ANTIPROTON SPECTRUM IN THE GALACTIC WIND MODEL

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ABSTRACT

The vast majority of cosmic-ray particles are protons and heavier nuclei. Antiprotons constitute only a small fraction of detected cosmic rays; and it is only recently that measurements with sufficient statistics in the range of 100 MeV to few GeV have been made and an accurate energy spectrum of antiprotons has been inferred. It is now becoming possible to compare and examine the prediction of various propagation models and search for a possible primary component of antiproton cosmic rays. In this paper we present the calculation of secondary antiproton spectrum in the Galactic Wind model. The effect of adiabatic loss in expanding Galactic wind leads to an antiproton spectrum different from the prediction of standard leaky-box model. This allows us to search for a signature of the Galactic wind in the cosmic-ray data.

INTRODUCTION

Antiprotons are produced in cosmic rays as secondary particles in a process of interaction of high-energy protons and nuclei with protons and nuclei in the interstellar gas. To a first approximation, the measured flux of antiprotons is consistent with fluxes of other secondary species in cosmic rays, such as B and Sc+Ti+V group nuclei. This means, in particular, that the same escape length $\lambda_{\rm esc}(E)$ explains all measurements. The escape length $\lambda_{\rm esc}$, in 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 a widely used leaky-box model of cosmic-ray transport. It is worth to note also that the interpretation of measurements of Galactic cosmic rays made in interplanetary space always includes some procedure of demodulation, i.e. the correction for the solar wind effects.

Though satisfactory in the first approximation, the picture 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. A number of effects were discussed in this context: 1) The presence of a small primary antiproton component is not excluded. On a theoretical level, there are ample reasons to suspect such 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 residual flux of low-energy antiprotons (Silk and Srednicki, 1984; Ullio, 1999). Antiprotons with a characteristic spectrum may also be produced in the decay of primordial black holes (MacGibbon and Carr, 1991). 2) Some essential features of the process of comic-ray modulation by the solar wind can in principle be studied with the use of precise antiproton measurements. In particular, a difference in the modulation of proton and antiproton components is expected since the signs of drift velocities in the heliospheric magnetic field are opposite for protons and positrons. The importance of this effect was discussed by Webber and Potgieter (1989) and Bieber et al. (1999). 3) The leaky-box model is only a simple approximation to the actual process of cosmic-ray transport in the Galaxy. 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 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.

STANDARD LEAKY BOX CALCULATIONS

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

$$I_{\bar{p}}(E)\,\left(\frac{1}{\lambda_{\rm esc}}+\frac{1}{\lambda_{\rm int}}\right)+\frac{d}{dE}\left(I_{\bar{p}}(E)\,\frac{dE}{dx}\right)=\frac{Q(E)\,+\,S(E)}{4\pi} \qquad (1)$$

where $\lambda_{\rm esc}$ is the model dependent escape length and $\lambda_{\rm int}=m/\sigma_{\rm total\,inelastic}$ is the interaction length of antiprotons. In these calculation the elastic cross section of $\bar{p}$ is not important. The production by primary cosmic rays is given by

$$Q(E)=2\,\epsilon\times\frac{4\pi}{m}\int_E^{\infty}I_p(E')\frac{d\sigma_{\rm pp\to\bar{p}}}{dE}\,dE' \qquad (2)$$

and may be written separately from the production by inelastic scattering of antiprotons from high to low energies

$$S(E)=\frac{4\pi}{m}\,\xi\int_E^{\infty}I_{\bar{p}}(E')\frac{d\sigma_{\rm \bar{p}p\to\bar{p}}}{dE}\,dE'. \qquad (3)$$

The factor 2 in Eq. (2) takes into account the production of antineutrons which subsequently decay to antiprotons and $\epsilon\approx 1.16$ and ξ are the heavy-nuclei correction factors of order unity (Mitsui, 1996). The ionization energy loss term

$$\left.\frac{dE}{dx}\right|_{\rm ion}\approx-\frac{3.1\,\times\,10^{-4}}{\beta^2}\left(11.2\,+\,\ln\frac{\beta^2}{1-\beta^2}-\beta^2\right)\quad\frac{\rm GeV\,cm^2}{\rm g} \qquad (4)$$

and the inelastic production $S(E)$ are important only at low energies and in some previously published work (Gaisser and Schaefer, 1992) have been neglected due to the numerical complexity of Eq. (1). These calculations underestimate the $\bar{p}$ flux at $E\lesssim 1\,$GeV. It is important to note that in calculating the primary proton flux the non-annihilation (energy degrading) inelastic scattering is seldom an issue because of the power-law nature of the interstellar proton spectrum. The annihilation of protons is also not important due to paucity of antiprotons in the interstellar medium. The circumstances are however completely different for secondary antiprotons where the spectrum is not expected to be monotonic due to the non-trivial form of $\bar{p}$ production cross sections. These cross sections are well parametrized by Tan and Ng (1983) and are not discussed here. The inelastic differential cross sections are not quite well known and a simplifying assumption that $d\sigma_{\mathrm{inel}}/dE_f = \sigma_{\mathrm{inel}}/T_i$, where E_f is the final energy of the antiproton and T_i is its initial kinetic energy, is made in this calculation.

The uncertainties in the cross sections (and the corresponding heavy nuclei corrections) as well as errors in primary flux translate to uncertainties in the calculated flux. For comparing the flux yield of different models it is therefore crucial to use identical input parameters. For these calculations we use the LEAP (Seo et al., 1991) flux of primary protons as a power law in momentum.

$$I_p = \frac{1.5}{\beta}\,[p(GeV/c)]^{-2.74} \qquad (\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}_{.} \tag{5}$$

For our calculations we use the escape length found by Ptuskin et al. (1999) from the fit to the B/C and (Sc + Ti +V)/Fe ratios.

$$\lambda_{\mathrm{esc}} = 11.3\,\beta\,\mathrm{gm/cm}^2 \quad R < 5GV; \qquad \lambda_{\mathrm{esc}} = 11.3\,\beta\,(R/5)^{-0.54}\,\mathrm{gm/cm}^2 \quad R > 5GV \tag{6}$$

where R is the rigidity of the particle.

GALACTIC WIND CALCULATIONS

We consider a simple one-dimensional Galactic Wind (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 is not proved and 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. (1999) 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

$$\left.\frac{dE}{dx}\right|_{\mathrm{ad}} = -\frac{2\,U}{3\,\mu}\,p \tag{7}$$

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

$$\lambda_{\mathrm{esc}} = \lambda_1\,\beta\left(1 - \exp\frac{-(R/R_0)^{-a}}{\beta}\right) \tag{8}$$

where the values of $\lambda_1 = 12.0\,\mathrm{g/cm}^2$, $U = 29$ km/sec, $R_0 = 12$ GV and a =0.73 was obtained by Ptuskin et al. (1999) from fitting B/C and (Sc + Ti + V)/ Fe ratios. The expression in the exponent of Eq. (8) is actually the dimensionless parameter UH/D where H is the thickness of Galactic cosmic-ray halo and $D \propto \beta R^{0.73}$ is the cosmic-ray diffusion coefficient.

Inserting Eqs. (2) through (8) in Eq. (1) we can solve for $I_{\bar{p}}$ in closed form

$$I_{\bar{p}}(E) = -\frac{1}{\frac{dE}{dx}}\int_E^{\infty}\left(\frac{Q(E')\,+\,S(E')}{4\,\pi}\right)\exp\left(\int_E^{E'}\left[\frac{1}{\lambda_{\mathrm{int}}(E'')} + \frac{1}{\lambda_{\mathrm{esc}}(E'')}\right]\left[\frac{dE}{dx}\right]^{-1}_{E''} dE''\right) dE' \tag{9}$$

The flux $I_{\bar{p}}(E)$ depends on $I_{\bar{p}}(E' > E)$ in the inelastic term $S(E')$, and care must be taken in numerical evaluation of the results which are discussed below.

RESULTS

To compare the calculated spectrum with observational data, the effect of solar modulation has to be properly considered. We use the Fisk model (Fisk, 1971). 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 experimental results of BESS (Orito et al., 2000), IMAX (Mitchell et al., 1996), CAPRICE (Boezio et al, 1997) and MASS91 (Basini et al., 1999) is shown in Figure 1. 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 and the calculations indicate that the modulated GW with realistic ϕ values of 300 MV and 500 MV fits the data better than the SLB model. This may be a first signature of Galactic wind in cosmic-ray data. More data however are needed to confirm this result. Ongoing antimatter experiments with high statistical accuracy and planned detectors (Ahlen et al., 1994; Morselli and Picozza, 1999) may clarify this question.

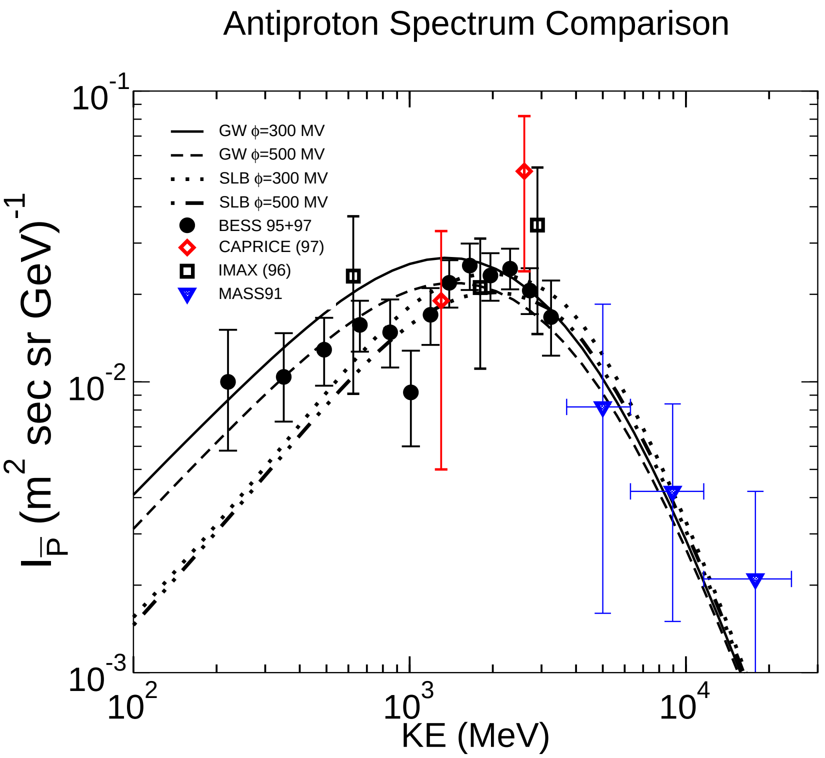

Fig. 1: Calculated Antiproton Flux for ϕ values of 300 MV and 500 MV

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