SH 3.1.05

Antiprotons as Probes of Solar Modulation

J. W. Bieber[1], R. A. Burger[2], R. Engel[1], T. K. Gaisser[1], and T. Stanev[1]
[1]*Bartol Research Institute, University of Delaware, Newark, DE 19716, U.S.A.*
[2]*Space Research Unit, School of Physics, Potchefstroom Univ, 2520 Potchefstroom, South Africa*

ABSTRACT

New measurements with good statistics will make it possible to observe the time variation of cosmic antiprotons at 1 AU through the upcoming peak of solar activity. We use a drift model of solar modulation to predict antiproton intensities as well as the antiproton/proton ratio throughout a 20–year solar magnetic cycle. Large variations in the ratio are predicted for the next decade, beginning with a sudden increase (factor of 3 at 1 GeV) in association with reversal of the Sun's polarity expected in 2000.

1 Charge Sign Dependent Solar Modulation:

The effect of gradient and curvature drifts on solar modulation has been intensively studied over the past 25 years (Jokipii, Levy, & Hubbard 1977; Kóta & Jokipii 1983; Potgieter & Moraal 1985; Webber & Potgieter 1989). Drifts in principle can provide a natural explanation for charge sign dependent modulation effects (Potgieter & Burger 1990), because particles with opposite charge drift in opposite directions. However, in recent years there has been an emerging consensus that drifts may be important for modulation during low solar activity, but that they become unimportant for several years around solar maximum, owing to the disordered magnetic structure of the heliosphere at that time (Haasbroek, Potgieter, & Le Roux 1995; Potgieter 1998).

Recent work (Burger & Hattingh 1998; Burger & Potgieter 1999) has challenged the conventional wisdom that drifts can be ignored during high solar activity. This work finds that drifts produce a strong differentiation between modulation of positive and negative charges even during high solar activity. There may be a brief interval during the polarity reversal when the heliosphere is in a "no drift" state, but the approach to and through this state is abrupt.

The observational evidence decisively favors this latter point of view. Figure 1 displays the ratio of cosmic electrons to cosmic helium observed over a 25 year period (Garcia–Munoz et al. 1991), together with recent observations of the electron to proton ratio made aboard Ulysses (Raviart et al. 1997). The largest variations are associated with reversals of the Sun's magnetic polarity (shaded bars), which occur near peak solar activity. In 1970 and again in 1990, the charge ratios decreased rapidly. In 1980 the ratio jumped upwards. If the pattern continues, another large, rapid increase in the negative/positive charge ratio will occur through the polarity reversal expected in 2000 or 2001.

2 Solar Modulation of Antiprotons:

The principal factors governing solar modulation are solar wind speed, the cosmic ray diffusion tensor (which also embodies the drift effect in its off–diagonal terms), and the tilt angle of the heliospheric current sheet. The input (unmodulated) spectrum was taken from a new computation of collisional production of interstellar antiprotons (Bieber et al. 1999; Gaisser et al. 1999). For wind speed, we use a simple latitude dependent model consistent with the average properties of the solar wind. Diffusion parameters were determined by fitting measured 1 AU proton spectra to a drift model of solar modulation. See Burger and Potgieter (1999) and references therein for a discussion of the model and its limitations. With the diffusion parameters set by the proton data, no additional free parameters were introduced in making our predictions of antiproton modulation as a function of current sheet tilt angle. For details see Bieber et al. (1999).

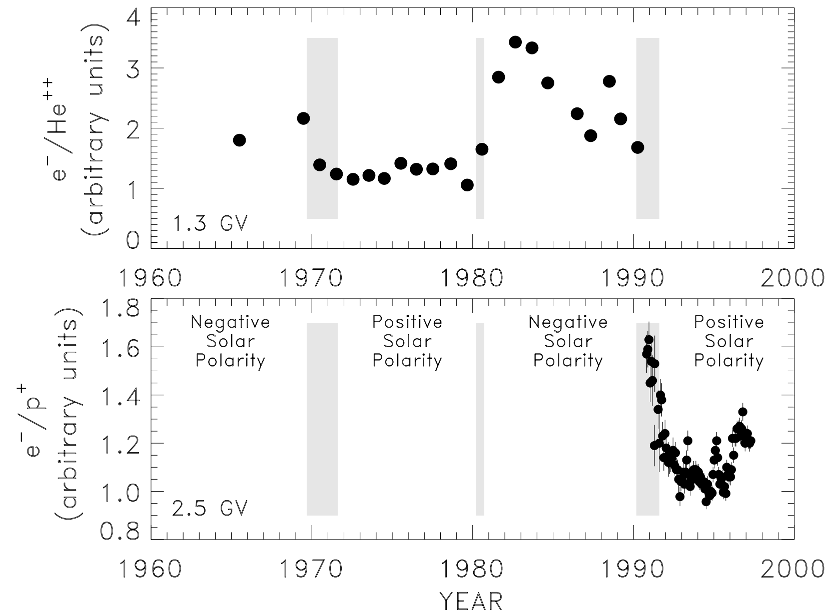

Figure 1. Ratio of (top) cosmic electrons to cosmic helium at 1.3 GV rigidity and (bottom) cosmic electrons to cosmic protons at 2.5 GV rigidity. Shaded areas delimit time periods when the Sun's poloidal magnetic field was reversing. Positive and negative solar polarity refer to epochs when the magnetic field emerging from the Sun's north pole point respectively outward and inward. Data are from Garcia–Munoz et al. (1991) and Raviart et al. (1997).

Results appear in Figure 2. Current sheet tilt angle serves as a proxy for the level of solar activity. With increasing tilt angle (increasing solar activity), the modulated antiproton intensity at 1 AU decreases, but there is a strong differentiation between the rate of decrease predicted for the two different polarities of the solar magnetic field. In both polarities, the intensities approach a common value at high tilt angles given by the no–drift solution. However, convergence to this common value is abrupt. At tilt angles of 80°, the differentiation between the two polarity states is still very strong. This implies that in this model drifts remain an important factor in modulation even during high solar activity.

Figure 3 displays the predicted dependence of the proton and antiproton intensity at 1 AU (relative to interstellar level) upon tilt angle of the heliospheric current sheet, as well as the predicted dependence of their ratio. Three energies are shown, and abscissa values have been arranged so that the curves have the appearance of two successive solar cycles evolving in time. The tilt angle is set at a hypothetical 90° (indicating a no–drift solution) at each of three successive solar activity maxima, and it decreases to a minimum value of 10° at the intervening solar minima.

The two upper panels display a well known feature of drift models (Kóta & Jokipii 1983): the curves for positive charges are broad during epochs of positive solar polarity (1990's), and pointy during epochs of negative polarity (decade beginning in 2000). The opposite relationship holds for negative charges.

Another difference is that protons have a greater modulation amplitude ($\sim 4\times$ at 1 GeV between solar maximum and solar minimum) than do antiprotons ($\sim 2\times$ at 1 GeV) (Labrador & Mewaldt 1997). This stems from the differing character of their unmodulated spectra. The antiproton production spectrum has a distinct peak around 2 GeV kinetic energy because of the high energy threshold for antiproton production in collisions, in sharp contrast (Gaisser & Levy

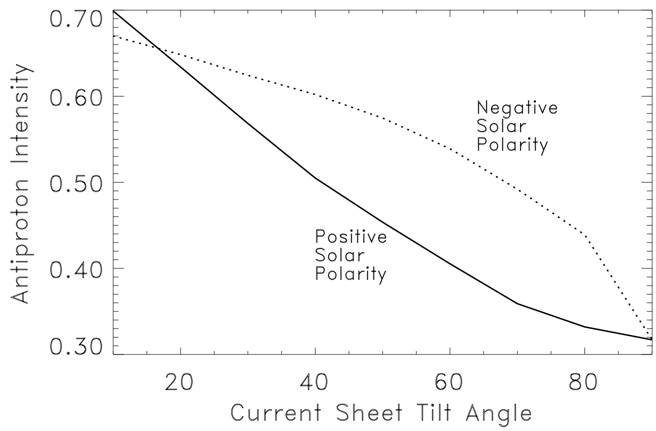

Figure 2. Predicted dependence of 1 GeV antiproton intensity at 1 AU upon tilt angle of the heliospheric current sheet. Strong differentiation between the two opposite solar polarities persists to very high tilt angles. The common 90° value is from a no–drift version of the modulation code.

1974) to the monotonic spectrum of interstellar cosmic ray protons. The antiproton input spectrum is thus "hard" compared to the protons, which makes them more resistant to modulation.

The spectral difference tends to counteract the shape difference during positive solar polarity, with the result that the antiproton/proton ratio (bottom panel) displays little variation during positive polarity. During negative polarity, however, the shape and spectral effects reinforce, producing a dramatic solar cycle variation in step with changes in the current sheet tilt. In addition, sudden changes in the ratio are predicted at each solar activity maximum in association with the change in solar magnetic polarity.

3 Conclusion:

The antiproton/proton ratio should display a much more interesting evolution during the next 10 years than it did during the 1990's, when the ratio was nearly constant. As we proceed through the sunspot maximum and polarity switch expected about 2000, we predict that this ratio will rapidly increase (factor of about 3 at 1 GeV). Then, during the following decade, it will display a large excursion closely tied to the variation of the current sheet tilt angle.

Actual observation of these variations would be a stunning validation of the importance of drift effects in solar modulation, at all phases of the solar activity cycle. Fortunately, new experiments (Hof et al. 1996; Mitchell et al. 1996; Boezio et al. 1997; Matsunaga et al. 1998; Adriani et al. 1999; Battiston et al. 1999; Bower et al. 1999) with good statistical accuracy are arriving just in time to provide the crucial measurements.

Acknowledgments: This work is supported by NASA Grant NAG5-5181. JWB is supported by NSF grant ATM-9616610 and by NASA grant NAG5-7142.

REFERENCES

Adriani, O., & PAMELA Collaboration 1999, Proc 26th ICRC (Salt Lake City), Paper OG 4.2.04

Battiston, R., Produit, N., & AMS Collaboration 1999, Proc 26th ICRC (Salt Lake City), Papers OG 4.2.02 and OG 4.2.03

Bieber, J. W., et al. 1999, Phys. Rev. Lett., submitted

Boezio, M., & CAPRICE94 Collaboration 1997, ApJ, 487, 415

Bower, C., & HEAT Collaboration 1999, Proc 26th ICRC (Salt Lake City), Paper OG 4.1.04

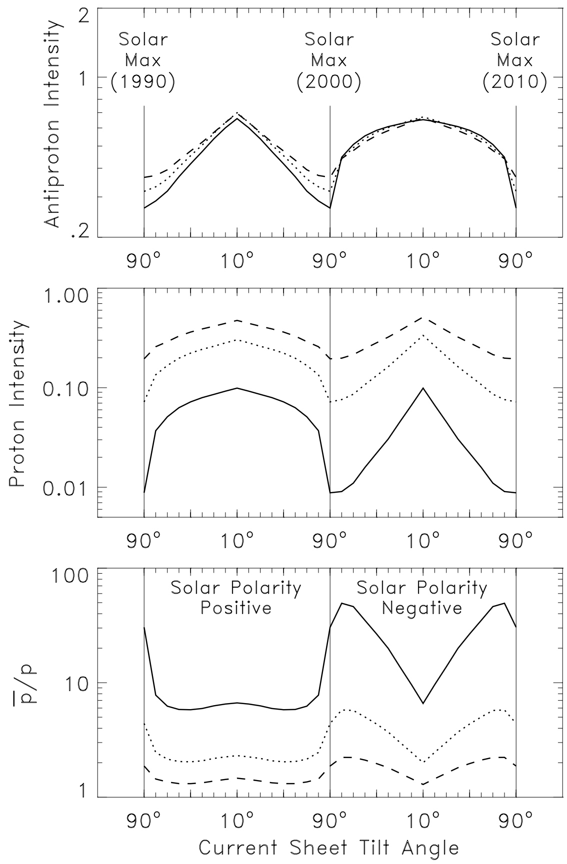

Figure 3. Predicted dependence upon current sheet tilt angle of (top) antiproton intensity, (middle) proton intensity, and (bottom) antiproton/proton ratio at 1 AU. Abscissa values are arranged so that the curves mimic the expected time variation through two solar cycles of opposite magnetic polarity (1990 to 2010). In each panel, three energies are shown: 0.3 GeV (solid), 1.0 GeV (dotted), and 1.9 GeV (dashed). Intensities are relative to interstellar level.

Burger, R. A., & Hattingh, M. 1998, ApJ, 505, 244
Burger, R. A., & Potgieter, M. S. 1999, Proc 26th ICRC (Salt Lake City), Paper SH 3.1.04
Gaisser, T. K., & Levy, E. H. 1974, Phys. Rev. D, 10, 1731
Gaisser, T. K., et al. 1999, Proc 26th ICRC (Salt Lake City), Paper OG 1.1.19
Garcia–Munoz, et al. 1991, Proc. 22nd ICRC (Dublin), 3, 497
Haasbroek, L. J., Potgieter, M. S., & Le Roux, J. A. 1995, Proc. 24th ICRC (Rome), 4, 710
Hof, M., & MASS91 Collaboration 1996, ApJ, 467, L33
Jokipii, J. R., Levy, E. H., & Hubbard, W. B. 1977, ApJ, 213, 861
Kóta, J., & Jokipii, J. R. 1983, ApJ, 265, 573
Labrador, A. W., & Mewaldt, R. A. 1997, ApJ, 480, 371
Matsunaga, H., & BESS Collaboration 1998, Phys. Rev. Lett., 81, 4052
Mitchell, J. W., & IMAX Collaboration 1996, Phys. Rev. Lett., 76, 3057
Potgieter, M. S. 1998, Space Sci. Rev., 83, 147
Potgieter, M. S., & Burger, R. A. 1990, A&A, 233, 598
Potgieter, M. S., & Moraal, H. 1985, ApJ, 294, 425
Raviart, A., et al. 1997, Proc. 25th ICRC (Durban), 2, 37
Webber, W. R., & Potgieter, M. S. 1989, ApJ, 344, 779