Secondary antiprotons in cosmic rays

I. V. Moskalenko[1,2]**, A. W. Strong**[3]**, J. F. Ormes**[4]**, M. S. Potgieter**[5]**, and U. W. Langner**[5]

[1]NRC-NASA/Goddard Space Flight Center, Code 660, Greenbelt, MD 20771, U.S.A.

[2]Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, 119 899 Moscow, Russia

[3]Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany

[4]NASA Goddard Space Flight Center, Code 660, Greenbelt, MD 20771, U.S.A.

[5]Unit for Space Research, Potchefstroom University for CHE, 2520 Potchefstroom, South Africa

Abstract.

High energy collisions of cosmic ray (CR) nuclei with interstellar gas are believed to be the mechanism producing the majority of CR antiprotons. The distinguishing spectral shape with a maximum at 2 GeV and a sharp decrease towards lower energies makes antiprotons a unique probe of the models of particle propagation in the Galaxy and modulation in the heliosphere. Besides, accurate calculation of the secondary antiproton flux provides a "background" for searches for exotic signals from the annihilation of supersymmetric particles and primordial black hole evaporation. Recently new data with large statistics on the antiproton flux have become available which allow for such tests to be performed. We use our 3D Galactic cosmic ray propagation code GALPROP to calculate interstellar propagation in several models. For our best model we make predictions of proton and antiproton fluxes near the Earth for different modulation levels and polarity using a steady-state drift model for heliospheric modulation.

1 Introduction

Most of the CR antiprotons observed near the Earth are secondaries produced in collisions of energetic CR particles with interstellar gas (Mitchell et al., 1996). Due to the kinematics of the process, the spectrum of antiprotons has a unique shape distinguishing it from other cosmic-ray species: it is expected to peak at about 2 GeV decreasing sharply towards lower energies. In addition to secondary antiprotons there are possible sources of primary antiprotons such as candidate dark matter particles and evaporating black holes.

Despite numerous efforts and overall agreement on the secondary nature of the majority of CR antiprotons, published estimates of the expected flux significantly differ (see e.g. Fig. 3 in Orito et al. 2000). The major sources of uncertainties are: (i) incomplete knowledge of cross sections for

Correspondence to: I. V. Moskalenko
(imos@milkyway.gsfc.nasa.gov)

antiproton production, annihilation, and scattering, (ii) parameters and models of particle propagation in the Galaxy, and (iii) modulation in the heliosphere. While the interstellar antiproton flux is affected only by uncertainties in the cross sections and propagation models, the final comparison with experiment can only be made after correcting for the solar modulation. Besides, the spectra of CR nucleons have been directly measured only inside the heliosphere while we need to know the spectrum outside in interstellar space to compute the antiproton production rate correctly.

We have developed a numerical method and corresponding computer code GALPROP for the calculation of Galactic CR propagation in 3D (Strong and Moskalenko, 1998). The code has been shown to reproduce simultaneously observational data of many kinds related to CR origin and propagation (Strong and Moskalenko, 1998; Moskalenko and Strong, 1998; Moskalenko et al., 1998; Strong et al., 2000). The code has been validated on direct measurements of nuclei, antiprotons, electrons, and positrons, and astronomical measurements of γ-rays and synchrotron radiation. These data provide many independent constraints on model parameters.

Here we use the GALPROP code for accurate calculation of production and propagation of secondary antiprotons. We explore the dependence of the antiproton flux on the nucleon injection spectrum and propagation parameters. The antiproton production is calculated using the pp production cross section and DTUNUC nuclear factors (Simon et al., 1998) or the pp production cross section scaled appropriately with atomic numbers. Inelastic scattering producing "tertiary" antiprotons and "secondary" protons is taken into account. The calculated local interstellar spectrum (LIS) is modulated using the steady-state drift model. For the calculation reported here, we use a cylindrically symmetrical Galactic geometry.

2 Propagation models and parameters

The propagation parameters have been fixed using the B/C ratio. Nucleon injection spectra were chosen to reproduce the local CR measurements. The source abundances of all

Table 1. Propagation parameter sets.

| Model | Injection index[a], γ | Diffusion coefficient[b] | | Reacceleration/Convection | |
		D_0, cm^2 s^{-1}	Index, δ	v_A, km s^{-1}	dV/dz, km s^{-1} kpc^{-1}
Stochastic Reacceleration (SR)	2.43	6.10×10^{28}	0.33	30	–
Minimal Reacceleration & Convection (MRC)	2.43	4.30×10^{28}	0.33	17	10
Plain Diffusion (PD)	2.16	3.10×10^{28}	0.6	–	–
Diffusion plus Convection (DC)	2.46/2.16[c]	2.50×10^{28}	0./0.6[b]	–	10

[a]For a power-law in rigidity, $\propto \rho^{-\gamma}$.

[b]$D = \beta D_0 (\rho/4\,\mathrm{GV})^\delta$, index δ is shown below/above 4 GV.

[c]Index below/above rigidity 20 GV.

isotopes $Z \leq 28$ are given in Strong and Moskalenko (2001). We thus use the same (Webber et al.) cross-section parametrization as in that work in our calculations.

In all cases the halo size has been set to $z_h = 4$ kpc, which is within the range $z_h = 3 - 7$ kpc derived using the GALRPOP code and the combined measurements of radioactive isotope abundances, ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn (Strong and Moskalenko 2001 and references therein). Note that the exact value of z_h is unimportant for antiproton calculations provided that the propagation parameters are tuned to match the B/C ratio.

The "tertiary" antiprotons (inelastically scattered secondaries), significant at the lowest energies, are important in interstellar space, but make no difference when compared with measurements in the heliosphere.

To investigate the range of interstellar spectra and propagation parameters we considered four basic models (Table 1). Our results are plotted in Figs. 1-3.

A model with the stochastic reacceleration (SR) reproduces the sharp peak in secondary to primary nuclei ratios in a physically understandable way without breaks in the diffusion coefficient and/or the injection spectrum (Strong and Moskalenko, 1998, 2001). However, this model produces a bump in proton and He spectra at ~ 2 GeV/nucleon which is not observed.[1] This bump can be removed by choosing an injection spectrum that hardens at low energies (Jones et al., 2001). There are however some problems with secondaries such as positrons and antiprotons that are more difficult to manage. A similar bump appears in the positron spectrum at ~ 1 GeV (Fig. 3), and the model underproduces antiprotons at 2 GeV by more than 30% (Fig. 2). Taken together they provide evidence against strong reacceleration[2] in the ISM.

Another model combining reduced reacceleration and convection (MRC) also produces too few antiprotons.

Using a plain diffusion model (PD) we can get good agreement with B/C above few GeV/nucleon, with nucleon spectra and positrons, but this model overproduces antiprotons at 2 GeV by ~ 20% and contradicts the secondary/primary nuclei ratio (B/C) below 1 GeV/nucleon.

A model including diffusion and convection (DC) is our

Fig. 1. Calculated proton LIS and modulated spectra ($\Phi = 550$ MV). The line coding: solid lines – DC model (thick line – modulated spectrum), dashes – DR, dots – PD. The upper curve is always LIS spectrum, the lower is modulated. Data: IMAX (Menn et al., 2000), CAPRICE (Boezio et al., 1999), AMS (Alcaraz et al., 2000), BESS (Sanuki et al., 2000).

best fitting model. It reproduces all the particle data "on average", although it has still some problem with the reproduction of the sharp peak in B/C ratio. In this model a flattening of the diffusion coefficient below 4 GV is required to match the B/C ratio at low energies.

To better match primaries (p, He) in the DC model, we introduced a steeper injection spectrum below 20 GV; such a break, however, has almost no effect on secondaries ($\bar{p}$, e^+). The existence of a sharp upturn below a few GeV/nucleon follows from SNR shock acceleration theory (Ellison et al., 2001); this is a transition region between thermal and nonthermal particle populations in the shock. Our model does not require a sharp break (0.3 in index is enough).

We use the DC model to calculate the LIS spectra of protons and antiprotons and then use the drift model to determine their modulated spectra and ratio over the solar cycles with positive ($A > 0$) and negative ($A < 0$) polarity

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[1]A similar bump is produced also in the electron spectrum.

[2]We define the reacceleration to be "strong" if the model is able to match the B/C ratio without invoking other mechanisms such as convection and/or breaks in the diffusion coefficient.
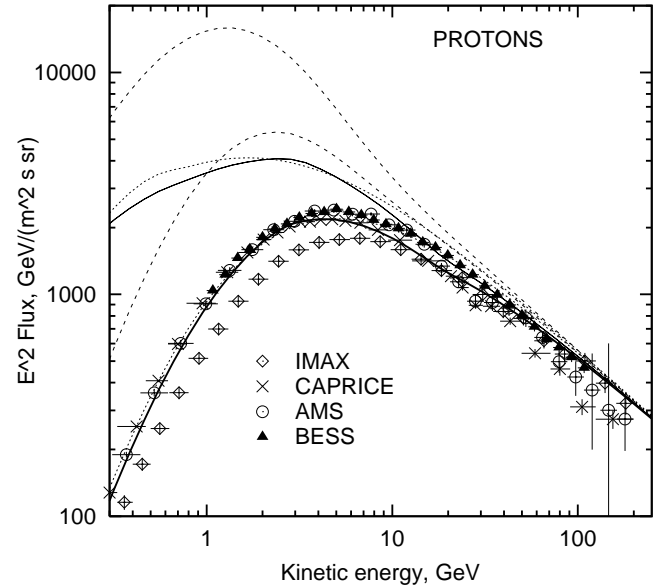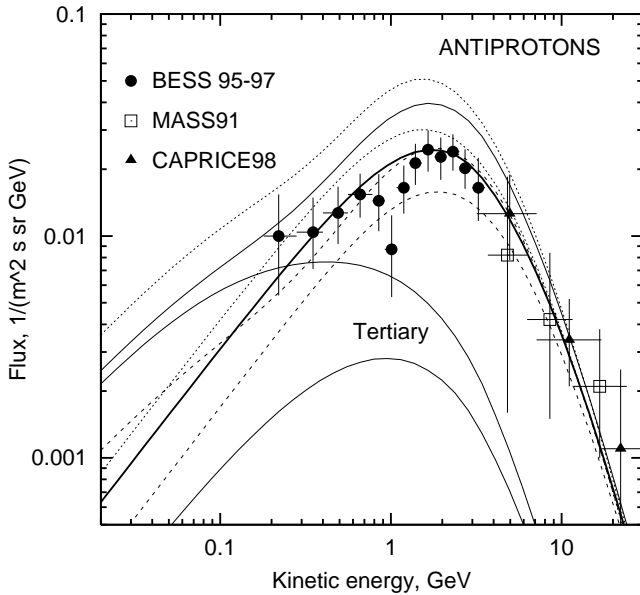
Fig. 2. Calculated spectrum of secondary $\bar{p}$'s for 3 models. For each model, the upper curve is the LIS, the lower curve – modulated ($\Phi = 550$ MV). Line coding as in Fig. 1. The two lowest curves show separately the LIS and modulated spectrum of the "tertiary" component in DC model. Data: BESS (Orito et al., 2000), MASS91 (Basini et al., 1999), CAPRICE98 (Boezio et al., 2001).

(Figs. 4, 5). The variations shown depend on the tilt angle.[3] This allows us to estimate the near-Earth spectra for arbitrary epochs in the past as well as make some predictions for the future. It may be also used to test the theory of heliospheric modulation (Langner and Potgieter, 2001).

3 Discussion

It appears quite difficult to get agreement with B/C, p & He spectra, and antiprotons spectrum simultaneously in the framework of simple "physical" reacceleration/convection models; this conclusion is mainly the result of the increased precision of the CR experimental data, and also the improved reliability of the calculations.

What could be the origin of this failure, apart from the propagation models ? For B/C, it seems unlikely that the cross-sections are sigificantly in error since for B production from C and O they are well measured at the relevant energies. For p and He the GeV bump produced by reacceleration seems to be outside the limits allowed by the modulation models and the observed fluxes, although the uncertainties in modulation are still considerable. Such a bump in the spectra of primaries (p, He, e^-) could be "removed" by including a flattening of the injection spectrum at low energies, while for secondaries (e^+, $\bar{p}$) we have no such freedom and the problem remains.
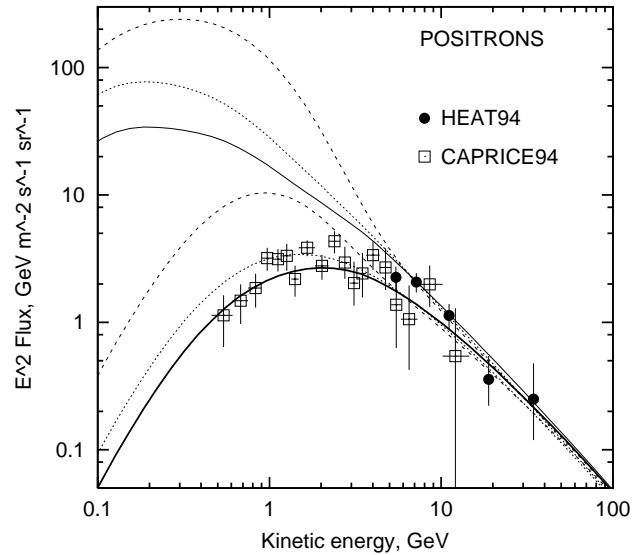

Fig. 3. Calculated positron flux for 3 models. For each model, the upper curve is the LIS, the lower curve – modulated ($\Phi = 600$ MV). Line coding as in Fig. 1. Data: HEAT94 (Barwick et al., 1998), CAPRICE94 (Boezio et al., 2000).

If we assume then that the problem is in the propagation models, we have shown that it *is* possible to construct a model (DC) which fits all these data, by postulating a significant flattening of the diffusion coefficient below 4 GV together with convection (and possibly with reduced reacceleration). This type of break in the diffusion coefficient is reminiscent of the standard procedure in "leaky-box" models where the escape time is set to a constant below a few GeV. This has always appeared a completely *ad hoc* device without physical justification, but the present analysis suggest it may be forced on us by these type of data, so that possibilities for its physical origin should be studied. At the same time the sensitivity of the whole analysis to the modulation models has to be investigated further.

References

Alcaraz, J., et al., Phys. Lett. B, 490, 27–35, 2000.

Barwick, S. W., et al., Astrophys. J., 498, 779–789, 1998.

Basini, G., et al., Proc. 26th ICRC (Salt Lake City), 3, 77–80, 1999.

Bergström, D., et al., Astrophys. J., 534, L177–L180, 2000.

Boezio, M., et al., Astrophys. J., 518, 457–472, 1999.

Boezio, M., et al., Astrophys. J., 532, 653–669, 2000.

Boezio, M., et al., astro-ph/0103513, 2001.

Ellison, D. C., Slane, P., and Gaensler, B. M., Astrophys. J., submitted, 2001.

Jones, F. C., et al., Astrophys. J., 547, 264–271, 2001.

Maeno, T., et al., astro-ph/0010381, 2001.

Menn, W., et al., Astrophys. J., 533, 281–297, 2000.

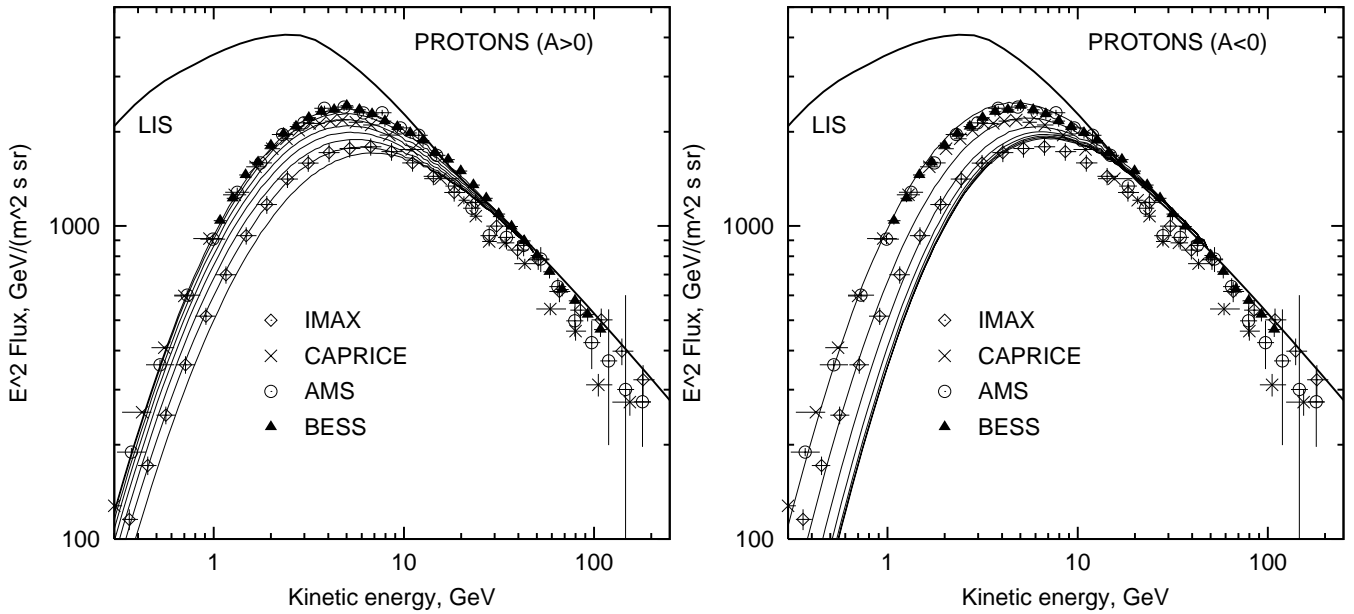[3]For Hoeksema's tilt angle models and updates see http://quake.stanford.edu/~wso/

Fig. 4. Calculated proton LIS and modulated spectra for the two magnetic polarity dependent modulation epochs, $A > 0$ (left) and $A < 0$ (right). Tilt angle from top to bottom: $5°, 15°, 25°, 35°, 45°, 55°, 65°, 75°$. The tilt angle corresponding to BESS and AMS data is $\sim 5° - 15°$ ($A > 0$) depending on the coronal field model. On the right panel, $A < 0$, the data are shown only for guidance. Data refences as in Fig. 1.
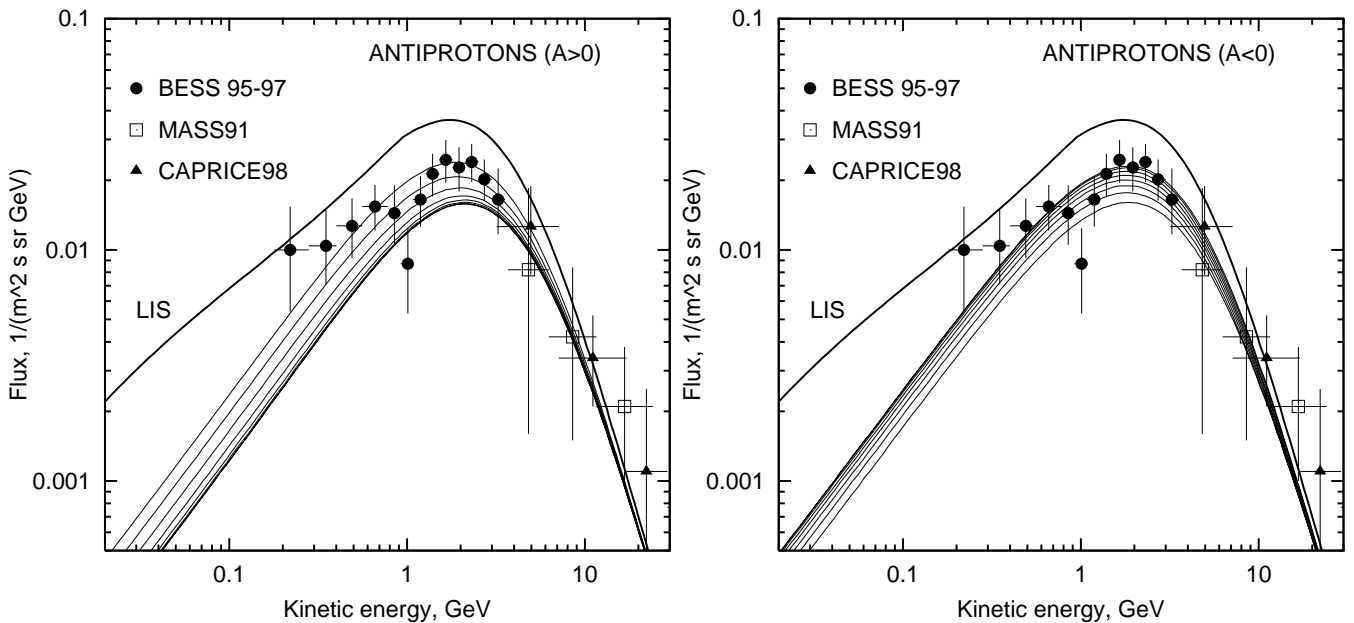

Fig. 5. Calculated antiproton LIS and modulated spectra for the two magnetic polarity dependent modulation epochs, $A > 0$ (left) and $A < 0$ (right). Tilt angle from top to bottom: $5°, 15°, 25°, 35°, 45°, 55°, 65°, 75°$. The tilt angle corresponding to BESS data is $\sim 5° - 15°$ ($A > 0$) depending on the coronal field model. On the right panel, $A < 0$, the data are shown only for guidance. Data references as in Fig. 2.

Mitchell, J. W., et al., Phys. Rev. Lett., 76, 3057–3060, 1996.

Moskalenko, I. V., and Strong, A. W., Astrophys. J., 493, 694–707, 1998.

Moskalenko, I. V., Strong, A. W., and Reimer, O., Astron. Astrophys., 338, L75–L78, 1998.

Orito, S., et al., Phys. Rev. Lett., 84, 1078–1081, 2000.

Langner, U. W., and Potgieter, M. S., this conference, SH 3.1, 2001.

Sanuki, T., et al., Astrophys. J., 545, 1135–1142, 2000.

Simon, M., Molnar, A., and Roesler, S., Astrophys. J., 499, 250–257, 1998.

Strong, A. W., and Moskalenko, I. V., Astrophys. J., 509, 212–228, 1998.

Strong, A. W., and Moskalenko, I. V., astro-ph/0101068, 2001.

Strong, A. W., Moskalenko, I. V., and Reimer, O., Astrophys. J., 537, 763–784, 2000. Erratum: Ibid., 541, 1109, 2000.