Observations of cosmic ray electrons and positrons during the early stages of the A- magnetic polarity epoch

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[1] As part of our ongoing investigation of the charge sign dependence in solar modulation, we measured the cosmic ray positron abundance (0.8 GeV to 4.5 GeV) and electron flux (20 MeV to 4.5 GeV) on balloon flights from Lynn Lake, Manitoba during August 2002. We find that the decrease in the positron abundance observed in 2000 persists in 2002. The low-energy electron flux observed on a very high altitude flight (48.8 km) reconfirms the negative slope in the spectrum. We compared our data with published data from the Ulysses spacecraft. Although other explanations are possible, we propose that finite heliospheric latitude gradients in electron fluxes have appeared in the A- polarity epoch, whereas no latitude gradients in electrons were observed in the A+ epoch. *INDEX TERMS:* 2162 Interplanetary Physics: Solar cycle variations (7536); 2104 Interplanetary Physics: Cosmic rays; 2134 Interplanetary Physics: Interplanetary magnetic fields; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; 7534 Solar Physics, Astrophysics, and Astronomy: Radio emissions; *KEYWORDS:* solar modulation, drifts, cosmic rays, heliospheric magnetic field, solar wind, particle gradients

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1. Introduction

[2] The anticorrelation between cosmic ray fluxes and the level of solar activity (solar modulation) is caused by magnetic field fluctuations carried by the solar wind that scatter charged particles out of the solar system and/or decelerate them. Even though the Sun has a complex magnetic field, the dipole term nearly always dominates the magnetic field in 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. 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. 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) 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. Cosmic ray electrons (which consist of both negatrons and positrons) 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.

[3] In this paper we report new observations of the positron abundance and electron (negatron plus positron) flux measured by the Antielectron Suborbital Payload (AESOP) and Low-Energy Electrons (LEE) instruments [*Clem et al.*, 1996, 2000], which were carried aloft by high-altitude balloons in August of 2002. LEE flew first on 13 August as part of our dual payload with the AESOP instrument, reaching an altitude of 40 km or 230 Pa (132 kft or 2.3 mbars). Then, on 25 August, LEE flew alone on the largest balloon ever successfully launched (60×10^6 ft^3 or 1.7×10^6 m^3) reaching an altitude of 48.8 km or 90 Pa (161 kft or 0.9 mbars). LEE and AESOP have been part of a single payload since the early 1990s; however, prior to this the LEE instrument had been flown 14 times beginning in 1967. It has provided a well-calibrated time series of cosmic electron spectra up to 5 GeV spanning over 35 years. The AESOP instrument, which began providing scientific data in 1997, separates positrons in the electron flux over a similar energy range.

2. New Observations

[4] The 2002 flight of AESOP provided only the third observation of the positron abundance with energies from 0.8 to 4.5 GeV [*Clem and Evenson*, 2002; *Fanselow et al.*, 1971] during an A+ polarity cycle. The positron abundance observed during the flight is shown in Figures 1 and 2. Positron abundances were quite low, particularly in the 1.2 GeV energy bin where only an upper limit could be

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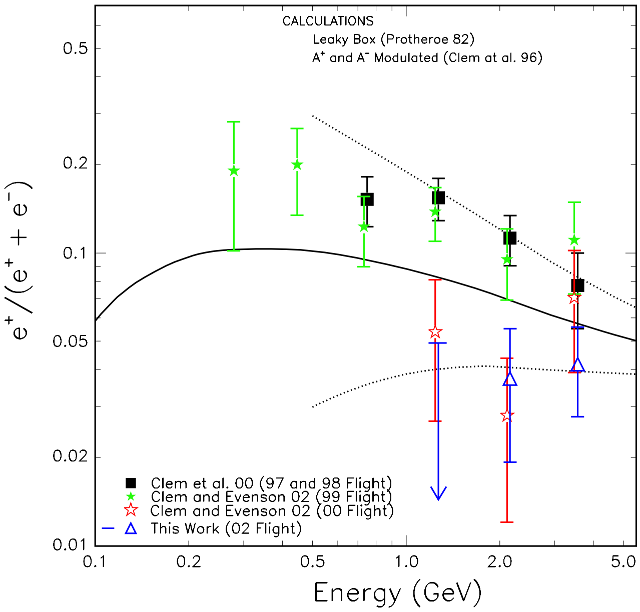

Figure 1. Compiled AESOP balloon instrument measurements and calculations of the positron abundance as a function of energy for different epochs of solar magnetic polarity. Solid line is the local interstellar space abundance as calculated by *Protheroe* [1982]. Dashed lines are from *Clem et al.* [1996] for A+ (top line) and A-. Solid symbols show data taken in the A+ state, while the open symbols represent data taken in the A- state.

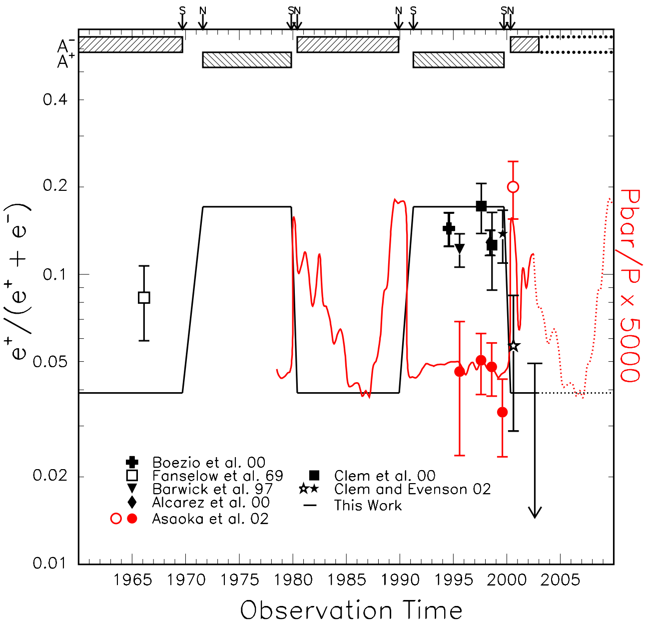

Figure 3. Time profile of positron abundance (black) and antiproton ratio (red) at a rigidity of roughly 1.3 GV. Solid symbols show data taken in the A+ state, while the open symbols represent data taken in the A- state. Shaded rectangles represent periods of well define magnetic polarity. The black line is a positron abundance prediction based on the analysis of *Clem et al.* [1996]. The red line is an antiproton/proton ratio drift (steady-state) model [*Bieber et al.*, 1999a, 1999b] interpolated to 1.3 GV. The current sheet tilt angles used in the drift model were obtained from the Wilcox Solar Observatory. Dashed lines represent the predicted results for future observations. The anti-protons were measured by the series of BESS flights [*Asaoka et al.*, 2002, and references therein].

determined. The large errors result primarily from the low number of positrons during an A- solar maximum epoch. As solar minimum approaches, our series of flights should yield improved statistical accuracy. Nevertheless, these new observations support the results from the 2000 flight which revealed a significant decrease in the positron abundance from observations in the A+ polarity state. There is a suggestion that the abundance has decreased somewhat since 2000, but the statistical errors preclude a definitive statement.

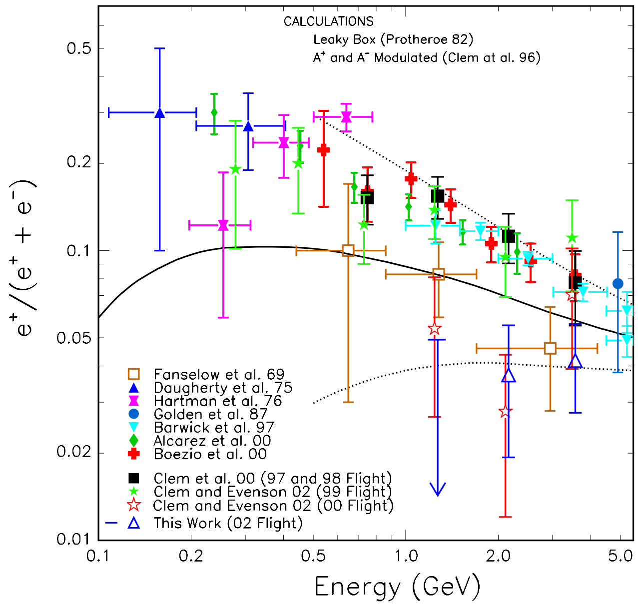

Figure 2. The world summary of positron abundance measurements, including those taken from *Alcarez et al.* [2000], *Barwick et al.* [1997], *Boezio et al.* [2000], *Daugherty et al.* [1975], *Fanselow et al.* [1971], *Golden et al.* [1987], and *Hartman and Pellerin* [1976].

[5] *Clem et al.* [1996] made a specific prediction of the expected positron abundance for both positive and negative polarity states based on the "leaky box" calculation by *Protheroe* [1982] of the Galactic positron abundance in the local interstellar medium. Ignoring adiabatic deceleration, his results were then corrected for charge sign modulation effects. Under the assumption that electrons and positrons behave symmetrically, *Clem et al.* [1996] examined electron fluxes at the same phase of successive solar cycles and then solved for the observed abundance as a function of rigidity in the two polarity states. This prediction, for the two polarity states, is displayed as dashed lines in Figures 1 and 2.

[6] Figure 3 displays cosmic ray positron abundance measurements at ~1.2 GV (black symbols) in chronological order. This plot illustrates the significant decrease between 1999 and 2000 from a level that remained relatively stable throughout the decade of the 1990s. It is tempting to suggest an additional decreased may have occurred between 2000 and 2002, even though the errors on the A- measurements

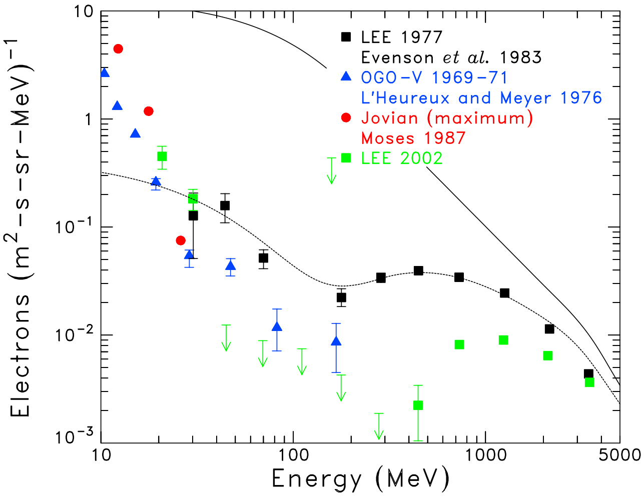

Figure 4. Measurements of the cosmic electron spectrum. Data for 1977, estimated local interstellar spectrum (solid line), and fit to the data are from *Evenson et al.* [1983]. Also shown are a spectrum for 1969–1971 from *L'Heureux and Meyer* [1976] and a 1 AU Jovian electron spectrum [*Moses*, 1987].

are comparatively large due to the low particle fluxes at solar maximum. Such a downward trend would be consistent with the observed decrease in the KET electron to proton ratio [*Heber et al.*, 2003]. The magnitude of the effect is consistent with the prediction [*Clem et al.*, 1996], with the inverse effect appearing in the antiproton/proton ratios at 1.3 GV (red circle symbols) measured by the BESS instrument. The structure in the predicted antiproton/proton ratio is significantly different from that in the positron abundance, primarily because of adiabatic deceleration. The local interstellar energy spectra of protons and antiprotons are quite different whereas the spectra of electrons and positrons are similar [*Heber*, 2001].

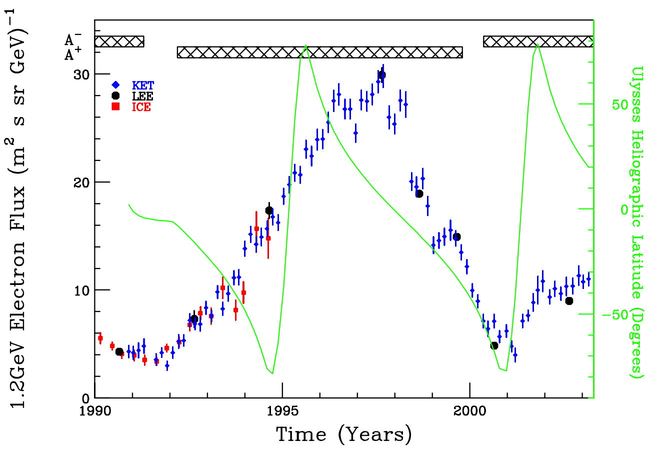

Figure 5. Measurements of electrons as a function of time at a rigidity of approximately 1.2 GV. The large solid circles are data from the LEE series of balloon flights. The red squares are data from the ISEE-3/ICE spacecraft and the blue diamonds are data from KET/Ulysses. The green line shows the heliograph latitudinal location of the Ulysses spacecraft. Epochs of well-defined heliospheric magnetic polarity are indicated by shaded rectangles.

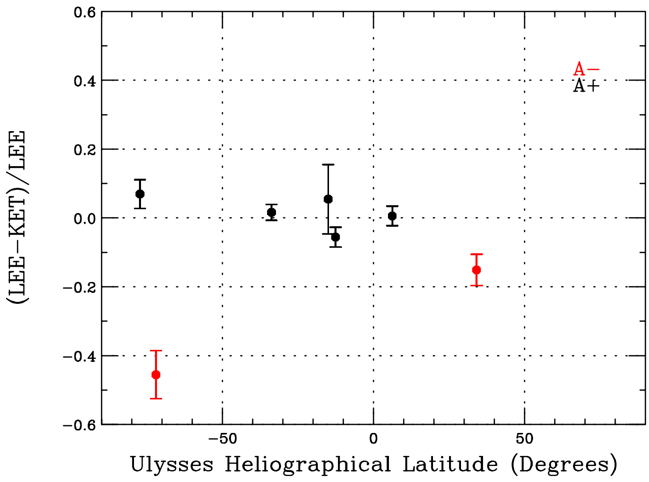

Figure 6. The fractional deviation between the observed LEE fluxes and KET fluxes of 1.2 GV electrons as a function of heliolatitude of the Ulysses spacecraft.

[7] The 2002 high-altitude LEE flight provided a low background environment particularly in the lower-energy regime. This reduced background combined with low atmospheric attenuation allowed the ability to measure low-energy primary electrons inaccessible at greater depths. In Figure 4, the LEE results are compared with previous observations. The most significant result is the persistence of the negative slope in the electron spectrum at low energies. Below 30 MeV, measured flux is consistent with the maximum Jovian flux determined by *Moses* [1987]; however the electrons above 30 MeV almost certainly have some other source. Understanding the electron spectrum in the energy range of 50–200 MeV remains elusive. The negative slope in the spectrum suggests a different energy dependence of electron diffusion from that predicted in quasilinear theory [*Fulks*, 1975; *Rockstroh*, 1977; *Evenson et al.*, 1979; *Rastoin et al.*, 1996; *Potigieter*, 1996].

[8] We may also compare our new observations of the electron flux at Earth with published data on the electron flux at the Ulysses spacecraft [*Heber et al.*, 2003]. As shown in Figure 5, fluxes measured by LEE and the Kiel Electron Telescope (KET) instrument on Ulysses were similar throughout the 1990s, but in both 2000 and 2002 the LEE flux was noticeably lower than the KET flux. Figure 6 displays the data from both instruments at the times of the LEE flights in a different format. To determine the significance of the deviation, we calculated the probability that the two points for the A- cycle are part of the same distribution. The A+ points as a group, independent of Ulysses heliolatitude, have a mean of 1.8×10^{-2} and a standard deviation of 4.4×10^{-2}. There is little significance to the near-zero mean, since the normalization of the KET data was derived by *Clem et al.* [2002], largely based on LEE data during the A+ cycle. (The 1994 LEE/KET point was excluded from the *Clem et al.* [2002] KET normalization analysis since Ulysses heliolatitude was ~75 degrees.). The standard deviation is very near 4.5×10^{-2}, which is the average of the standard deviations (shown as error bars) resulting from the propagation of errors for each point. Using the larger of these numbers and the "t" test analysis, we calculate the probability that the 2000 point is a

fluctuation as 1.1×10^{-5}, while the probability for the 2002 point is 3.0×10^{-2}. The probability that they are both fluctuations is thus approximately 3.3×10^{-7}.

[9] The most obvious inference is that a latitudinal gradient has been established. In fact this is more or less expected, since in the A+ cycle there were latitudinal gradients in protons but not electrons [*Clem et al.*, 2002] and the latitude gradient in protons disappeared with the change in polarity [*Heber et al.*, 2003]. We also note that the possible latitude gradient in electrons is in the same sense (fewer particles near the equator) as that observed previously for protons.

[10] There are alternate explanations but we find them less likely. The KET electron data were corrected for heliospheric radial gradients. *Clem et al.* [2002] demonstrated that in the previous polarity state, 1.2 and 2.5 GV electron radial gradients were indistinguishable from those of positive charged particles of the same rigidity. At this time, we have no way independently to determine radial gradients, so we indeed simply must make the assumption that the radial gradients have not changed.

[11] There is also the chance that the differences may be due to local spatial or temporal variations. In all cases we are comparing a flux integrated over about 1 day at Earth with a 27-day average at Ulysses. One can only note the trend of the Ulysses points near the LEE measurements in Figure 5 and how well clustered the data are for the previous cycle in Figure 6. As noted before, the deviations are in the right direction and roughly the right magnitude that would be predicted on the assumption that the electrons exhibit the same gradient as the protons of the previous cycle. It would be nice if there were more observations of electrons, but that is not the case. Given the current evidence, we thus find latitudinal gradients to be the most likely explanation for our observations, but the case is far from proven. We hope to continue our collaboration with our colleagues in the KET investigation to do a more comprehensive analysis of this issue.

3. Summary

[12] Cosmic ray positron abundance and electron fluxes were measured on two balloon flights from Lynn Lake, Manitoba during August 2002. The positron abundance observations confirm results from the 2000 flight which revealed a significant decrease in the positron abundance at the time of the solar polarity reversal. Data from 2002 flight suggest that the positron abundance may have decreased from 2000 to 2002. The magnitude of the decrease remains consistent with the model of *Clem et al.* [1996]. Comparison between the 1.2 GeV KET/Ulysses electron flux and the 2000 and 2002 LEE fluxes reveal a systematic difference that is consistent with the emergence of an electron latitudinal gradient in the heliosphere during the early stages of the current A- polarity state. At this point, however, temporal variations or radial gradient changes cannot be conclusively eliminated. A more thorough analysis of a possible electron latitudinal gradient will be presented in a future publication.

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