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Charge sign dependent modulation of cosmic ray electrons

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Abstract. On August 25, 2000 (from Lynn Lake, Manitoba) we conducted a balloon flight of the LEE/AESOP payload to measure the spectrum of cosmic ray electrons (resolved into negatrons and positrons) from 500 MeV to 3 GeV. Analysis of the data from that flight reveals a significant decrease in the cosmic ray positron abundance from a level that remained relatively stable throughout the decade of the 1990's. Errors on the new determination are comparatively large due to the low particle fluxes at solar maximum. Nevertheless, the magnitude of the effect is consistent with predictions based on the assumption that cosmic ray modulation effects with 22-year periodicity are related simply and directly to charge sign and large-scale structure of the heliospheric magnetic field.

1 Introduction

The sun has a complex magnetic field, but 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 A^+ state, or negative, which we refer to as the A^- state. At each sunspot maximum, the dipole reverses direction, leading to alternating magnetic polarity in successive solar cycles. 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 A^+ state. Many 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 when the solar polarity reverses (Evenson and Meyer 1984; Garcia-Munoz *et al.* 1986; Ferrando *et al.* 1995).

Electromagnetic theory has an absolute symmetry under simultaneous interchange of charge sign and magnetic field direction, but positive and negative particles can exhibit systematic differences behavior when propagating through a magnetic field that is not symmetric under reflection. Two systematic deviations from reflection symmetry of the interplanetary magnetic field have been identified – one in the large-scale field, the other in the turbulent, or wave component. The Parker field has opposite magnetic polarity above and below the helio-equator, but the spiral field lines themselves are mirror images of each other. This antisymmetry produces drift velocity fields that (for positive particles) converge on the heliospheric equator in the A^+ state or diverge from it in the A^- state. (Jokipii and Levy 1977). Negatively charged particles behave in the opposite manner, and the drift patterns 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.

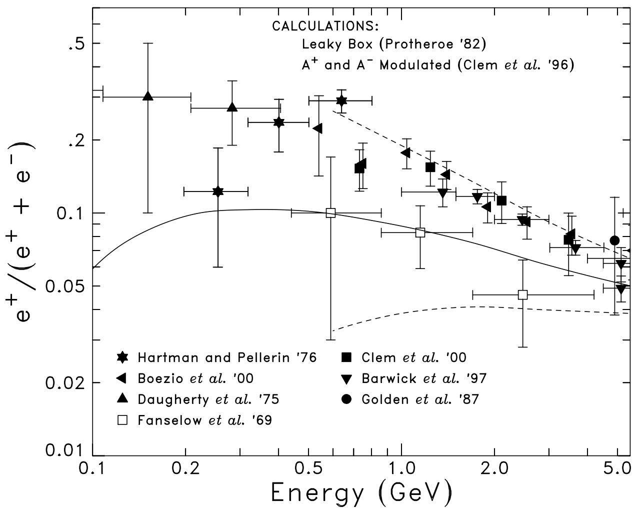

Fig. 1. Measurements of cosmic ray positron abundance made prior to 1998, corrected to the top of the atmosphere. Closed symbols indicate measurement made in the A^+ polarity state, and open symbols the A^- state.

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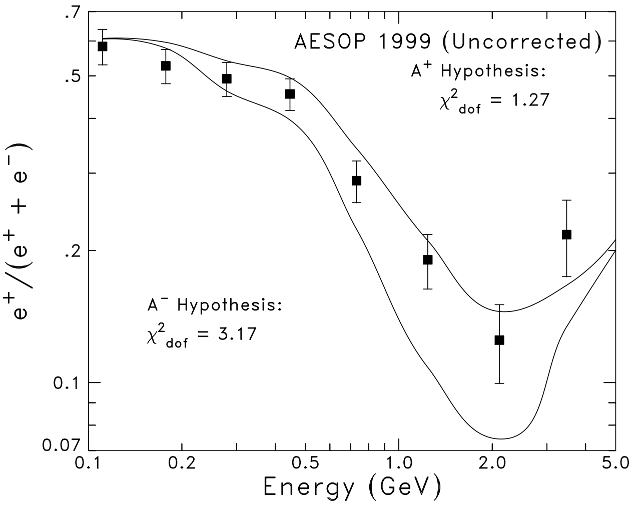

Fig. 2. Uncorrected AESOP observations from August 1999 compared to model predictions for the A^+ and A^- solar polarity states. Statistically, the A^+ hypothesis is a much better choice.

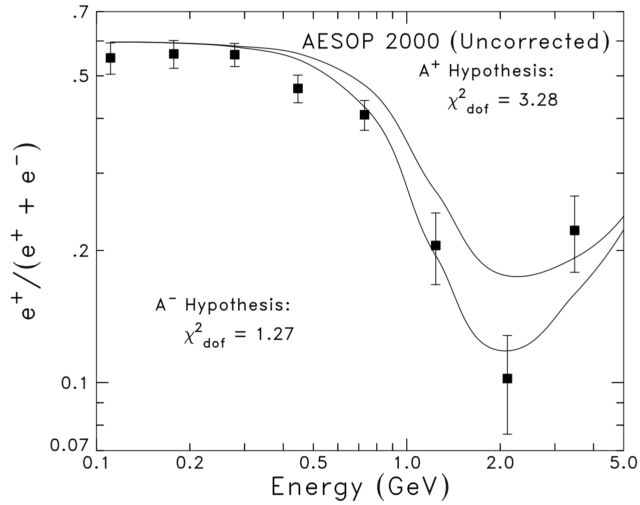

Fig. 3. Uncorrected AESOP observations from August 2000 compared to model predictions for the A^+ and A^- solar polarity states. Now the A^- hypothesis is statistically favored.

Cosmic electrons are predominantly negatively charged, even in the A^+ polarity state, so differential modulation of electrons and nuclei provides a direct way to study the lack of reflection symmetry in solar wind magnetic fields. Accurate measurements of the relative modulation of negative and positive electrons (negatrons and positrons) are beginning to enable a more precise investigation of the "pure" charge sign dependence of modulation. Figure 1 shows a selective compilation of published data on the positron abundance in the energy range most relevant to the modulation problem. We use the term "abundance" consistently to mean the ratio of one component of a population to the total population. Thus the positron abundance is (positron flux)/(positron flux + negatron flux). Evenson (1998) and Clem *et al.* (1996) discuss the selection of data taken prior to 1994. No selection has been applied to data published subsequently.

Before any of the data from the 1990's were published, Clem et al. (1996) made a specific prediction of the expected positron abundance for both positive and negative polarity states. We based this on the "leaky box" calculation by Protheroe (1982) of the positron abundance in cosmic rays. Protheroe (1982) included solar modulation in his calculation, but assumed that both charge signs modulated in the same way. Determining solar cycle "phase" by neutron monitor count rate, we examined electron fluxes at the same phase of successive solar cycles. Under the assumption that electrons and positrons behave symmetrically, via a "binary" function of rigidity, we solved for the observed abundance as a function of rigidity in the two polarity states. This prediction is displayed in our various figures as dashed lines.

2 New Observations

In this paper we report two new measurements of the positron abundance, obtained from flights of the AESOP instrument (Clem *et al.* 1996, 2000) in August of 1999 and August of 2000. Positron abundances discussed later in this paper, corrected to the top of the atmosphere, were obtained from the raw data by the procedure discussed by Clem *et al.* (2000). Briefly, in this analysis, the total electron (positrons and negatrons together) spectrum is measured accurately as a function of altitude by the LEE instrument (Hovestadt *et al.* 1970), which is carried on the same balloon payload as AESOP. We carefully select "night-time" data, namely data taken when the time variable geomagnetic cutoff is clearly below the observation energy, using the LEE payload. With standard techniques (Fulks and Meyer 1974; Fulks 1975) we determine the contribution of atmospheric secondaries to the total electron flux at the float altitude of the payload and the primary electron spectrum at the top of the atmosphere. We then calculate the positron abundance in the atmospheric secondaries using the FLUKA code (Fasso *et al.* 1997). Adding the AESOP determination of the positron abundance at float altitude, we solve self consistently for the primary positron abundance at the top of the atmosphere.

For 1999, the analysis is straightforward and immediately produces convincing results. Interpretation of AESOP 2000 data is more complicated because the level of modulation is much higher, and comparatively large corrections are necessary for atmospheric secondary electrons. In fact, the positron abundance observed at the payload is very similar for 1999 and 2000 but the inferred abundance at the top of the atmosphere is quite different. To gain confidence in our result, we have incorporated all of the factors of which we are aware into a Monte Carlo simulation. The primary and secondary electron spectra derived from LEE are inputs to the simulation, but we do not in any way "fit" the AESOP data. For each year we run the simulation twice, once using our predicted A^+ state abundance (upper dashed curve in Figure 1) and once using our predicted A^- state abun-

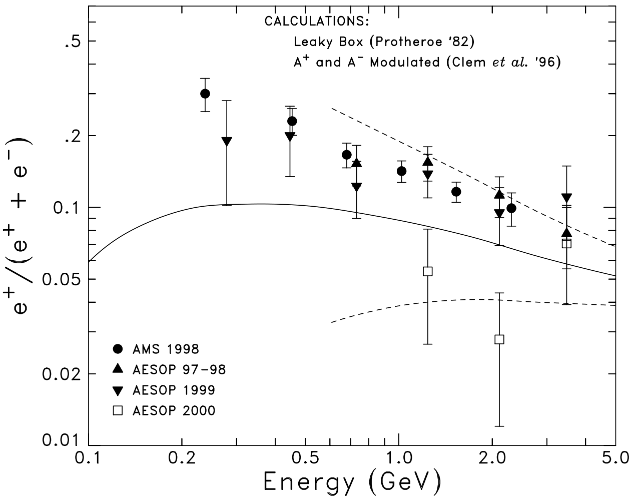

Fig. 4. Observations of the positron abundance made since 1997. Note the excellent consistency among the measurements through 1999, and the much lower values obtained from the AESOP 2000 flight.

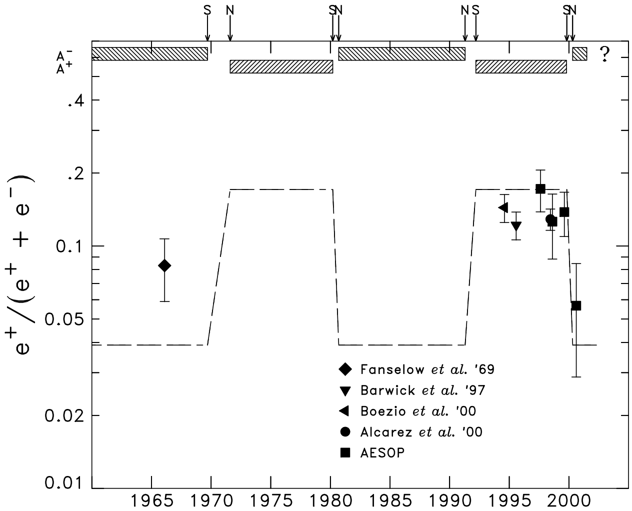

Fig. 5. Time profile of cosmic ray positron abundance at a rigidity of approximately 1.3 GV. Solar polar field reversals and solar polarity state are indicated, along with the prediction of Clem *et al.* (1996)

dance (lower dashed curve in Figure 1). Results of the calculation are shown in Figures 2 and 3, along with the measured positron abundance at float altitude. At low energy, in spite of the wide divergence of the assumed primary positron abundance in the two cases, there is almost no distinction between the two hypotheses. However the A^+ hypothesis provides a better overall fit to the AESOP 1999 data and the A^- hypothesis provides a better fit to the AESOP 2000 data.

The top of the atmosphere positron abundance measured by AESOP since 1997 since shown in Figure 4, along with the abundance derived from the 1998 exposure of AMS on the Space Shuttle (Alcarez *et al.* 2000). Agreement between AESOP and AMS is essentially perfect, within errors. AESOP measurements prior to 2000 are also within errors of each other, but not so the measurement in 2000. Between the last two AESOP flights, data on the solar magnetic field provided by the Wilcox Observatory at Stanford (see below) indicate that both poles reversed. It thus appears that we have indeed confirmed the lower abundance measured by Fanselow *et al.* (1969) in the only previous determination in an A^- state.

3 Discussion

In Figure 5 we show the time dependence of the positron abundance at approximately 1.3 GV, along with a record of the solar magnetic polarity. Timing of earlier polarity reversals is derived from the literature (Howard 1974; Webb *et al.* 1984; Lin *et al.* 1994), but for the most recent case we have used the time that the polar field strength first crosses zero in the filtered time series provided on the Wilcox Solar Observatory web site (http://quake.stanford.edu/≈wso/Polar.ascii).

Enough data now exist to show that the positron abundance is slightly lower than our prediction during the A^+ cycle of the 1990's although the the energy dependence is in excellent agreement with our prediction. It is of course premature to draw specific conclusions about the average abundance in the A^- state, but it is clear that both our AESOP 2000 determination and that of Fanselow *et al.* (1969) lie above the prediction. Therefore, it appears that the full (22 year) magnetic cycle average abundance (which presumably is directly related to the interstellar abundance, transformed by adiabatic deceleration) is consistent with the leaky box calculation calculation of Protheroe (1982). Moskolenko and Strong (1998) have presented several new calculations of the positron abundance which fit the observed abundances during the A+ epoch without considering charge sign dependence of modulation. It is likely that these calculations overestimate the interstellar positron abundance.

We finally have an observation of "pure" charge sign dependence at a solar polarity transition. It is a little smaller than our estimate of a few years ago, but it is still much larger than any variations throughout the rest of the solar cycle. Thus the mystery remains: Why is the leading term in the charge sign dependence such a simple, binary function of polarity state, when the magnetic structure of the heliosphere itself is so complex? Heber *et al.* (1999) in particular, have identified small amplitude variations in the ratio of electrons to protons and alpha particles that are clearly correlated with details of the heliospheric field, most notably the "tilt angle". However these variations are small compared to the scatter of (and error bars on) the various determinations of the positron abundance in the decade of the 1990's. Large changes in the ratio of protons and alpha particles to electrons (and now, also apparently positrons to electrons) occurring very near the reversal of the polar fields remain basically unexplained in quantitative terms.

4 Conclusions

Current observations of the positron abundance in cosmic rays are consistent with the interstellar positron abundance in galactic cosmic rays calculated by Protheroe (1982) using the leaky box assumption. It is likely that the recent work of Moskolenko and Strong (1998), which fits the observed abundance during the A^+ epoch overestimates the interstellar abundance. The Clem *et al.* (1996) prediction seems somewhat to underestimate the magnitude of the abundance transition but it is based on an extremely simple model that uses neutron monitors to define the phase of the solar cycle at which to compare the far less rigid electrons. We are in the process of examining the electron spectra obtained from LEE, and are working with other groups to collect the necessary data to put the observations in the proper context.

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