Antiprotons in the Galaxy

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We present a new calculation of the interstellar spectrum of secondary antiprotons produced in collisions of cosmic rays with interstellar gas. Differences from previous calculations result from an improved treatment of non-annihilation inelastic scattering of antiprotons and use of recent data on primary cosmic rays to obtain a better estimate of the parent interstellar spectrum of protons and helium.

1 Introduction

Cosmic-ray antiprotons are an interesting probe of solar modulation for several reasons. One is that the interstellar spectrum of secondary antiprotons is peaked around 2 GeV because of the kinematic properties of their production in collisions of primary cosmic rays with gas in interstellar space. This gives a distinctive feature as compared to the interstellar proton spectrum, which continues to increase at low energy. Another factor is that their interstellar spectrum depends only on the high energy ($\gtrsim 10$ GeV) part of the primary spectrum in interstellar space, which can be obtained with little uncertainty due to demodulation starting from measurements made at 1 AU. In addition, having identical properties to protons except for charge as regards propagation in the solar wind, antiprotons are useful for study of charge-sign-dependent effects in solar modulation. We have recently discussed antiprotons as probes of solar modulation elsewhere [Bieber *et al.*, 1999]. In this paper we describe in somewhat more detail our calculation of the interstellar antiproton spectrum.

2 Calculation

In the framework of the standard leaky box model the continuity equation describing secondary antiproton production [Gaisser & Schaefer, 1992] can be written as

$$\frac{1}{\lambda_e} J_{\bar{p}}(E_{\bar{p}}) + \frac{1}{\lambda_i} J_{\bar{p}}(E_{\bar{p}}) = \frac{c}{4\pi\langle m\rangle} Q(E_{\bar{p}}; J_{\bar{p}}(E_{\bar{p}})), \tag{1}$$

where λ_e is the characteristic escape length, $J_{\bar{p}}(E_{\bar{p}})$ denotes the antiproton intensity, and λ_i is the interaction length for inelastic collisions of antiprotons with the interstellar gas (annihilation plus non-annihilation). The mean free path length is $\lambda_i(E_{\bar{p}}) = \langle m\rangle / \langle \sigma_{\bar{p}}^{\rm inel}(E_{\bar{p}})\rangle$, where $\langle m\rangle$ and $\langle \sigma_{\bar{p}}^{\rm inel}(E_{\bar{p}})\rangle$ denote the target mass and inelastic cross section averaged over the composition of the interstellar gas, respectively. The mean escape length λ_e is taken from the recent fit to ratios of secondary to primary nuclei by Webber *et al.* [1996].

The source term Q is split into two parts [Simon, Molnar & Roesler, 1998]:

$$Q(E_{\bar{p}}; J_{\bar{p}}(E_{\bar{p}})) = Q_{\rm prod}(E_{\bar{p}}) + Q_{\rm scatt}(E_{\bar{p}}). \tag{2}$$

Here, $Q_{\rm prod}$ is the source function for the production of antiprotons due to collisions of primary cosmic rays with the interstellar gas

$$Q_{\rm prod}(E_{\bar{p}}) = \frac{4\pi}{c} \sum_{i,j} n_j \int_{E_{\rm th}}^{\infty} \frac{2\, d\sigma_{i,j\to\bar{p}}}{dE_{\bar{p}}} J_i(E_i) dE_i \;, \tag{3}$$

and $Q_{\rm scatt}$ takes the inelastic scattering of antiprotons on the interstellar gas into account

$$Q_{\rm scatt}(E_{\bar{p}}) = \frac{4\pi}{c} \sum_{j} n_j \int_{E_{\bar{p}}}^{\infty} \left\{ \frac{d\sigma_{\bar{p},j\to\bar{p}}}{dE_{\bar{p}}} + \frac{d\sigma_{\bar{p},j\to\bar{n}}}{dE_{\bar{n}}} \right\} J_{\bar{p}}(E) dE \;. \tag{4}$$

The index i sums over primary cosmic ray particles (protons and alpha-particles in our calculation) and j runs over all interstellar gas target particle species (H, He, C, N, and O). The particle abundances n_j with $\sum_j n_j = 1$ are taken from the data compiled by Meyer [1985]. The antiproton production and inelastic scattering cross sections have been calculated with a new version of the DTUNUC Monte Carlo event generator [Ferrari *et al.*, 1996; Roesler, Engel & Ranft, 1998] which uses PHOJET [Engel & Ranft, 1995] for simulation of elementary nucleon-nucleon collisions.

3 Primary spectrum in interstellar space

The interstellar primary spectrum in the energy range between 10 and 100 GeV/nucleon is most important for production of antiprotons in the GeV energy range [Gaisser & Schaefer, 1992]. Because a series of recent results [Seo *et al.*, 1991; Menn *et al.*, 1997; Barbiellini *et al.*, 1997; Basini *et al.*, 1998; S. Orito *et al.*, 1998] indicates that the proton spectrum in this energy range is significantly lower than previously assumed [Webber, Golden & Stephens, 1987], we have correspondingly revised downward the standard interstellar proton spectrum [Webber, 1987] in this energy range. We show in Fig. 1 the data and fits that represent the interstellar spectra of hydrogen and helium we have used. In each case, the measurements were demodulated with the standard force field approximation [Gleason & Axford 1967, 1968]. We used the modulation parameter given by each group as appropriate for the solar epoch of their measurement. Details of the modulation procedure are unimportant in the energy region above 10 GeV that is relevant for production of antiprotons. The curves connect smoothly to the original results of Webber [1987] in the low energy region (< 7 GV) and to the more recent data at higher energy.

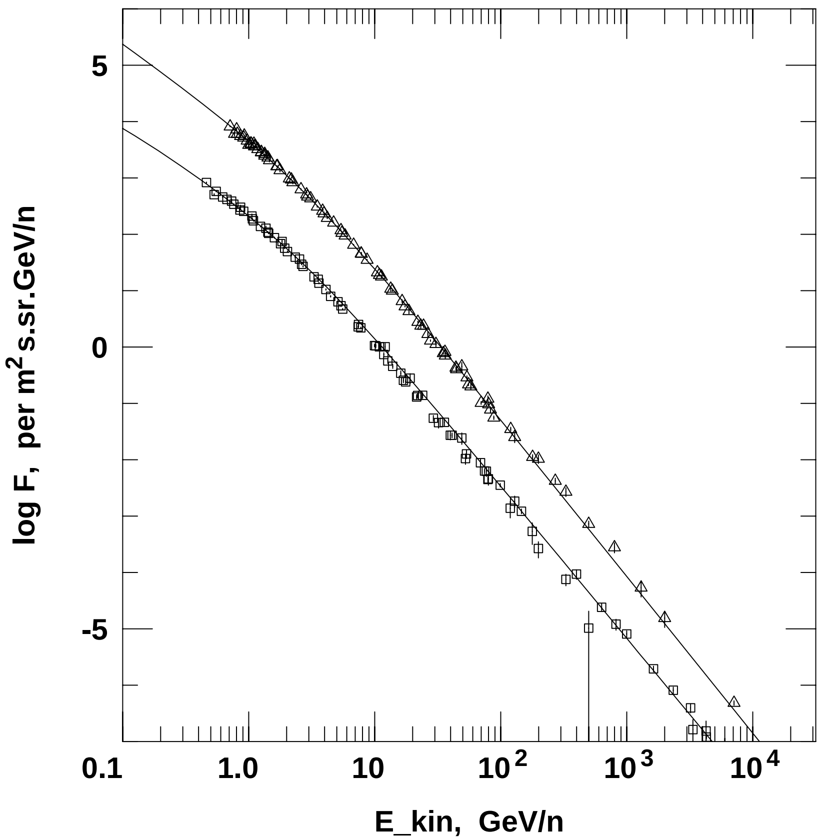

Figure 1: Interstellar spectra of hydrogen and helium.

The interstellar spectra we use can be expressed by

$$\begin{aligned} \frac{d\,N_i}{dE} &= A\,R^{-\alpha}, \quad R > 10\,GV \\ &= \frac{1}{(R + R_0)^p}\,B\,R^{-\gamma}, \quad R < 10\,GV. \end{aligned} \tag{5}$$

Table 1 contains the values of the constants in Eq. (5) for protons and helium. Units are particles per (cm^{2}sr s GeV/nucleon).

Table 1: Parameterizations of interstellar fluxes

	A	α	B	γ	R_0	p
protons	1.89	2.78	2.65	1.88	0.75	1.03
helium	0.288	2.704	0.418	0.25	0.46	3.056

4 Results

We find the interstellar antiproton spectrum shown as the heavy solid line in Fig. 2. Antiproton production in pp collisions has been tuned in the interaction model to fit the data summary of Antinucci *et al.* (1973). The data in the important range between 30 and 70 GeV/c are from collisions on nuclear targets. To convert to proton targets, Antinucci *et al.* assumed that the multiplicity of antiprotons scaled with target mass in the same way as pions. In fact, in this energy range we expect different dependencies for the pion and the antiproton multiplicities on the target mass. If so, antiproton production should be increased somewhat in the range of momentum, which would lead to somewhat higher predicted flux of interstellar antiprotons. We are currently investigating this point.

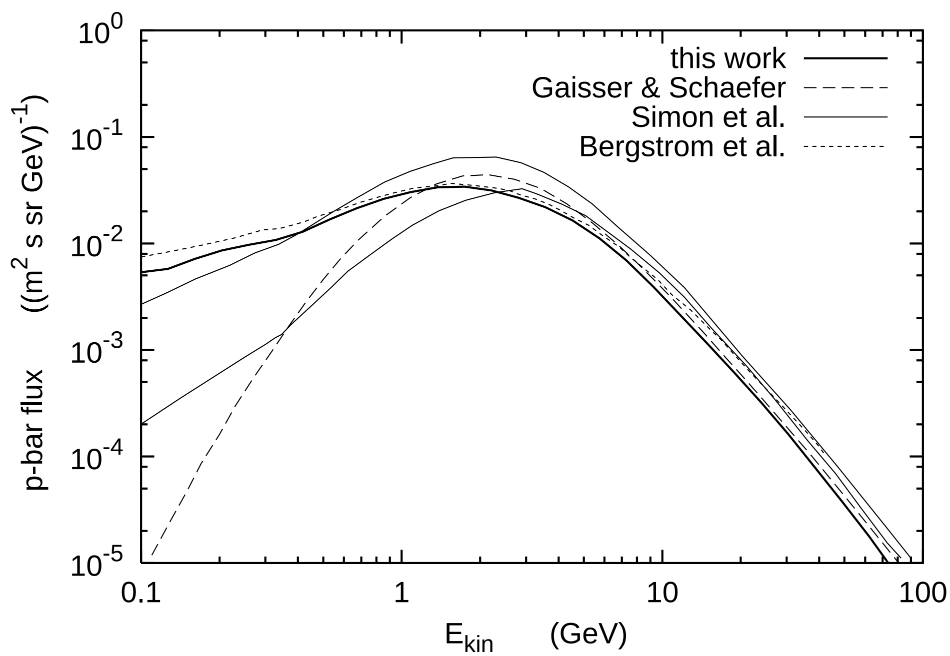

Figure 2: Interstellar antiproton flux. The two curves for Simon *et al.* correspond to their upper and lower predictions obtained by varying the escape length distribution.

We also compare our interstellar antiproton spectrum with some other results in Fig. 2. The spectrum of Gaisser & Schaefer [1992] is below the others at low energy because inelastic, non-annihilation interactions of antiprotons are neglected in that calculation. In the energy region above 5 GeV our result falls below the band of Simon, Molnar & Roesler [1998], possibly as a result of the new interstellar spectrum that we use. Most remarkably, our result agrees well with the much more elaborate calculation of Bergstrom, Edsjo & Ullio [1998], which is based on a solution of the coupled equations for cosmic-ray propagation in a realistic model of the interstellar medium and the galactic halo. Together these results suggest that the kinematic peak in the production spectrum of antiprotons is to a large extent smeared by downscattering and that the interstellar antiproton spectrum is therefore relatively soft at low energy. This will make it more difficult to detect a component of primary antiprotons above the background of secondaries.

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