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The spectrum of secondary antiprotons

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Abstract. The cosmic-ray antiproton spectrum may be an important tool for understanding and constraining the nature of dark matter and baryon-symmetric cosmological models. Its understanding requires a good theoretical modeling of antiprotons produced as secondary particles in the interactions of high-energy protons and nuclei with interstellar gas. The production rate of antiprotons in cosmic-ray interactions depends on physical and astrophysical parameters whose values have recently been revised and refined. In this paper we describe the wind-diffusion model of antiprotons and discuss uncertainties in the flux calculation.

1 Introduction

The interaction of primary cosmic-ray nuclei with the intervening medium produces a small, but measurable, flux of secondary antiprotons. Whether the flux of these secondary antiprotons is complemented by a primary component is still unknown. From the theoretical perspective, there are ample reasons to suspect that a primary component exists. The most widely favored candidate for non baryonic dark matter are stable supersymmetric particles whose annihilation in the Galactic halo could produce a flux of low energy antiprotons (Silk and Srednicki, 1984; Bottino et al., 1998; Ullio , 1999; Bergström et al., 1999). Antiprotons may also be produced with a characteristic spectrum in the decay of primordial black holes (MacGibbon and Carr, 1991). An independent confirmation of the existence of these sources has not yet been made. Doing this necessitates distinguishing and isolating a primary component of antiprotons from the well established secondary component. This, however, requires an accurate calculation of the secondary flux which depends on the propagation model, as well as the precise measurement of the cosmic-ray antiproton spectrum.

It is now becoming possible to compare and examine the prediction of various propagation models and to search for a possible primary component of cosmic-ray antiprotons. The recent and ongoing balloon measurements (Mitchell et al., 1996; Boezio et al., 1997; Basini et al., 1999; Bieber et al., 1999; Maeno et al., 2000; Bergström et al., 2000) have improved the statistics considerably, and the currently planned space borne experiments (Ahlen et al., 1994; Morselli and Picozza, 1999) promise to improve the measurements further to unprecedented accuracies. From a different perspective, it is also becoming increasingly possible to test the predictions of various propagation models by a priori assumption that all detected antiprotons are secondary. Many calculations in the past have been given in the context of the standard leaky box, diffusion or stochastic reacceleration models (Moskalenko et al., 2001; Mitsui, 1996; Simon and Heinbach, 1996). In this paper we present a calculation of the secondary antiproton spectrum in the Galactic Wind model. The effect of adiabatic loss in the expanding Galactic wind leads to an antiproton spectrum different from the prediction of other models. This allows us to search for a signature of the Galactic wind in the cosmic-ray data.

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2 Secondary Production of Antiprotons

In the standard propagation models, secondary antiprotons are expected to be produced in the interaction of primary high-energy cosmic-ray protons and nuclei with the interstellar gas. The production rate depends on the interaction cross sections, as well as the cosmic-ray flux and the composition of the interstellar medium. The dominant process is the interaction of protons with interstellar hydrogen (Gaisser, 1990), $p + p \rightarrow p + p + p + \bar{p}$, which in the lab frame has a threshold kinetic energy of $6\, m_p c^2$. At the threshold energy the antiproton is not produced at rest, but necessarily has a finite momentum. From the kinematics of the interaction it can thus be inferred that very low energy antiprotons can only be produced by higher energy protons (Gaisser amd Levy, 1974) and therefore the production rate is expected to have a peak in the GeV range. The cross section for this interaction is well parameterized by Tan and Ng (1983).

The secondary productions rate of $\bar{p}$, per unit mass of the interstellar gas, per second, and per unit energy is given by

$$Q(E) = \frac{8\,\pi\, \sum_i \sum_j \int_E^\infty I_i(E')\, n_j\, \frac{d\sigma_{\mathrm{ij}\to\bar{\mathrm{p}}}}{dE}\, dE'}{\sum_j n_j\, m_j}, \qquad (1)$$

where I_i is the flux of primary element i with energy E', n_j and m_j are the number density and the mass of the interstellar element j, and $\sigma_{ij\to\bar{p}}$ is the cross section for $\bar{p}$ production in the interaction of elements i and j. The factor $8\,\pi$ in Eq. (1) is due to integration over $4\,\pi$ stradian and a factor 2 is included to account for the production of antineutrons which decay to antiprotons of almost same energy.

The dominance of protons in the cosmic-ray flux and in the interstellar medium implies that heavy nuclei contribute to only a small fraction of the production rate. From the careful analysis of spectral composition of primary cosmic-rays and a simple scaling law for the cross sections, Gaisser and Schaefer (1992) and Mitsui (1996) have found that the effect of heavy nuclei on the production rate rate can be approximated by an energy independent correction factor $\epsilon \approx 1.16$, with $Q(E) = \epsilon\, Q_{pp}(E)$, where

$$Q_{pp}(E) = \frac{8\,\pi\, \int_E^\infty I_p(E')\, \frac{d\sigma_{\mathrm{pp}\to\bar{\mathrm{p}}}}{dE}\, dE'}{m_p} \qquad (2)$$

is the production rate by interacting protons only.

In this analysis, an important distinction has been made between the secondary production of antiprotons by primary cosmic rays, and the tertiary production of antiprotons by inelastic interaction of antiprotons themselves with interstellar nuclei, $\bar{p} + X \;\rightarrow\; \bar{p} + X'$, which downgrades them to lower energies. The latter production rate is

$$S(E) = \frac{4\,\pi}{\sum_j n_j\, m_j}\, \sum_j \int_E^\infty I_{\bar{p}}(E')\, n_j\, \frac{d\sigma_{\bar{\mathrm{p}}\mathrm{j}\to\bar{\mathrm{p}}}}{dE}\, dE', \qquad (3)$$

which clearly has an energy dependence different from production by primary particles. It is significant mainly at low energies. Since $S(E)$ depends on the antiproton flux, which we aim to calculate, a recursive procedure is used to evaluate it in this work.

We use the interstellar (demodulated) LEAP flux (Seo et al., 1991) and the Tan and Ng (1983) cross section to empirically fit the antiproton production rate. For antiproton kinetic energies between 200 MeV and 1.5 GeV, the production rate can be approximated as

$$Q_{pp}(E) \approx \exp(w) \qquad (\mathrm{gm\,sec\,GeV})^{-1}. \qquad (4)$$

For energies between 200 MeV and 1.5 GeV

$$w = -12.95 \,+\, 1.1325\,\eta \,-\, 0.767\,\eta^2, \qquad (5)$$

while for energies between 1.5 GeV and 400 GeV

$$w = -12.42 \,-\, 24.94\,\eta \,+\, 13.75\,[\eta \,+\, \ln(1+\eta)]^{1.115}. \qquad (6)$$

Here $\eta \equiv \ln(E_k/\mathrm{GeV})$ and E_k is the kinetic energy of the antiproton. This approximation is valid to 4% for energies up to 100 GeV and 5% for energies thereafter up to 400 GeV. The secondary production Q_{pp} is characterized by a peak around 2 GeV and is shown in Fig. 1. Once the production rate is computed, the flux of antiprotons, which is the observed variable, can be calculated from the propagation model.

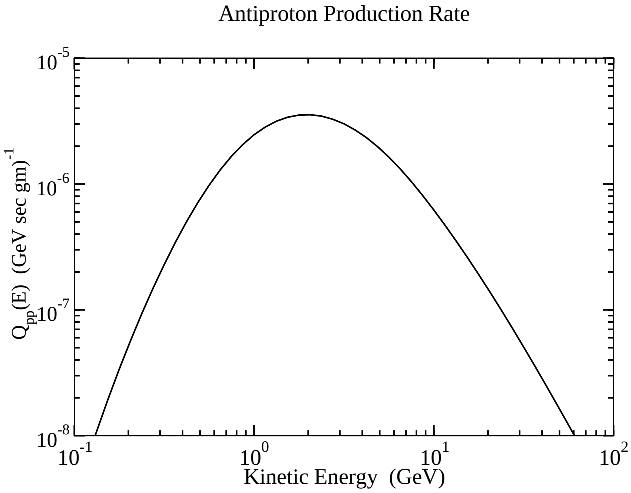

Fig. 1. The production rate of antiprotons in pp interactions.

3 Antiproton Spectrum

The simplest model for propagation of cosmic rays in the Galaxy is the Leaky Box model. In this model cosmic-ray particles diffuse rapidly and then leak out of the Galaxy after crossing an energy dependent grammage (Berezinskii et al., 1990; Gaisser, 1990). The leakage, or escape, path length λ_{esc}, in $\mathrm{g/cm^2}$, characterizes the thickness of matter traversed by cosmic rays when they diffuse out from the Galaxy, and it is the main parameter of the widely used model.

In the Standard Leaky Box (SLB) model the expected flux of antiprotons is describe by

$$\frac{I_{\bar{p}}(E)}{\Lambda(E)} \;+\; \frac{d}{dE}\left(I_{\bar{p}}(E)\,\frac{dE}{dx}\right) \;=\; \frac{Q_T(E)}{4\,\pi}, \qquad (7)$$

where $Q_T(E) \equiv Q(E) \,+\, S(E)$ is the total (secondary plus tertiary) production of antiprotons and

$$\Lambda(E) \equiv \left(\frac{1}{\lambda_{\mathrm{esc}}} \;+\; \frac{1}{\lambda_{\mathrm{int}}}\right)^{-1} \qquad (8)$$

is the effective path length which includes the possibility of interaction before leakage. In the SLB model the energy of antiprotons changes during propagation solely due to ionization losses. Since dE/dx is negative, the solution to Eq.(7), which is a first order differential equation, can readily be written down

$$I_{\bar{p}}(E) = -\,\frac{1}{\frac{dE}{dx}} \int_E^\infty \frac{Q_T(E')}{4\,\pi}\; \exp(\mathcal{L}(E\,,\,E'))\; dE', \qquad (9)$$

where

$$\mathcal{L}(E\,,\,E') \equiv \int_{E}^{E'} \left[\frac{1}{\Lambda(E'')}\right] \left[\frac{dE}{dx}\right]^{-1}_{E''} dE'' \qquad (10)$$

is effectively the propagator for antiprotons. For our calculations we use the escape length found by Jones et al. (2001) from the fit to the B/C and (Sc + Ti +V)/Fe ratios:

$$\begin{aligned} \lambda_{\rm esc} &= 11.8\,\beta \quad R < 4.9\,{\rm GV}, \\ &= 11.8\,\beta\,(R/4.9)^{-0.54} \quad R \geq 4.9\,{\rm GV} \end{aligned} \qquad (11)$$

with the units of ${\rm gm/cm^2}$. R here is the rigidity of the particle. It is evident that at large rigidities, where ionization losses are small, the escape length falls rapidly with energy. Therefore, for R much larger than 5 GV, the production energy, E', can contribute to flux at E only if $E' \approx E$; and asymptotic expansion of integral in Eq. (9) gives the simple solution

$$I_{\bar{p}}(E) = \frac{Q_T(E)\,\Lambda(E)}{4\,\pi} \qquad (E \gg 5\,{\rm GeV}) \qquad (12)$$

which is exactly the solution of Eq. (7) when the energy loss term is neglected. At these energies the effect of inelastic production (Eq. 3) is small and $Q_T \approx Q$. At low energies both ionization losses and inelastic production are however important and full solution of Eq. (9) must be considered. The antiproton spectrum in the context of SLB is fully discussed by Mitsui (1996).

The leaky-box model is however only a simple approximation to the actual process of cosmic-ray transport in the Galaxy. It allows some refinements in the limits of existing experimental uncertainties of the antiproton measurements and in the limits of existing uncertainty in the modeling of interstellar and interplanetary propagation of cosmic rays. Due to the specific kinematic suppression of secondary antiprotons produced below about 1 GeV, the shape of their interstellar spectrum is sensitive to the possible redistribution of cosmic-ray particle energies. Besides the ionization energy losses, which always should be taken into account, the effect of distributed stochastic acceleration on the antiproton spectrum was studied by Simon and Heinbach (1996), and Mitsui (1996). In the present work, we calculate the spectrum of secondary cosmic-ray antiprotons in the Galactic Wind (GW) model. Cosmic rays experience adiabatic cooling in the expanding wind flow and the shift of the position of characteristic peak in the antiproton spectrum might serve as a signature of the Galactic wind.

We consider a simple one-dimensional GW model where cosmic-ray transport is provided by their diffusion in Galactic magnetic fields and by the convection with constant wind velocity U directed outward of the Galactic disk (Jokipii, 1976; Jones 1979). More advanced models of Galactic wind are available now (see Ptuskin et al. (1997) and references therein), but the mere existence of wind in our Galaxy has not been proven, so we prefer here to use the simplest model where the effect of cosmic-ray adiabatic cooling, the object of our investigation, is present. It was shown by Jones et al. (2001) that for an observer at the Galactic plane, the diffusion-convection equation for cosmic-ray intensity is reduced to the equation which has the form of the leaky-box equation but with an additional adiabatic loss term and with some specific expression for the escape length. The energy loss due to adiabatic cooling of the particles is equal to

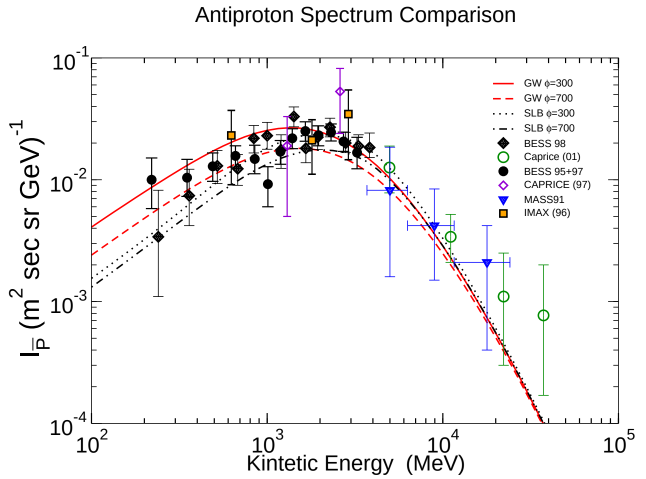

Fig. 2. Comparison of the calculated spectrum of the Galactic Wind (GW) model with that of the Standard Leaky Box (SLB) for modulation ϕ values of 300 and 700.

$$\left.\frac{dE}{dx}\right|_{\rm ad} = -\frac{2\,U}{3\,\mu}\,p, \qquad (13)$$

where $\mu = 2.4 \times 10^{-3}\,{\rm g/cm^2}$ is the surface gas density of the Galactic disk. An effective escape length in this model is

$$\lambda_{\rm esc} = \lambda_1\,\beta\left(1 - \exp\frac{-(R/R_0)^{-a}}{\beta}\right) \qquad (14)$$

where the values of $\lambda_1 = 12.5\,{\rm g/cm^2}$, $U = 29$ km/sec, $R_0 = 11.8$ GV and a =0.74 was obtained by Jones et al. (2001) from fitting the B/C and (Sc + Ti + V)/ Fe ratios. The expression in the exponent of Eq. (14) is actually the dimensionless parameter UH/D where H is the thickness of Galactic cosmic-ray halo and $D \propto \beta\,R^{0.74}$ is the cosmic-ray diffusion coefficient.

4 Comparison With Observation and Conclusion

To compare the calculated spectrum with observational data, the effect of solar modulation has to be properly considered. Several modulation schemes have been proposed (Webber and Potgieter, 1989; Bieber et al., 1999). We use the numerical solution of the steady state and spherically symmetric Fokker-Plank equation (Fisk et al., 1973). The comparison of SLB and GW calculations, corrected for solar modulations at two different ϕ values (ϕ is the parameter which characterizes the level of solar modulation), with the recent experimental results of BESS (Orito et al., 2000; Maeno et al., 2000), IMAX (Mitchell et al., 1996), CAPRICE (Boezio et al., 1997; Bergström et al., 2000) and MASS91 (Basini et al., 1999) is shown in Fig. 2.

The two models studied in this paper predict different spectra for the secondary antiprotons, and these predictions can be verified. It is evident that in the GW model there is a higher flux at low energies due to adiabatic energy loss. Although both models are consistent with the observations, The GW model has a better fit at low energies to the BESS 95+97 data which correspond to solar minimum and therefore are associated with a low ϕ value. Ongoing antimatter experiments with high statistical accuracy and the planned detectors (Ahlen et al., 1994; Morselli and Picozza, 1999) may distinguish between these models.

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