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POSITRON ABUNDANCE IN GALACTIC COSMIC RAYS

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ABSTRACT

On 2000 August 25 from Lynn Lake, Manitoba, we conducted a balloon flight of the LEE/AESOP (Low Energy Electrons/Anti-Electron Sub Orbital Payload) 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 1990s. 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 yr periodicity are related simply and directly to charge sign and large-scale structure of the magnetic field embedded in the solar wind.

Subject headings: cosmic rays — solar wind

1. INTRODUCTION

Shortly after the discovery of electrons in galactic cosmic rays (Earl 1961; Meyer & Vogt 1961), DeShong, Hildebrand, & Meyer (1964) found a large excess of negative electrons compared to positrons. This led them to conclude that the electron component consists mainly of ambient particles that have been accelerated to cosmic-ray energy. The mechanism responsible for accelerating these electrons remains elusive (Ellison, Berezhko, & Baring 2000), but a considerable amount of attention (Protheroe 1982; Moskalenko & Strong 1998) has been paid to the secondary positrons produced by interactions of cosmic-ray nuclei with the interstellar medium. Positrons provide an important diagnostic for models of cosmic-ray propagation and also for studies of the modulation of cosmic-ray fluxes by the solar wind.

Consequently, in recent years a series of observations of the positron abundance in cosmic rays have been made. Figure 1 shows a selective compilation of published data on the positron abundance in the energy range most relevant to our current results. 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 our critical selection of data taken prior to 1994. No selection has been applied to data published subsequently. Most of the recent measurements of the positron abundance lie significantly above that measured in the earliest determination (Fanselow et al. 1969), although none of the observations yield an abundance high enough to require a revision in the understanding that cosmic-ray electrons consist predominantly of particles accelerated from the interstellar medium. It has been our contention for several years (Clem et al. 1996) that this discrepancy is not instrumental but that it results from the differential modulation of positive and negative particles in the heliosphere.

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 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 polar region change to positive polarity and the southern polar region change to negative polarity, which 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 & 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 propagate differently in a magnetic field that is not symmetric under reflection. Two deviations from reflection symmetry of the interplanetary magnetic field have been identified: one in the large-scale field, and the other in the turbulent, or wave component. The Parker field has opposite magnetic polarity above and below the helioequator, but the spiral field lines themselves are mirror images of each other. This antisymmetry produces drift velocity fields that (for positive particles) either converge on the helioequator in the A^+ state or diverge from it in the A^- state (Jokipii & 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, & Matthaeus (1987) can cause diffusion coefficients to depend directly on charge sign and polarity state.

Prior to the publication of observations made during the 1990s, 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 (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. We determined solar cycle "phase" by neutron monitor count rate and compared 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

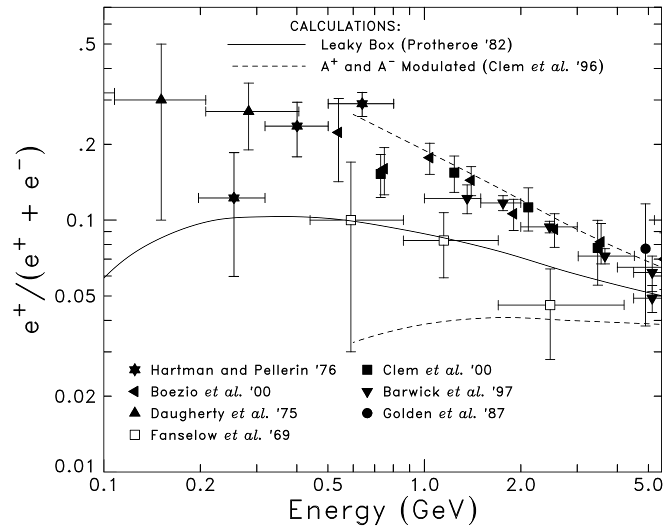

FIG. 1.—Measurements of cosmic-ray positron abundance made prior to 1998, corrected to the top of the atmosphere. Filled symbols indicate measurements made in the A^+ polarity state, and open symbols indicate measurements made in the A^- state. The " leaky box " calculation of Protheroe (1982) is represented as a solid line, while our modifications to this calculation (Clem et al. 1996) are represented as dashed lines.

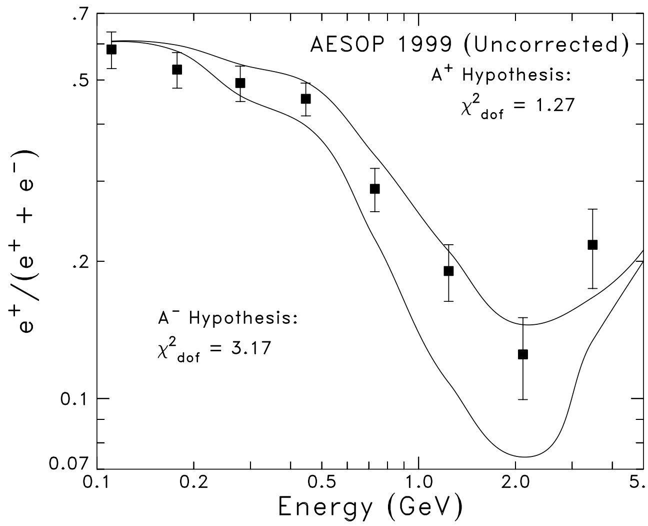

FIG. 2.—Uncorrected AESOP observations from 1999 August compared to model predictions for the A^+ (*top curve*) and A^- (*bottom curve*) solar polarity states. Statistically, the A^+ hypothesis is a much better choice.

states. This prediction is displayed in Figure 1 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 1999 August and 2000 August. Positron abundances, corrected to the top of the atmosphere, were obtained from the raw data by the procedure developed 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 (Low Energy Electrons) instrument (Hovestadt, Meyer, & Schmidt 1970), which is carried on the same balloon payload as AESOP (Anti-Electron Suborbital Payload). We carefully select " nighttime " data, namely data taken when the time-variable geomagnetic cutoff is clearly below the observation energy, using the LEE payload (Jokipii, L'Heureux, & Meyer 1967). With standard techniques (Fulks & 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 particle physics Monte Carlo simulation package (Fasso et al. 1997). Using 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.

When we apply this technique to the AESOP 1999 flight, we immediately obtain statistically convincing results. This is not the case for the AESOP 2000 data because a much higher level of modulation (i.e., much lower particle fluxes) requires relatively larger corrections for atmospheric secondary electrons. If we consider each energy interval in isolation, then the error estimates could be consistent with a statistically insignificant change in the positron abundance.

To gain confidence in our result, we incorporated all known factors into a Monte Carlo simulation and considered the data in totality. Primary and secondary electron spectra derived from LEE were inputs to the simulation, but we did not in any way " fit " the AESOP data. For both 1999 and 2000 we ran the simulation twice, once using our predicted A^+ state abundance (Fig. 1, *upper dashed curve*) and once using our predicted A^- state abundance (Fig. 1, *lower dashed curve*). Apart from these two different hypotheses, there are no free parameters. Results of the simulation are represented in Figures 2 and 3, along with the measured positron abundance at float altitude. Note that although the positron abundance observed at the payload is very similar for 1999 and 2000, the statistical inference is quite different. The A^+ hypothesis provides a much better overall fit to the AESOP 1999 data, and the A^- hypothesis provides a similarly better fit to the AESOP 2000 data.

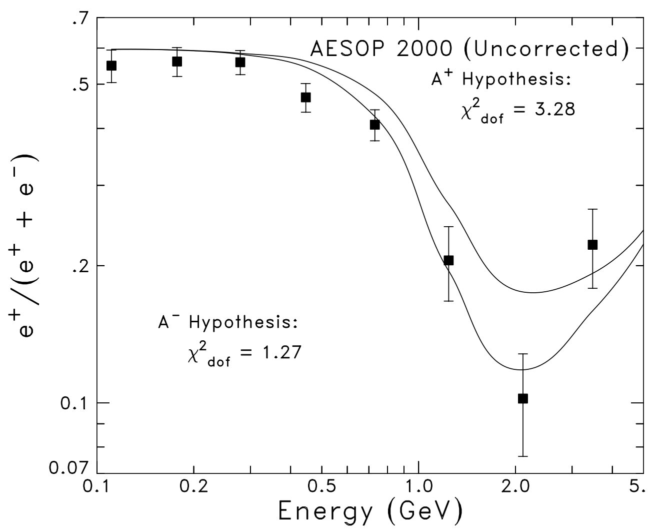

FIG. 3.—Uncorrected AESOP observations from 2000 August compared to model predictions for the A^+ (*top curve*) and A^- (*bottom curve*) solar polarity states. Now the A^- hypothesis is statistically favored.

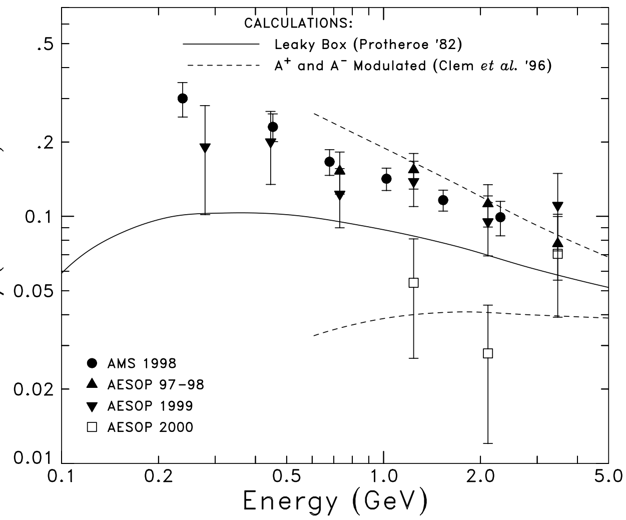

FIG. 4.—Observations of the positron abundance made since 1997. Note the excellent consistency among the measurements through 1999 and the much lower values obtained from the AESOP 2000 flight.

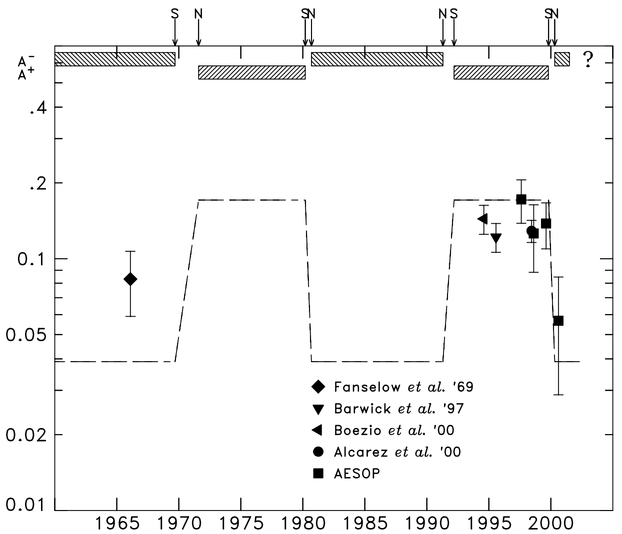

FIG. 5.—Time profile of cosmic-ray positron abundance at a rigidity of approximately 1.3 GV. Solar polar field reversals and solar polarity state are indicated, along with the predictions of Clem et al. (1996).

With this validation that there is indeed a difference between the two observations, we show in Figure 4 the positron abundance at the top of the atmosphere measured by AESOP since 1997 using the Clem et al. (2000) analysis method. We also show the abundance derived from the 1998 exposure of the Alpha Magnetic Spectrometer (AMS) on the Space Shuttle (Alcarez et al. 2000). AESOP and AMS are completely consistent within errors. AESOP measurements prior to 2000 are also within errors of each other, but the measurement in 2000 is significantly lower. Between the 1999 and 2000 AESOP flights, data on the solar magnetic field provided by the Wilcox Observatory at Stanford indicate that both poles reversed. It thus appears that our new observations in 2000 are consistent with 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. We display this time series because it represents the most commonly observed energy in the historical data set. It also happens to correspond to a rather flat regime of the electron energy spectrum, so errors in energy determination and different energy bins used by different investigators do not have a large effect on flux measurements. AESOP data in Figure 5 are the points plotted at 1.2 GeV in Figure 4. Figure 5 also contains a record of the solar magnetic polarity state. Timing of earlier polarity reversals is derived from the literature (Howard 1974; Webb, Davis, & McIntosh 1984; Lin, Varsik, & Zirin 1994), but for the most recent case we have shown the time that the polar field strength first crosses zero in the filtered time series provided by the Wilcox Solar Observatory.

Considering all the data, we note that the positron abundance is slightly lower than our prediction during the A^+ cycle of the 1990s, but 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 both our AESOP 2000 determination and that of Fanselow et al. (1969) are statistically consistent with the prediction. Therefore, it appears that the average abundance over a full (22 yr) magnetic cycle (which presumably is directly related to the interstellar abundance, transformed by adiabatic deceleration) is consistent with the "leaky box" calculation of Protheroe (1982). Moskalenko & Strong (1998) have presented several new calculations of the positron abundance that fit the observed abundances during the A^+ epoch without considering charge sign dependence of modulation. It is therefore likely that these calculations overestimate the interstellar positron abundance.

We finally have an observation of "pure" charge sign dependence at a solar polarity transition. This may be 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 1990s. Large changes in the ratio of protons and alpha particles to electrons (and now, apparently positrons to electrons also) occurring very near the reversal of the polar fields remain basically unexplained in quantitative terms.

4. CONCLUSIONS

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. More recently, Moskalenko & Strong (1998) have considered a series of models, apparently chosen to fit the observed abundance during the A^+ epoch but without consideration of charge sign dependence. It is therefore likely that all of these models overestimate the true interstellar abundance. The Clem et al. (1996) prediction may slightly overestimate 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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