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Charge Sign Dependence of Cosmic Ray Modulation At 1 GV Rigidity

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Abstract

New observations of electron fluxes made in 1997 and 1998 extend our ongoing investigation of the relative modulation of positively and negatively charged particles. We compare the electron fluxes measured on high altitude balloon flights with helium fluxes measured by the IMP-8 spacecraft. We also report new measurements of the primary cosmic ray positron abundance in 1997 and 1998.

1 Introduction:

Although the sun has a complex magnetic field, the dipole term nearly always dominates the magnetic field of the solar wind. The projection of this dipole on the solar rotation axis (A) can be either positive, which we refer to as the $\mathbf{A}^+$ state, or negative, which we refer to as the $\mathbf{A}^-$ state. At each sunspot maximum, the dipole reverses direction, leading to alternating magnetic polarity in successive solar cycles. This reversal is better viewed as a collapse and regeneration, rather than a rotation.

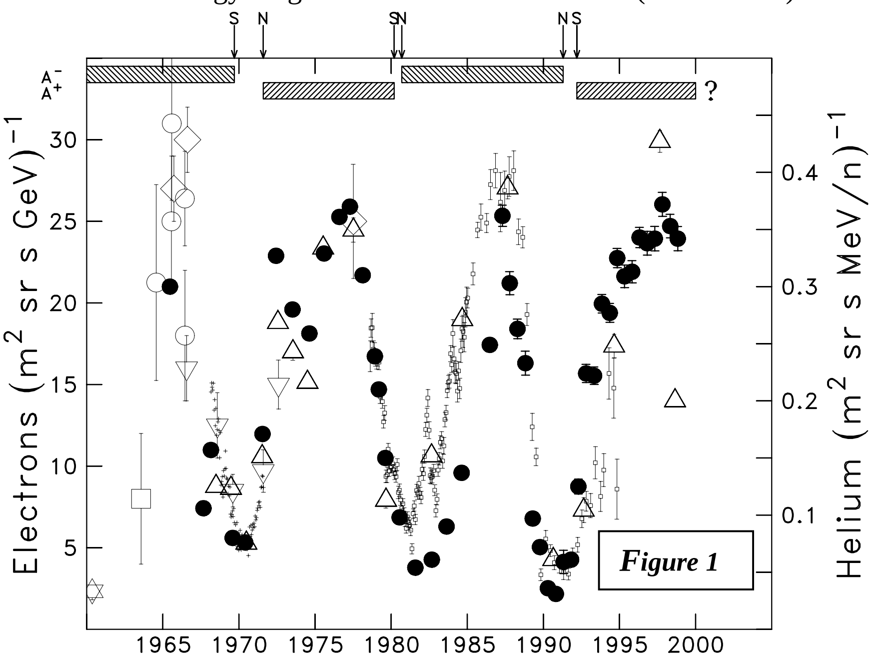
Electromagnetic theory has an absolute symmetry under simultaneous interchange of charge sign and magnetic field direction. Positive and negative particles cannot have systematic differences in their propagation in a magnetic field that is symmetric under reflection. Differential measurements of cosmic ray charge sign dependence thus provide a direct way to study the lack of reflection symmetry in solar wind magnetic fields.

Two types of deviation from reflection symmetry of the magnetic field have been considered to date -- one in the large-scale field, the other in the turbulent, or wave component. Opposite magnetic polarity above and below the helio-equator, coupled with Parker spiral field lines that are mirror images of each other, produces drift velocity fields that (for positive particles) converge on the heliospheric equator in the $\mathbf{A}^+$ state or diverge from it in the $\mathbf{A}^-$ state. (Jokipii and Levy 1977). Negatively charged particles behave in the opposite manner. The drift patterns of course interchange when the solar polarity reverses. Alternatively, systematic ordering of turbulent helicity discovered by Bieber, Evenson, and Matthaeus (1987) can cause diffusion coefficients to depend directly on charge sign and polarity state.

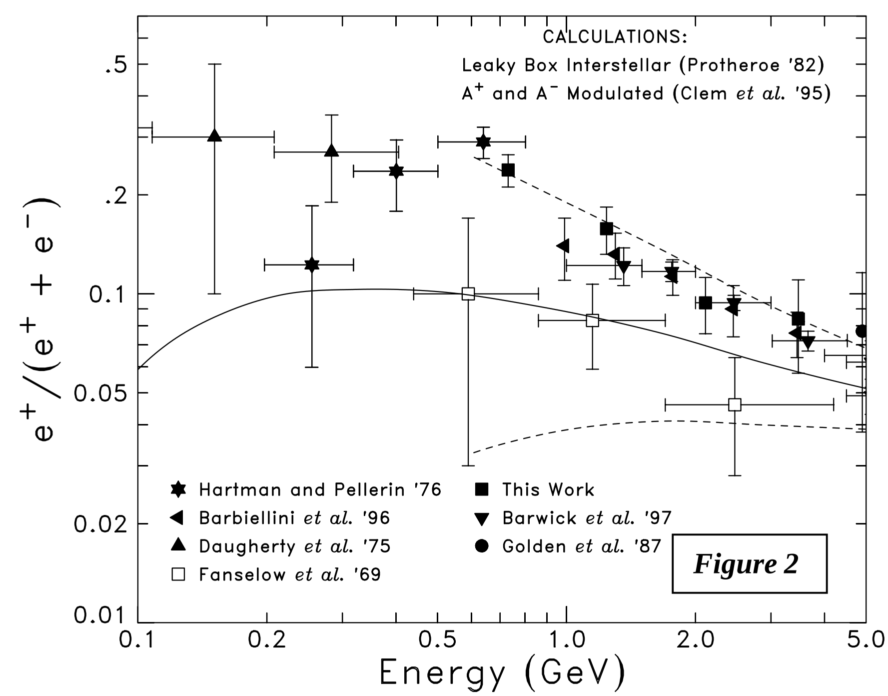
Babcock (1959) was the first to observe a change in the polarity state when he observed the northern (southern) polar region change to positive (negative) polarity, that is a transition to the $\mathbf{A}^+$ state. Such polarity reversals, derived from magnetogram observations taken over the last four solar cycles (Babcock 1959; Howard 1974; Webb *et al.* 1984; Lin *et al.* 1994), are indicated in Figure 1. The symbols “N” and “S” show the best estimates of when the polar regions reversed polarity. The polarity reversals are based on data from heliographic latitudes greater than 70 degrees, except for the first, which covers 50-80 degrees latitude in each hemisphere.

2 Observations:

Several modulation phenomena have different patterns in solar cycles of opposite polarity. Possibly the most striking of these is the change in the flux of electrons relative to that of protons and helium that occurs near the time the solar polarity reverses (Evenson and Meyer 1983; Garcia-Munoz *et al.* 1986; Ferrando *et* *al.* 1995). Cosmic electrons are predominantly negatively charged, even in the **A**$^+$ polarity state. Figure 1 illustrates the behavior of the electrons and helium, near a rigidity of 1.2 GV, as a function of time. Evenson (1998) gives references to the historical electron data (open symbols). In this paper we report two new measurements of the electron flux at 1240 MeV, taken in 1997 and 1998 by the balloon borne instrument LEE (large open triangles). We also present an extension of the measurements made by the University of Chicago instrument on IMP-8 of helium in the energy range 160 MeV/n to 220 MeV/n (solid circles).



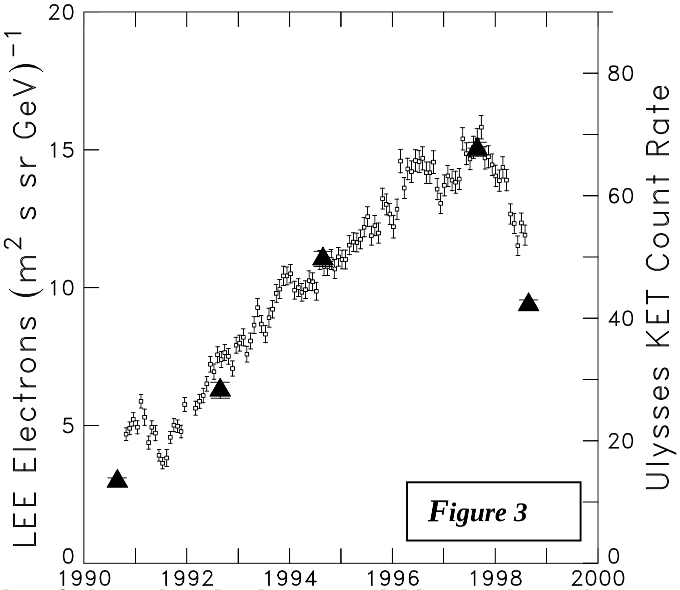
Both drifts and helicity effects can operate at the same time, and observations as to which may dominate are ambiguous, partly because specific predictions are highly model dependent. Particle drifts cause great model sensitivity to the geometry of the heliospheric current sheet, leading to a natural prediction of the apparent alternation of "flat" and "peaked" solar cycles. An inescapable prediction is that a flat cycle in positive particles should be peaked in negative, and *vice versa*. Examining Figure 1, a case can be made that in the 1980's the electron profile is rather flatter than that of the helium, whereas the new data tend to show a peaked electron flux and flat helium flux in the 1990's. In the 1970's, however, the fluxes track each other closely, in contradiction to the drift model prediction. The rapid shift in the ratio of electrons to nuclei near each of the polarity reversals can follow naturally from the turbulent helicity explanation. Present drift models do not directly address this issue, as they are typically considered valid only near solar minimum.



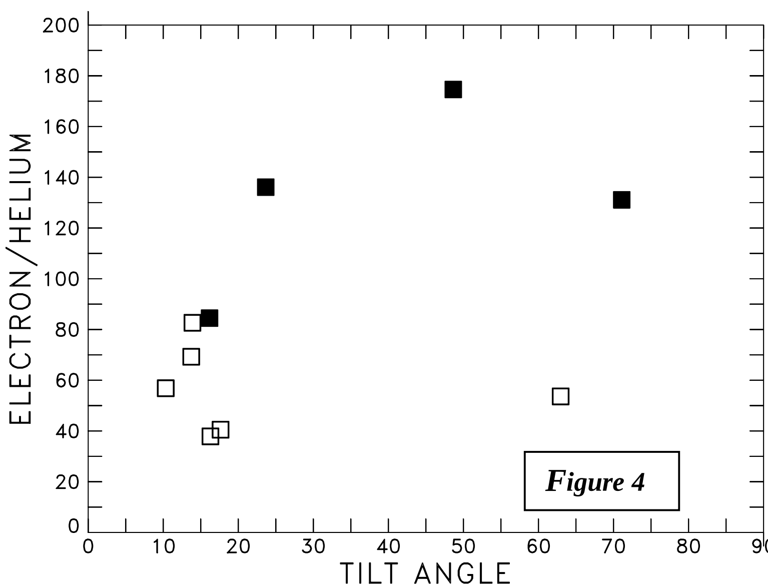
Comparing relative modulation of cosmic negatrons and positrons is a promising way to study the details of charge sign dependent modulation. Figure 2 shows a selective compilation of published data on the positron abundance in the energy range most relevant to the modulation problem. Data where the reported positron flux is within one standard deviation of zero, integral points, and measurements not demonstrably free of atmospheric return albedo contamination are excluded from this compilation. Several pioneering measurements were published before the time dependent nature of this albedo contamination was established (Jokipii, L'Heureux and Meyer 1967). We also include in Figure 2 the first of what we hope will be many measurements of the positron abundance made with our new AESOP instrument, described by Clem *et al.* (1995). We plot the average of our measurements made in 1997 and 1998, since the individual measurements are statistically indistinguishable. Our data also agree well with other measurements made over the past few years, indicating that the abundance of positrons is relatively stable, at least near the time of solar minimum.

3 Discussion:

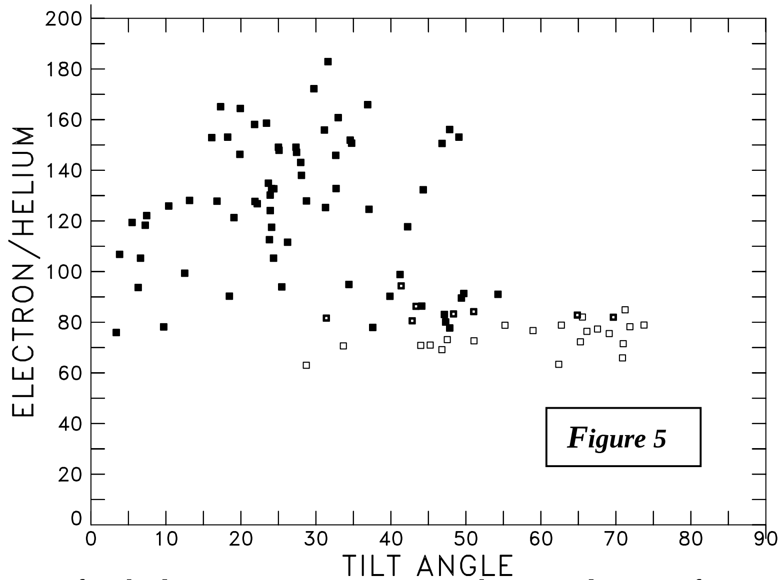
Heber *et al.* (1999a,b) have pointed out that the variation in the relative flux of protons and electrons at the Ulysses spacecraft is ordered by the "tilt angle" of the heliospheric magnetic field. For reference, Figure 3 shows the counting rate of 2.5 GeV electrons measured by Ulysses, with an arbitrary normalization, along with the flux of electrons at 2.2 GeV measured in our series of balloon flights. Agreement is quite good, with the possible exception of the final balloon flight (August 29 -- 31, 1998). This measurement was made in the recovery phase of a large Forbush decrease.



For times since 1976, the estimated tilt angle of the solar dipole is available on the web page http://quake.stanford.edu/~wso/Tilts.html. Using the mean position of the maximum extent of the current sheet (new method) as a measure of tilt angle, Figure 4 shows the electron (from balloon flights) to helium (from IMP-8) flux ratio at 1.2 GV as a function of tilt angle. Solid symbols indicate **A**$^-$ measurements and open symbols denote **A**$^+$. Our result is consistent with the observations of *Heber et al.* (1999a,b), who observe approximately a 20% rise in the electron to proton flux ratio with decreasing tilt angle in the current (**A**$^+$) polarity state. There may be a corresponding drop in the ratio during the **A**$^-$ state, but the conclusion would rest on one measurement.



We also made a similar plot, shown in Figure 5, using 27 day average electron measurements taken between 1978 and 1988 by the University of Chicago electron experiment on the ISEE-3/ICE mission and helium fluxes interpolated from the points shown in Figure 1. Low tilt angles in the **A**$^+$ state were not observed, but the data at high tilt angle show little scatter and are certainly consistent with the Heber *et al.* (1999a,b) report. The data from the **A**$^-$ state show much greater variability, with perhaps a slight tendency to lower overall values at low tilt angle, but the scatter is larger than the trend. In particular, the sharp rise in the helium flux in 1987 (refer back to Figure 1) does not stand out as correlated with an equally sharp feature in the tilt angle.



The variation in the electron to proton ratios reported by Heber et al. (1999a,b) in the present solar cycle may or may not be present in an inverse way during the previous cycle. We are in the process of producing helium flux measurements with higher time resolution to determine if the scatter in our observations results from fluctuations in the electrons alone, or whether both species simply fluctuate more in the **A**$^-$ cycle. The relative constancy of the positron abundance may argue for the latter point. In any event, the most dramatic feature associated with charge sign dependence remains the large shift that occurs very near the reversal of the solar polar field. We look forward to continued flights with our new positron instrument to investigate the phenomenon in greater detail over the coming field reversal.

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