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EFFECTS OF SOLAR MODULATION ON THE LOW-ENERGY COSMIC-RAY ANTIPROTON/PROTON RATIO

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ABSTRACT

We examine the transport of cosmic-ray protons and anitprotons from local interstellar space through the interplanetary medium to Earth and discuss the resulting effects on the low-energy antiproton/proton ratio at 1 AU. We find that the antiproton/proton ratio at energies above ~ 3 GeV is a useful diagnostic of cosmic-ray transport in the Galaxy. However, at energies below ~ 1 GeV the expected ratio is much more uncertain because of differences in the energy spectra and the resulting relative modulation of protons and antiprotons over the solar cycle, as well as uncertainties in the interstellar spectra. Using calculated interstellar spectra as references, we find that the antiproton/proton ratio at low energies varies by as much as an order of magnitude over the solar cycle. As a result, we recommend that attention be given instead to interpretation of the measured cosmic-ray antiproton energy spectrum rather than to the antiproton/proton ratio.

Subject headings: cosmic rays — interplanetary medium

1. INTRODUCTION

Since the discovery of cosmic-ray antiprotons more than 15 years ago, there has been considerable interest in possible sources of these particles in cosmic rays. Although there have been a wide variety of possible sources proposed (see Stephens & Golden 1987 for a review), the only cosmic-ray antiprotons that are required to exist are "secondary" antiprotons produced by high-energy interactions of "primary" cosmic-ray protons and heavier nuclei with the interstellar medium. The resulting interstellar spectrum of secondary antiprotons can then be predicted assuming that the standard acceleration/transport models (e.g., the leaky box model) with parameters derived from measurements of heavier nuclei (e.g., the B/C ratio) also apply to cosmic-ray protons and He. The threshold for antiproton production in the $p + p \rightarrow 3p + \bar{p}$ reaction is ~ 6 GeV for the incident proton, and the interstellar spectrum of secondary antiprotons from this reaction is expected to peak at ~ 2 GeV, with a sharp decline at lower energies because of kinematic constraints and at higher energies because of the sharp falloff of the primary proton spectrum (e.g., Gaisser & Levy 1974; Stephens 1981; Stephens & Golden 1987).

Cosmic-ray antiproton investigations have traditionally expressed their results in terms of the antiproton/proton ratio, which is somewhat easier to obtain than proton and antiproton flux measurements. To model the expected ratio at 1 AU one must take into account the effects of solar modulation on both the primary proton spectrum and the secondary antiproton spectrum. Although previously published antiproton measurements (with the exception of the work by Golden et al. 1984 and Hof et al. 1995) have been at energies below ~ 5 GeV/nucleon, most of these reports have not taken solar modulation effects into account in a systematic fashion.

2. SOLAR MODULATION CALCULATIONS

To investigate the effects of solar modulation we use as a reference the interstellar antiproton spectrum from a calculation by Webber & Potgieter (1989) based on the standard rigidity-dependent leaky box model for cosmic-ray transport in the galaxy. For consistency, we also use the interstellar proton spectrum from Webber & Potgieter. Gaisser & Schaefer (1992) have reviewed the effect of uncertainties in the interstellar proton spectra on antiproton flux calculations. However, because their calculation of the interstellar antiproton spectrum does not include the effects of inelastic scattering, which are particularly important at low energies, their results are not employed directly in this paper.

The effects of solar modulation were calculated using the standard spherically symmetric approach of Fisk (1971), including the effects of diffusion, convection, and adiabatic deceleration. In this calculation, the propagation of cosmic rays into the solar system is described by the Fokker-Planck equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r^2 V U) - \frac{1}{3}\left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V)\right]\left[\frac{\partial}{\partial T}(\alpha T U)\right] - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial U}{\partial r}\right) = 0 , \quad (1)$$

where U is the cosmic-ray density, V is the solar wind velocity, T is kinetic energy, and r is radial distance from the Sun. We assume a modulation boundary at 100 AU and a solar wind velocity V of 400 km s^{-1}, and our diffusion coefficient takes the form

$$\kappa = k\beta R , \quad (2)$$

where k is a constant (i.e., independent of radius) and R is rigidity. The diffusion coefficient multiplier constant (or the "radial part of the diffusion coefficient"), k, may be used to calculate the modulation strength parameter of Gleeson & Axford (1968):

$$\Phi = \frac{1}{3}\int_{r=1\ \mathrm{AU}}^{D} \frac{V(r)}{\kappa(r)}\, dr = \frac{V(D-1)}{3k} , \quad (3)$$

where the "modulation boundary," D, is taken to be 100 AU.

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The strength of the modulation is adjusted to fit proton spectra measured at 1 AU in a series of reference years (1979, 1980, 1985, 1986, 1987, 1991, 1992, and 1993), when antiproton observations are available (see Table 1). We have also considered 1977 and 1990, the years of minimum and maximum modulation over the past three solar cycles. The proton spectra were modulated to coincide with *Interplanetary Monitoring Platform* (*IMP*) *8* proton flux measurements at 131–230 MeV (McGuire, Schuster, & McDonald 1995), which are available in the form of 26 day averages from November 1973 to the present. Although corresponding proton spectrum measurements over a broader energy interval are generally unavailable for all the antiproton measurements to date, the *IMP 8* data are consistent with other proton flux measurements at various times in the solar cycle (e.g., Evenson et al. 1983, 1985). Therefore, we take the *IMP 8* measurements at the time of the various antiproton measurements as reference proton measurements. Finally, we ignore the effects of drifts (e.g., Kóta & Jokipii 1983; Burger & Potgieter 1989; Webber & Potgieter 1989), thereby obtaining a lower limit to possible solar cycle effects on the antiproton/proton ratio. We modulate the antiproton spectra with the same modulation parameters used for protons for our various reference years.

Figures 1 and 2 illustrate the effects of solar modulation on two artificially constructed interstellar spectra. The figures (modeled after similar figures from Goldstein, Fisk, & Ramaty 1970) show Gaussian "interstellar" proton and antiproton fluxes centered at 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 50 GeV. The amplitudes of the peaks correspond to the proton and antiproton fluxes calculated by Webber & Potgieter for these energies. Also shown (*dashed lines*) are the same fluxes modulated to 1 AU with a modulation parameter $\phi = 750$ MV, which corresponds roughly to the modulation levels for 1992. As can be seen in the figures, the effect of modulation is not only to reduce the amplitude of the peaks but also to shift fluxes lower in energy, through adiabatic energy loss, and to spread them out in energy. The resulting flux at 1 AU is dependent on the strength of the modulation, as well as on the interstellar spectrum.

Note that our approach differs from that of Perko (1992), who obtains modulation parameters for protons and antiprotons (electrons) separately and then "demodulates" the 1 AU measurements via the force-field approximation and presents results for the local interstellar medium. Our results have the advantage of being directly comparable to available measurements. Furthermore, Perko's demodulation process assumes a one-to-one correspondence between points on the modulated flux curve and the interstellar flux curve, which is not borne out by calculations

TABLE 1

DATES OF ANTIPROTON OBSERVATIONS AND FITTED MODULATION PARAMETERS

Date of Flight	Φ^a (MV)	Reference
1979 Jun 21–22......	613	1
1984–1985	673	2
1986–1988	540	3
1980 Jun 18.........	770	4
1987 Aug 13	493	5
1987 Aug 21	493	6, 7
1991 Sep	981	8
1992 Jul 16	726	9
1993 Jul 26	565	10

[a] See eq. (3).

REFERENCES.—(1) Golden et al. 1984; (2) Bogomolov et al. 1987; (3) Bogomolov et al. 1990; (4) Buffington et al. 1981; (5) Salamon et al. 1990; (6) Moats et al. 1990; (7) Stochaj 1990; (8) Hof et al. 1995; (9) Mitchell et al. 1996; (10) Yoshimura et al. 1995.

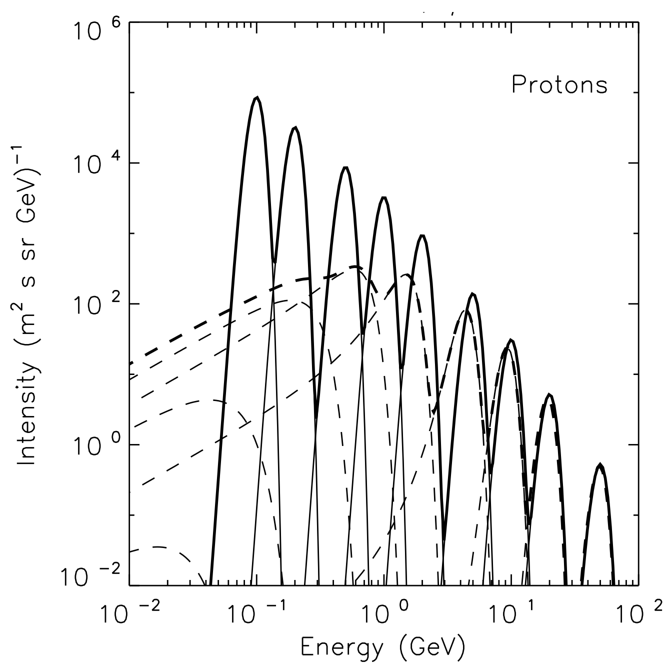

FIG. 1.—Gaussian "interstellar" proton fluxes at 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 50 GeV, modulated to 1 AU with a modulation strength of 750 MV. The peak intensities correspond to the proton spectrum of Webber & Potgieter (1989).

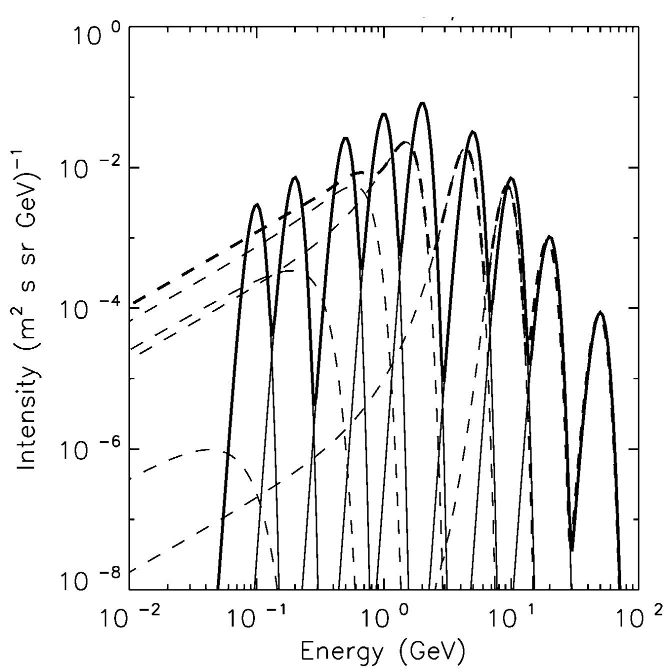

FIG. 2.—Gaussian "interstellar" antiproton fluxes at 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 50 GeV, modulated to 1 AU with a modulation strength of 750 MV. The peak intensities correspond to the antiproton fluxes calculated by Webber & Potgieter (1989).

such as those given in Figures 1 and 2. From Figure 1, where the amplitudes of the peaks correspond to the Webber & Potgieter interstellar proton flux, the modulated flux level at $\sim$0.2 GeV has roughly equal contributions from the interstellar 0.5 and 1 GeV peaks and negligible contribution from 0.2 GeV itself. However, the modulated antiproton spectra in Figure 2 show a significantly different mix of contributions at $\sim$0.2 GeV. It is clear from these figures that one cannot reliably "demodulate" low-energy measurements of the antiproton/proton ratio. A similar conclusion was also drawn for low-energy protons and helium nuclei by Gleeson & Urch (1971).

Figure 3 shows modulated proton spectra for the case of near solar minimum (*top*, 1977), solar maximum (*bottom*, 1990), and intermediate levels of modulation. Note that for each interstellar proton spectrum it is possible to obtain a reasonable fit to the measured intensity levels over the solar cycle simply by varying the magnitude of the diffusion coefficient. Although it is possible that the rigidity dependence of the diffusion coefficient also varies over the solar cycle (e.g., Palmer 1982; Bieber et al. 1994), we consider only the simplest possible solar cycle variations to illustrate their effect.

Figure 4 shows the modulated antiproton spectra at 1 AU for these same cases. Antiprotons observed at 1 AU with energies ≤ 1 GeV are primarily the result of adiabatic deceleration of higher energy antiprotons (see Fig. 2). As a result, the low-energy antiproton flux varies much less over the solar cycle than does the flux of low-energy protons (Fig. 3), because most of the antiprotons originate in the interstellar medium at $\sim$1–2 GeV, where the effects of solar modulation are much less.

Figure 5 shows the resulting antiproton/proton ratio. Note that the ratio at several hundred MeV varies by almost 1 order of magnitude over the solar cycle. Inspection of Figures 3 and 4 indicates that these variations in the antiproton/proton ratio are mainly due to variations in the 1 AU proton flux rather than to variations in the antiproton flux. Figure 6 shows the proton flux at 131–230 MeV as measured by *IMP 8* (McGuire et al. 1995) between 1973 and 1995, as well as the estimated antiproton flux at roughly the same energy. From these solar modulation calculations, it is apparent that although the low-energy proton flux can vary

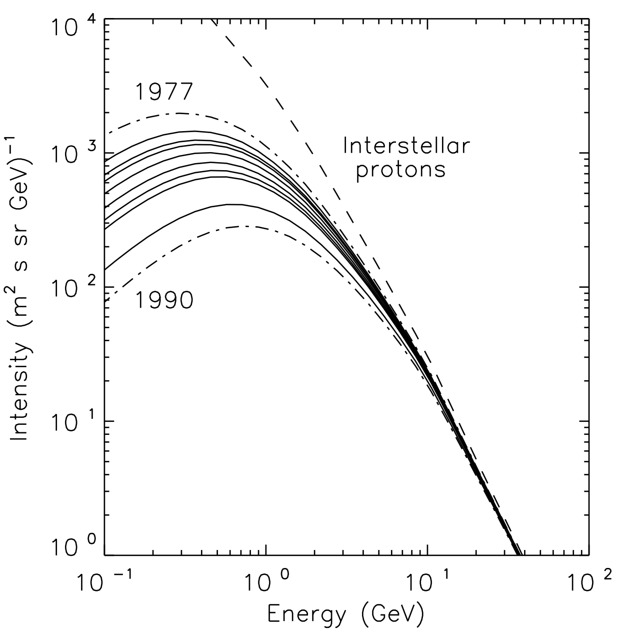

FIG. 3.—The interstellar proton spectrum of Webber & Potgieter (1989), modulated to agree with measured proton flux lvels at 1 AU for years when cosmic-ray antiproton measurements are available. The reference years are (*solid lines*, from top to bottom) 1987, 1986, 1993, 1979, 1985, 1992, 1980, and 1991. The dash-dotted lines represent the 1977 solar minimum and 1990 solar maximum fluxes.

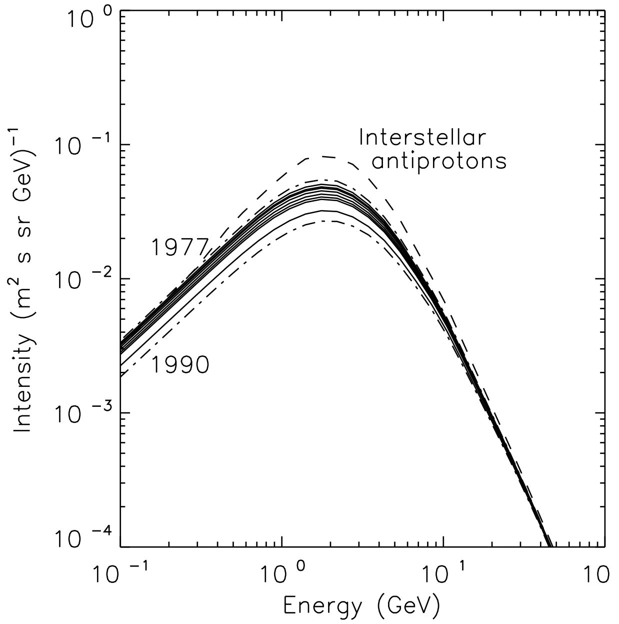

FIG. 4.—The interstellar antiproton flux of Webber & Potgieter (1989), modulated with the same parameters used for the spectra in Fig. 3, to produce expected spectra at 1 AU for the same years (from top to bottom). The dash-dotted lines represent the 1977 solar minimum and 1990 solar maximum fluxes.

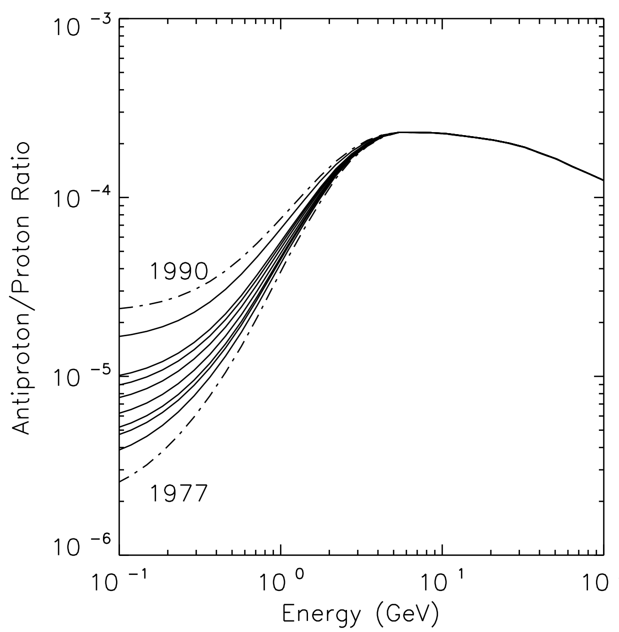

FIG. 5.—The antiproton/proton ratio at 1 AU, derived from the modulated spectra in Figs. 3 and 4 for the years 1987, 1986, 1993, 1979, 1985, 1992, 1980, and 1991 (*solid lines*, from bottom to top). The dash-dotted lines represent the 1977 solar minimum and 1990 solar maximum ratios.

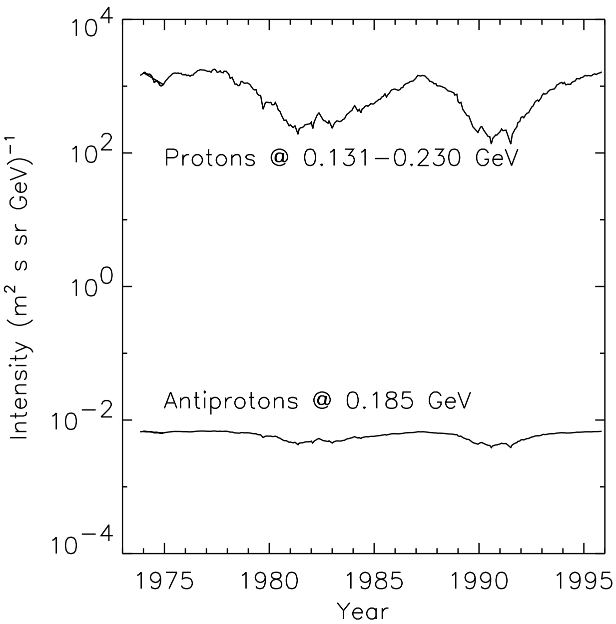

FIG. 6.—Proton fluxes measured by *IMP 8* (McGuire et al. 1995) at 131–230 MeV/nucleon from 1973 to 1995. The antiproton flux at 0.185 GeV is calculated by modulating the Webber & Potgieter (1989) interstellar antiproton spectrum, using the same modulation parameters that fit the low-energy proton measurements.

by as much as 1 order of magnitude over the solar cycle, the low-energy antiproton flux varies by less than a factor of 2. We therefore recommend that it may be more useful to compare low-energy antiproton measurements to the expected antiproton spectrum rather than to the antiproton/proton ratio, which has traditionally been considered.

In addition to the effects of solar modulation, there are also additional uncertainties in the interstellar spectra. For example, the assumed interstellar spectra adopted by Gaisser & Schaefer (1992) differ from those of Webber & Potgieter (1989). In a previous paper (Labrador & Mewaldt 1995), we attempted similar calculations using the Gaisser & Schaefer interstellar spectra. However, because their calculation concentrates on the high-energy antiproton flux and antiproton/proton ratio, effects such as inelastic scattering during propagation were explicitly neglected. The result is that their low-energy interstellar antiproton spectrum has a steeper slope below 2 GeV and underestimates the antiproton flux from 0.1 to 1 GeV. As a result, their antiproton flux is more sensitive to adiabatic energy loss, and the resulting antiproton/proton ratios varied even more over the solar cycle than those based on the Webber & Potgieter curves. However, because the Webber & Potgieter calculations include inelastic scattering, the results of solar modulation on the Webber & Potgieter curves are probably more correct at low energies.

The effect of uncertainties in the low-energy interstellar proton spectrum can be demonstrated by a slight modification of the Webber & Potgieter proton flux: We extend their proton flux to low energies with the same spectral index as at energies above 5 GeV, in effect eliminating much of the low-rigidity turnover. The result is a higher interstellar proton flux at low energies, which requires more solar modulation to match the observations. Because antiprotons are produced by cosmic rays with energies above $\sim$6 GeV/nucleon, we may adopt the Webber & Potgieter interstellar antiproton flux unchanged. The solar modulation calculations are repeated, with smaller diffusion coefficients needed to fit the interstellar proton fluxes to the *IMP 8* data. Figures 7 and 8 show the new solar minimum and solar maximum proton and antiproton spectra, using

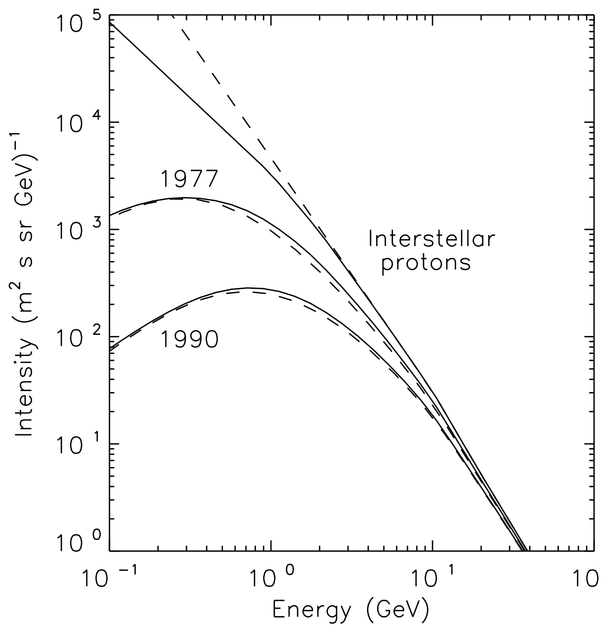

FIG. 7.—Illustration of the effects of solar modulation on a modified interstellar proton spectrum that includes additional low-energy flux. The solid lines are the original Webber & Potgieter (1989) interstellar flux and modulated curves from Fig. 3, and the dashed lines are the modified flux curves. Results are shown for the 1977 solar minimum and 1990 solar maximum.

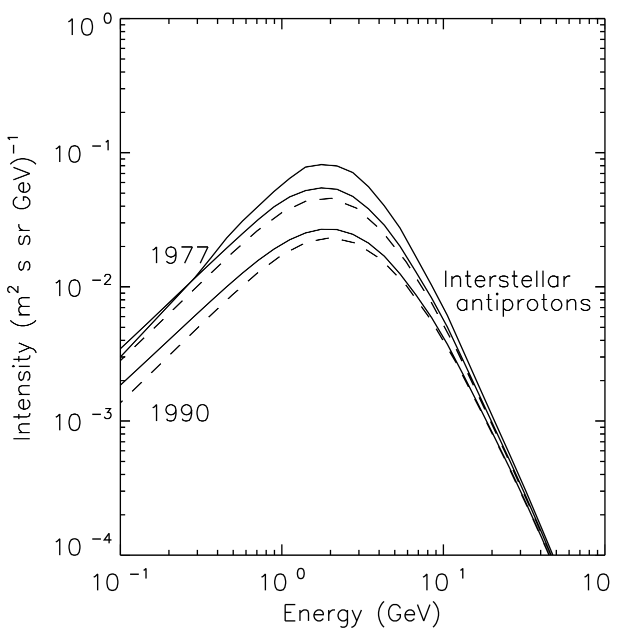

FIG. 8.—Interstellar antiproton spectrum of Webber & Potgieter (1989), modulated with the same parameters employed for Fig. 7 (*dashed lines*). The solid lines are the original Webber & Potgieter (1989) interstellar spectrum and the modulated curves from Fig. 4.

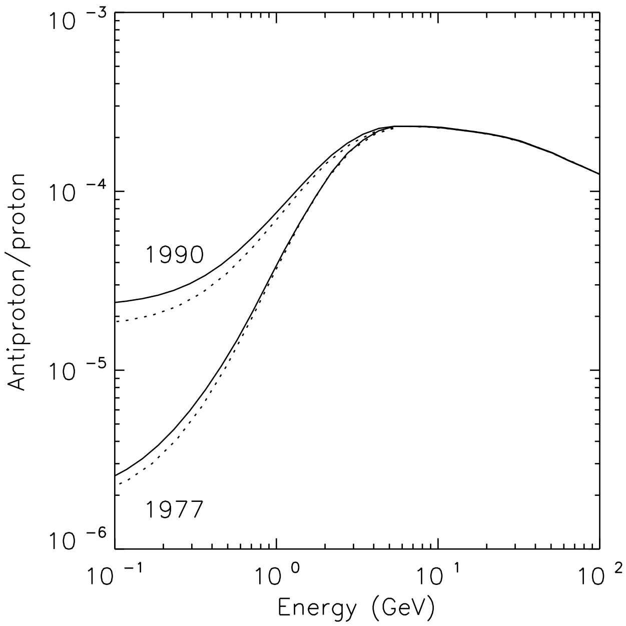

FIG. 9.—Illustration of the effect of uncertainties in the low-energy interstellar proton spectrum on the antiproton/proton ratio at 1 AU. The solid curves are from Fig. 5 for the nominal Webber & Potgieter (1989) interstellar spectra. The dashed curves are the ratios calculated from the modified fluxes of Figs. 7 and 8.

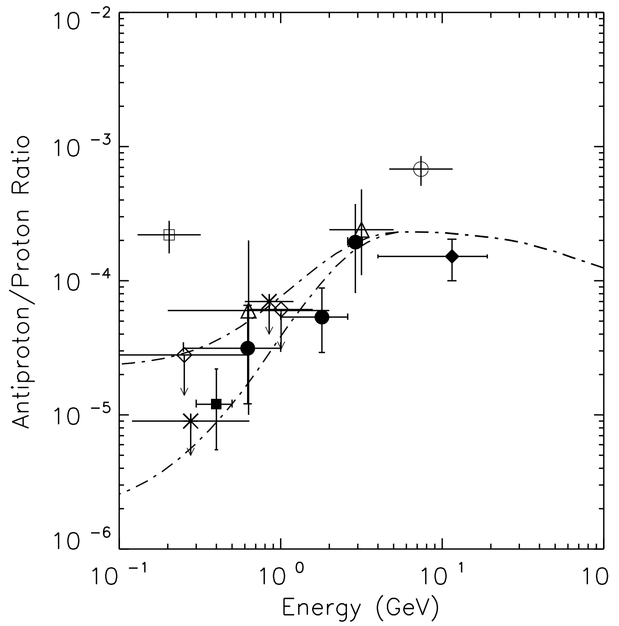

FIG. 10.—Summary of antiproton/proton measurements to date. The points are from Golden et al. (1984; open circle), Bogomolov et al. (1987, 1990; open triangle), Buffington et al. (1981; open square), Salamon et al. (1990; open diamond), Stochaj (1990; cross) and Moats et al. (1990; cross), Hof et al. (1995; filled diamond), Mitchell et al. (1996; filled circle), and Yoshimura et al. (1995; filled square). The curves are for the 1977 solar minimum and 1990 solar maximum.

the modified Webber & Potgieter interstellar proton fluxes. Figure 9 illustrates that the new antiproton/proton ratios give slightly less variation over the solar cycle, as well as lower overall ratios in comparison to the previous calculation.

3. DISCUSSION

Figure 10 gives a summary of the antiproton/proton ratios reported to date, along with solar minimum and solar maximum curves from our calculations with the Webber & Potgieter curves. Because the data were taken at many different times over the solar cycle, it is incorrect to compare all the measurements directly to each other. To account for the effects of solar modulation on all the measurements, and thereby compare them to a common reference, we have divided all measurements by the corresponding calculated ratio for their time of measurement. The results are shown in Figure 11. Note that the only two measurements that differ significantly from the calculations are two of the very first cosmic-ray antiproton observations (Golden et al. 1984; Buffington, Schindler, & Pennypacker 1981), both of which indicate a significant excess. All other measurements published to date are generally consistent with the cosmic-ray antiproton abundance arising solely from interactions of primary cosmic rays with the interstellar medium.

If cosmic-ray antiprotons are of "secondary" origin, produced by interactions of "primary" protons with the interstellar medium, they are daughters of cosmic rays with energies greater than 6 GeV/nucleon. Note in Figure 4 that the expected antiproton/proton ratio at energies greater than ~ 3 GeV is very insensitive to the effects of solar modulation, and it is therefore a useful diagnostic of cosmic ray transport in the Galaxy. However, at lower energies (e.g., less than 1 GeV), the expected antiproton/proton ratio is much more uncertain because of solar cycle variations and uncertainties in the interstellar spectra. With few exceptions, most discussions of the antiproton/proton ratio have not taken these uncertainties into account. With a number of improved antiproton measurements made recently available from experiments like IMAX (Mitchell et al. 1996), BESS (Yoshimura et al. 1995), and MASS2 (Hof et al. 1995), it is important to take these effects into account in their

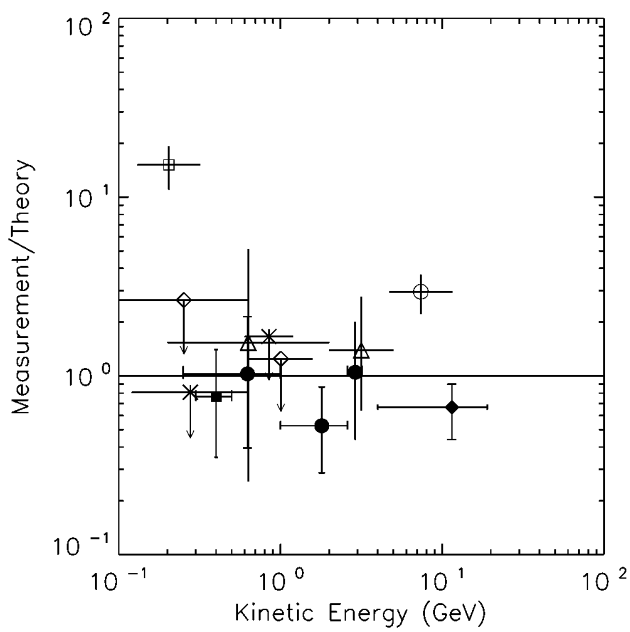

FIG. 11.—Ratio of the measured antiproton/proton ratios to the theoretical values calculated from solar modulation of the Webber & Potgieter (1989) interstellar spectra. The points are the same as Fig. 10.

interpretation. For these three most recent measurements, a simple average of the measurement-to-theory ratio yields $0.81^{+0.33}_{-0.20}$; implying rough agreement with the Webber & Potgieter calculation.

Several authors (e.g., Rudaz & Stecker 1988) have suggested that dark matter candidates such as 15 GeV higgsinos may decay and produce low-energy antiprotons. Such dark matter decays would result in low-energy antiproton abundances and antiproton/proton ratios above those expected from standard leaky box model calculations. At energies below a few hundred MeV, the effects of solar modulation discussed in this paper will complicate the search for low-energy signatures of dark matter decay. However, it may be possible to correct for such effects once their magnitude is established by direct observation.

It should be pointed out that our calculations of the effects of solar modulation do not include the effects of gradient and curvature drifts in the large-scale interplanetary magnetic field, which may lead to solar cycle–dependent differences in the relative modulation of positively and negatively charged particles with the same rigidity. To incorporate these effects would require a more sophisticated solar modulation code than is generally available (e.g., Kóta & Jokipii 1983). During even-numbered solar cycles (e.g., the 1970s and 1990s) positive particles drift from the poles of the heliosphere toward the equator and then out along the current sheet, while during the odd-numbered solar cycles the direction of drift is reversed. Negative particles always drift in the opposite direction as positively charged particles. The result is a 22 year solar modulation cycle. For observations made in the ecliptic plane, we might expect low-energy protons to be favored during the 1970s and 1990s, with antiprotons favored during the 1980s.

Although there is some evidence for charge sign–dependent effects on the modulation of electrons and He of the same rigidity (Evenson et al. 1985), the magnitude of such effects is not well established experimentally. Webber & Potgieter (1989) have estimated that drift effects might vary antiproton/proton ratio by as much as a factor of 2 at 200 MeV, depending on the tilt of the heliospheric current sheet, but the magnitude of these effects is very model dependent. In any case, the results in this paper should be regarded as a lower limit to the effects that solar modulation processes can have on the antiproton/proton ratio over the course of the solar cycle.

In summary, because solar modulation yields greater time variation in proton spectra than in antiproton spectra, the resulting low-energy antiproton/proton ratio will have large time variations arising mainly from solar cycle variations in the proton flux. The low-energy antiproton flux at 1 AU will have far smaller time variation than either the proton flux or the antiproton/proton ratio. We therefore recommend that interpretations of low-energy antiproton measurements focus on the antiproton spectrum rather than the antiproton/proton ratio.

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