \frac{\partial}{\partial E}\left\{ \left(\left\langle \frac{\partial E}{\partial t} \right\rangle_{ion} + \left\langle \frac{\partial E}{\partial t} \right\rangle_{reacc} \right) \cdot N_{\bar{p}}(E) \right\} \\ &+ \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{ \left\langle \frac{\Delta E^2}{\Delta t} \right\rangle_{reacc} \cdot N_{\bar{p}}(E) \right\} \end{aligned} \tag{1}$$

and for the one dimensional DHM we solved:

$$\begin{aligned} 0 = &\frac{\partial}{\partial z}\left\{ D(E,z) \cdot \frac{\partial}{\partial z} N_{\bar{p}}(E,z) \right\} \\ &- \frac{N_{\bar{p}}(E,z)}{{}_{\bar{p}}\tau_{int}(E,z)} + Q_{\bar{p}}(E,z) + Q_{\bar{p}}^{non}(E,z) \\ &- \frac{\partial}{\partial E}\left\{ \left(\left\langle \frac{\partial E}{\partial t} \right\rangle_{ion} + \left\langle \frac{\partial E}{\partial t} \right\rangle_{reacc} \right) \cdot N_{\bar{p}}(E,z) \right\} \\ &+ \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{ \left\langle \frac{\Delta E^2}{\Delta t} \right\rangle_{reacc} \cdot N_{\bar{p}}(E,z) \right\} \end{aligned} \tag{2}$$

These two equations contain similar and different terms. The quantity $N_{\bar{p}}(E)$ stands for the number density of cosmic ray antiprotons and in Equation 2 $N_{\bar{p}}(E,z)$ denotes the number density of antiprotons at a given position z, away from the galactic plane. The first term of the right side in Equation 2 describes the diffusion and $D(E,z)$ means the diffusion coefficient at position z. For simplicity we allow $D(E)$ to be independent of position. The second term on the right side of Equation 2 accounts for the losses of antiprotons similar to those in Equation 1, where ${}_{\bar{p}}\tau_{int}(E)$ stands for the mean lifetime of antiprotons against interaction in the interstellar gas. $\frac{\partial}{\partial E}\{\ldots\}$ and $\frac{\partial^2}{\partial E^2}\{\ldots\}$ account in both equations for the energy changing processes. The losses are due to ionization and the two energy gain terms, which are due to stochastic reacceleration, are given by:

$$\left\langle \frac{\partial E}{\partial t} \right\rangle_{reacc} = \eta \beta E_{tot} \left(\frac{R}{MV} \right)^{-\alpha}$$
$$\left\langle \frac{\Delta E^2}{\Delta t} \right\rangle_{reacc} = \frac{\eta}{2} \beta^3 E_{tot}^2 \left(\frac{R}{MV} \right)^{-\alpha} \qquad (3)$$

$\eta[s^{-1}]$ and α are free parameters. For the LBM η can be written as $\eta = \eta_x n\, m\, c$ where $n[cm^{-3}]$ denotes the mean interstellar gas density and $m[g]$ the mean mass of an interstellar gas particle. We assumed for the interstellar gas a mixture of 90% hydrogen and 10% helium. The main parameter in the LBM ist the mean escape length $\lambda_{esc} = n\, m\, \beta\, c\, \tau_{esc}$. In both equations (Equation 1 and 2) $Q_{\bar{p}}(E)\,[cm^{-3}s^{-1}GeV^{-1}]$ denotes the source term for secondary $\bar{p}$ and carries all information on the interactions of cosmic ray particles with the different target particles of the interstellar gas. Thus the source term $Q_{\bar{p}}(E)$ stretches over two sums:

$$Q_{\bar{p}}(E) = 2 \sum_{j}^{ISM} \sum_{i}^{CR} 4\pi n_j \int_{E_{thr}}^{\infty} \frac{d\sigma_{\bar{p}}^{i,j}}{dE}(E, E_i) \cdot I_i(E_i) dE_i \quad (4)$$

The index j stands for the target particle, i for the cosmic ray projectile and the factor 2 accounts for $\bar{p}$ produced by $\bar{n}$ decay. $I_i(E_i)$ is the flux of cosmic ray particles of type i with kinetic energy E_i and the quantity $n_j[cm^{-3}]$ is the number density of the j-type target particle of the interstellar gas. The expression $(d\sigma_{\bar{p}}^{ij}/dE)(E, E_i)$ stands for the inclusive differential $\bar{p}$ production cross section for an interaction which involves an i-type projectile of kinetic energy E_i and a j-type target particle at rest producing an antiproton of kinetic energy E. The source term $Q_{\bar{p}}^{non}(E)$ accounts for the nonannihilation process, that allows antiprotons to emerge from an inelastic scattering with an interstellar gas particle. These antiprotons have a lower energy than the incoming antiprotons and the energy spectrum is determined by the differential cross section $d\sigma_{\bar{p}}^{non}/dE$ for this process:

$$Q_{\bar{p}}^{non}(E) = 2 \cdot 4\pi n \int_{E}^{\infty} \frac{d\sigma_{\bar{p}}^{non}}{dE}(E', E) \cdot I_{\bar{p}}(E') dE' \qquad (5)$$

where $n\,[cm^{-3}]$ is the mean interstellar gas density. For a more detailed description of this term and further information about the various inputs to the calculation we refer to Simon, Molnar and Roesler (1998).

3 Results of the Calculation

We solved the above equations under four different situations: the LBM and the DHM with and without reacceleration. In all four cases one deals with free parameters. We used for the four models a collection of data for the B/C ratio (see Molnar and Simon 2001) to determine which parameters best fit this ratio. We obtained the following results for the LBM without reacceleration:

$$\lambda_{esc} = \begin{cases} \lambda_0 \left(\frac{R}{4.7\,GV}\right)^{0.8} & for\ R < 4.7\,GV \\ \lambda_0 \left(\frac{R}{4.7\,GV}\right)^{-0.57} & for\ R > 4.7\,GV \end{cases} \qquad (6)$$

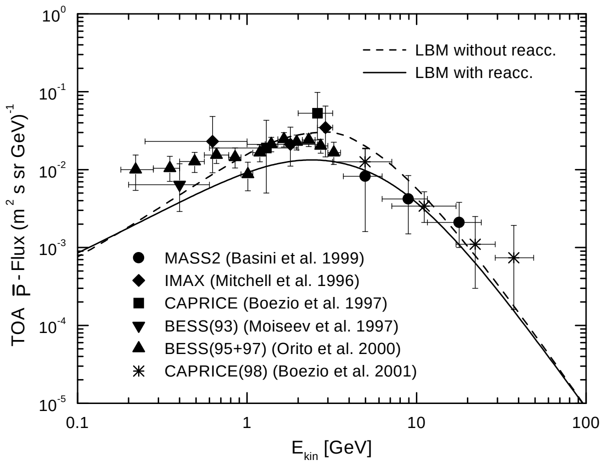

Fig. 1. The two curves show the calculated $\bar{p}$-Flux in the framework of the LBM, with and without reacceleration. Data are as indicated. The curves are solar modulated with modulation parameter $\Phi = 350\,MV$

with $\lambda_0 = 12.8\,g\,cm^{-2}$ and for the LBM with reacceleration:

$$\lambda_{esc} = (64\,g\,cm^{-2})\,(R/MV)^{-0.3} \qquad (7)$$

with the following parameters for the reacceleration terms: $\eta_x = 0.64(g\,cm^{-2})^{-1}$ and $\alpha = 0.3$. In the framework of the LBM the mean gas density n of the confinement volume was derived by matching the calculated ratio of the radioactive ^{10}Be to the stable ^{9}Be isotope with data. We obtain a mean gas density of $n = 0.23cm^{-3}$ in the case of no reacceleration and $n = 0.22\,cm^{-3}$ with reacceleration.

In the DHM without reacceleration the fit to the B/C ratio only allows to determine the ratio of the diffusion coefficient $D(E)$ to the halo size H. The best fit was obtained with the following parameters:

$$\frac{D(R)}{H} = \begin{cases} \nu_0 \beta \left(\frac{R}{4.7\,GV}\right)^{-0.8} & for\ R < 4.7\,GV \\ \nu_0 \beta \left(\frac{R}{4.7\,GV}\right)^{0.57} & for\ R > 4.7\,GV \end{cases} \qquad (8)$$

with $\nu_0 = 1.7 \cdot 10^6\ cm\,s^{-1}$. This D/H ratio can be disentangled by matching the calculated ^{10}Be/^{9}Be ratio with data. For the halo size one obtains $H = 3.5\ kpc$. In the presence of reacceleration we also fit the B/C ratio and the ^{10}Be/^{9}Be ratio simultaneously and for the following parameters we obtain the best fit:

$$D = D_0 \beta\,(R/MV)^{1/3} \qquad (9)$$

with $D_0 = 2.52 \cdot 10^{27}\ cm^2 s^{-1}$ and $\eta = 3.06 \cdot 10^{-15}\ s^{-1}$, $\alpha = 1/3$ and halo size $H = 3.8\ kpc$.

With these various conditions, which fit the B/C ratio and the $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratio simultaneously, we calculated the antiproton flux. Figure 1 and 2 show the results of these calculations.

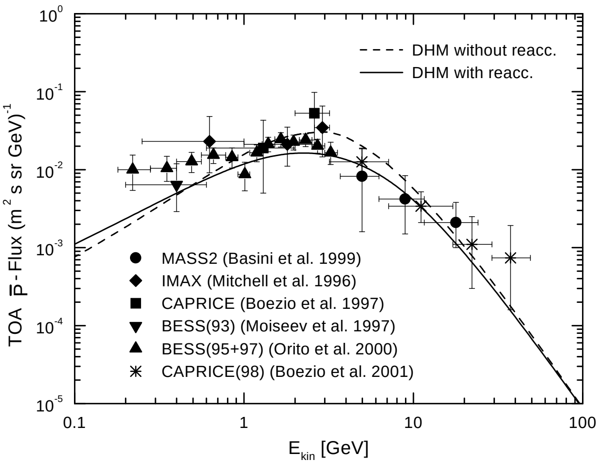

Fig. 2. The two curves show the calculated $\bar{p}$-Flux in the framework of the DHM, with and without reacceleration. Data are as indicated. The curves are solar modulated with modulation parameter $\Phi = 350\ MV$

4 Conclusion

As can be seen in Figure 1 and 2 the data on the measured antiproton flux are in general in good agreement with the theoretical expectations. Pursuant to these expectations antiprotons are produced as secondary particles in cosmic ray interactions with the interstellar gas. The models of propagation which fit the cosmic ray nuclei seem also capable of fitting the antiprotons, thus particles with $Z = 1$. The small differencies between the LBM and the DHM in the presence of reacceleration we attribute to the different reacceleration strengths in the two models, which were adjusted to reproduce the B/C ratio involving particles with $Z/A \approx 1/2$. Whether the lower energy data, which lie above the calculated curves, indicate a new source of antiprotons or the necessity for modifications of the propagation conditions is subject to further investigations (see also Moskalenko et al. 2001). At higher energies, above 20 GeV, the data do not exclude either the existence of other sources for antiproton production (Bergström, Edsjö and Ullio 1999).

References

Basini, G., et al., Proc. of 26th ICRC, Salt Lake City, 3, 77, 1999
Bergström, L., Edsjö, J. and Ullio, P., ApJ, 526, 215
Boezio, M., et al., ApJ, 487, 415, 1997
Boezio, M., et al., submitted to ApJ, preprint: astro-ph/0103513, 2001
Mitchell, J.W., et al., Phys. Rev. Lett., 76, 3057
Moiseev, A., et al., ApJ, 474, 479, 1997
Molnar, A. and Simon, M., Proc. of 27th ICRC, Hamburg, OG 1.3, 2001
Moskalenko, I.V. et al., to be published in COSPAR Colloquia Series, eds. H. J. Fahr et al., preprint: astro-ph/0102207, 2001
Orito, S., et al., Phys. Rev. Lett. 84, 1078, 2000
Simon, M., Molnar, A. and Roesler, S., ApJ, 499, 250, 1998