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Solar modulation of galactic antiprotons

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Summary. Galactic antiproton data of current interest lie in an energy regime heavily influenced by solar modulation. Correcting for it needs to be done more carefully than it has been in the past. I apply the well-known "force-field" analytic approximation of the spherically-symmetric, steady-state, cosmic-ray transport equation to account for modulation down to at least 100 MeV. I give a sample solution which applies to the currently available antiproton data set (1979–80), and can be used to accurately modulate any possible interstellar antiproton spectrum. The solution is easily adapted for comparison to future measurements. It also shows that boosting the low-energy (< 600 MeV) side of the interstellar antiproton spectrum will not affect the low-energy spectrum at 1 AU, due to strong adiabatic deceleration during that time. One needs an excess of particles at around 1 GeV to fit the intense low-energy measurement.

Key words: cosmic rays – interplanetary medium – solar modulation – antiprotons

Various researchers have conducted balloon flights to measure antiprotons ($\bar{p}$) which originate outside the heliosphere, the region in which the solar wind and the interplanetary magnetic field hold sway over medium-energy cosmic rays. In 1979, Golden et al. (1984) measured antiproton-proton ($\bar{p}/p$) ratios in the interval between 4.4 and 13.4 GeV. Bogomolov et al. (1980) reported data in the range of 2–5 GeV. And most recently, Buffington et al. (1981) claimed an astonishingly high measurement at about 200 MeV. In order to test theories of the origin of these antiprotons, the effects of solar modulation on their spectral and spatial distribution must be calculated before comparing results to data measured inside the heliosphere, as first detailed by Perko (1984). The need is evident for a simple, rigorous procedure to do this, which is what follows.

Gleeson and Axford (1968) and Fisk et al. (1973) showed that, at high enough energies, cosmic-ray transport in the solar wind can be expressed in the spherically-symmetric case as

$$\frac{\partial f}{\partial r} + \frac{VP}{3k}\frac{\partial f}{\partial P} \simeq 0, \tag{1}$$

where f is the omni-directional, cosmic-ray distribution function, r is the heliocentric radial distance, and P is particle rigidity (defined here as pc, where p is momentum and c is the speed of light). The value f is related to the particle differential intensity j by $j = P^2 f$; j is the value reported most often by observationists. Also V is the solar wind speed and k is the diffusion coefficient for radial propagation. Equation (1) includes the effects of diffusion, convection, and adiabatic deceleration.

The exclusion of gradient and curvature drifts in the interplanetary magnetic field allows one to use this simplified, one-dimensional, force-field approximation. These drifts would transport antiprotons and protons in opposite directions and thus the modulated spectra of the two species would differ to some degree (See, for example, Jokipii and Kopriva, 1979, and references therein.) The search for drift effects in the ecliptic has been elusive. The present form of drift theory, for example, incorrectly predicts the relative shapes of time graphs of positive and negative particle intensities (Garcia-Munoz et al., 1986). In any case, recent calculations that include maximum drift effects show a particle-intensity difference at 200 MeV of only ±18% between positive and negative drift directions (equivalent to positive and negative particles of the same mass); this difference decreases with increasing energy (Potgieter and Moraal, 1985). On the other hand, the total uncertainty of Buffington's datum at 200 MeV is about ±30%, eclipsing any drift effect. At higher antiproton energies, the effect becomes negligible, especially when compared to the data's uncertainty. From here on, then, I will assume that protons and antiprotons are modulated identically.

Equation (1) is solved by integrating over curves of constant f and substituting that result into the interstellar spectrum to be modulated (See Fisk et al., 1973). The solution is particularly simple with forms of k which are separable in space and rigidity. A defensible form of the diffusion coefficient is as follows:

$$k = A\beta P_c \quad \text{for } P < P_c$$

and

$$k = A\beta P \quad \text{for } P > P_c \tag{2}$$

where β is the speed of the particle divided by the speed of light, and A and P_c are constants. This form satisfies quasi-linear theory at high energies (Jokipii, 1971) and at low energies is consistent with solar-flare particle studies (Zwickl and Webber, 1977). Using the force-field method of Fisk et al. (1973) and Eqs. (1) and (2), one can solve for the characteristic curves of constant f, which relate the energy (E) at the heliospheric boundary to the energy (E_r) and rigidity (P_r) at some radius r:

$$E = P_c \ln\frac{P_r + E_r}{P_c + E_c} + E_c + \frac{(R - r)V}{3A} \quad \text{for } P_r < P_c \tag{3}$$

and

$$E = E_r + (R - r)V/(3A) \quad \text{for } P_r > P_c \tag{4}$$

Total energy is used here for convenience; that is, $E = (P^2 + T_0^2)^{1/2}$, and similarly for E_r and E_c. To get the solution at some radius r, substitute Eq. (3) or (4) into an appropriate interstellar boundary spectrum. Let us take

$$F(E) = 19{,}300\beta E^{-2.7}/P^2\,, \tag{5}$$

which is the local interstellar proton spectrum derived from measurements up to extremely high energies (Ryan et al., 1972). Substitute Eq. (3) or (4) for E in Eq. (5), and $F(E)$ becomes the solution $f(P_r, r)$.

Now let $A = 17.0$, $R = 50$ AU, $V = 400\,\mathrm{km\,s^{-1}}$ (independent of r), and $P_c = 1.015$ GV. Figure 1 is a plot of $j = P_r^2 f(P_r, r = 1\,\mathrm{AU})$ versus T_r, the kinetic energy equivalent to P_r; that is

$$T_r = (P_r^2 + T_0^2)^{1/2} - T_0\,.$$

The upper solid curve is the interstellar proton spectrum, the lower solid curve is the force-field solution we have just calculated, from about 60 GeV to 30 MeV. The dashed curve is an exact numerical solution of the full cosmic-ray transport equation (Eq. (5) of Fisk et al., 1973) using the method of Fisk (1971), with the same parameters as the force-field solution. The circles are proton data of 1981 (Webber et al., 1983) adjusted upward slightly to match ISEE-3 spacecraft data in its 127–220 MeV channel, taken around mid-June, 1980 (McDonald et al., 1985), the period in which Buffington's 130–220 MeV antiproton measurement was made. The choice of parameters that fit the data is by no means unique, but is consistent with data taken from deep space probes.

The force-field approximation held very well down to lower energies than in the past, and compared favorably with the exact

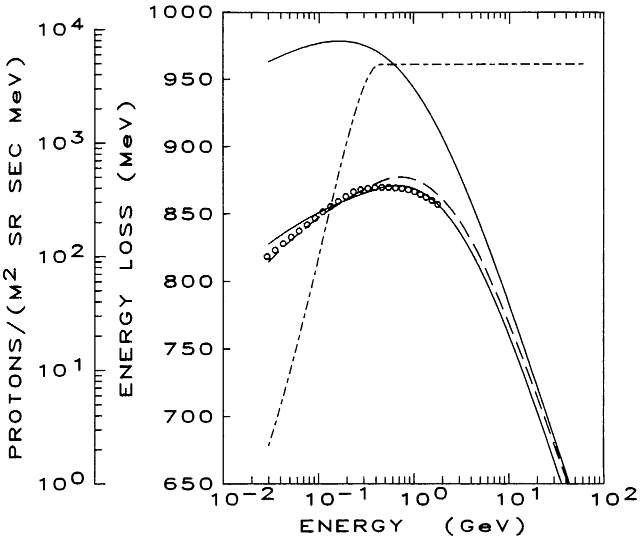

Fig. 1. Top curve is the interstellar proton spectrum in units of differential intensity from Ryan et al. (1972); data tabulated by the University of Chicago; the dashed curve is the exact, numerically modulated solution at $r = 1$ AU; the lower solid line is the corresponding force-field solution; the circles are 1981 proton balloon data from Webber et al. (1983), adjusted slightly to fit low-energy satellite data; the error bars of Webber's data are negligible. The dot-dash curve is average energy loss with the corresponding vertical scale on the right

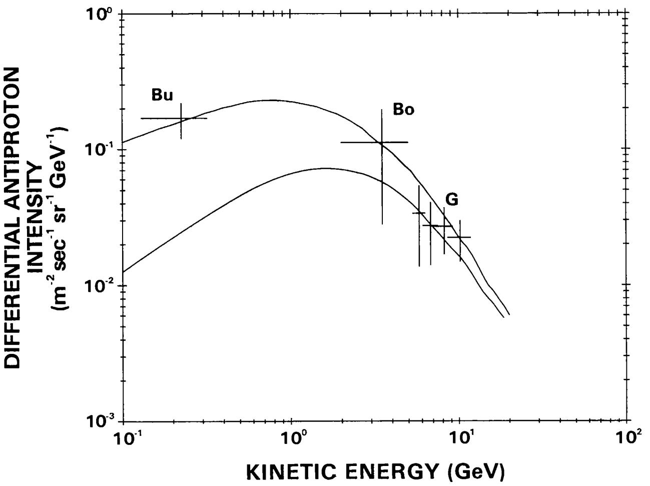

Fig. 2. Top curve is the upper limit of Tan and Ng's (1983) "non-uniform galactic disk" model for an interstellar antiproton spectrum; lower curve is the exact numerical modulation solution at 1 AU using model and modulation parameters of Fig. 1; "Bu" is data of Buffington et al. (1981), "Bo" is data of Bogomolov et al. (1981), and "G" is data of Golden et al. (1984)

solution, due to the more precisely defined diffusion coefficient of Eq. (2). The parameters I used also accurately fit the proton data, and so can now be used with confidence to test theoretical, interstellar antiproton spectra and to compare the results with the data reported up to this time (1979–80). At other points in the solar cycle, only the values of A and P_c need be changed to fit proton spectra, and thus cover future antiproton measurements, since the functional forms of diffusion coefficients do not seem to change over at least a solar half-cycle (Urch and Gleeson, 1972).

Let us use this model to test a recent attempt to fit the antiproton data. Figure 2 is Tan and Ng's (1983) "non-uniform galactic disk" model. The top curve is their calculation of an interstellar spectrum of secondary antiprotons. The point marked "Bo" is the antiproton datum of Bogomolov et al., the four points marked "G" are the data of Golden et al., and the point marked "Bu" is the datum of Buffington et al. The lower curve is the spectrum at 1 AU, here calculated by the exact numerical solution as before, and using the same parameters. It falls well short at low energies.

A rough estimate of the average energy loss for the protons (or antiprotons) comes from equation (3) or (4). The dot-dash curve in Fig. 1 is the average cosmic-ray energy loss between the outer heliospheric boundary and 1 AU, as a function of energy. For a particle measured at 200 MeV near 1 AU, the average loss $(E - E_r)$ is about 900 MeV. Note, however, that we cannot calculate the momentum trajectory of individual particles entering the modulation region at the heliospheric boundary ($r = R$) with rigidity P. An antiproton measurement at, say, 200 MeV at 1 AU is in fact a collection of particles which entered the solar system with a range of energies (see, for example, Goldstein et al., 1970).

Nonetheless, one could still say that at least a significant excess of particles around 1 GeV, more than conventional secondary production models provide, is necessary to boost the low-energy side of the near-Earth spectrum and agree with the data. Figure 3, reconstructed from Stecker et al. (1985), is a correctly modulated primary antiproton spectrum from dark matter

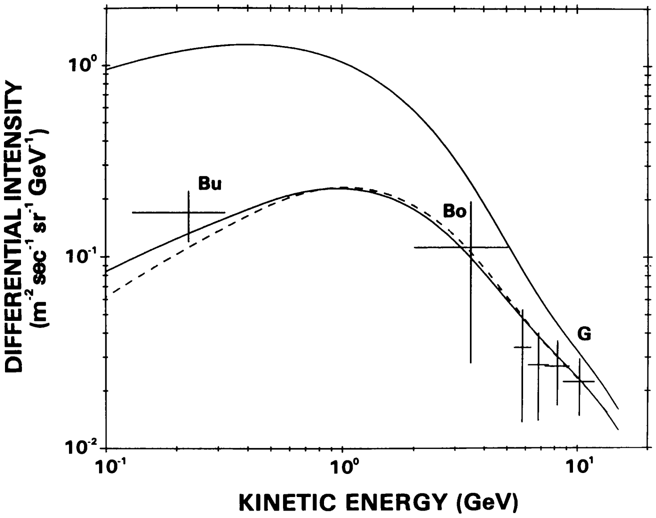

Fig. 3. Top curve is a primary, interstellar, antiproton spectrum reconstructed from Stecker et al. (1985) and based on photino annihilation; the lower curve is the spectrum at 1 AU, which was modulated by an exact numerical solution, using the same parameters that are in this paper; the data points are the same as in Fig. 2

sources in the galaxy. The upper curve is the interstellar spectrum, the lower solid curve is the force-field spectrum at 1 AU, and the lower dashed curve is the exact numerical spectrum at 1 AU. The steepness of the high-energy end of the interstellar spectrum and the consequent excess around 1 GeV are the result of an exponential spectrum rather than the more typical power-law spectra found in most secondary production and propagation models.

Raising the portion of the interstellar spectrum below about 600 MeV, a common way of trying to fit the 200 MeV data, will not significantly affect the low-energy side of the near-Earth spectrum, since 200 MeV particles at 1 AU originate at much higher energies (>1 GeV) and are cooled down by adiabatic deceleration in the solar wind. Indeed, the shape of the low-energy side of a galactic proton spectrum at Earth is virtually independent of the shape of the interstellar spectrum (Fisk, 1979).

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