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Cosmic Ray Electron Spectrum in 2009

PAUL EVENSON[1] AND JOHN CLEM[1]
[1]*Univestity of Delaware Department of Physics and Astronomy*
evenson@udel.edu

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Abstract: The 2009 flight of the balloon borne instrument LEE returned a truly exciting result. Although the payload only reached about 141,000 feet, significantly less than the record flight to 161,000 feet in 2002, the extremely low modulation level allowed a complete electron spectrum from 20 MeV to 5 GeV to be observed for the very first time. The nearly power law behavior of the spectrum below 100 MeV now stands out as clearly distinct from the Jovian spectrum. The possibility that these electrons come from Jupiter via simple diffusion in the interplanetary magnetic field is essentially eliminated. Direct measurements of the electron spectrum in the outer heliosphere from the Voyager spacecraft are also now available. Surprisingly the electron fluxes at 1 AU are intermediate between the levels observed at two locations in the outer heliosphere. We discuss possible interpretations of these observations.

Keywords: Modulation, electron, solar magnetic polarity.

1 Introduction

Anti-correlation between cosmic ray fluxes and solar activity (solar modulation) is caused by magnetic field fluctuations in the solar wind that carry 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 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^{pos} state, or negative, which we refer to as the A^{neg} state. At each sunspot maximum, the dipole reverses direction, creating 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 in behavior when propagating through non-axisymmetric magnetic fields such as those with gradients or curvature.

Spiral curvature of the Parker field produces drift velocity fields for positive particles directed toward the heliospheric equator in the A^{pos} state and away from the equator in the A^{neg} state [1]. Negatively charged particles behave in the opposite manner; drift patterns interchange when the solar polarity reverses. Primary cosmic ray electrons are predominantly negatively charged, even during the A^{pos} state, so differential modulation of total electrons (unresolved as to charge) and nuclei provides a direct way to study the lack of reflection symmetry in solar wind magnetic fields.

Electrons and nuclei have greatly different charge/mass ratios, hence the relation between velocity and magnetic rigidity is very different for these two particle species. Careful study of the behavior of cosmic ray positrons, relative to negative electrons (which have an identical relationship between velocity and rigidity) allows a definitive separation of the effects due to charge sign from the effects arising in velocity differences. Our 2000, 2002 and 2006 AESOP (Anti-Electron Sub-Orbital Payload) flights revealed a significant decrease in the positron abundance from a level that remained relatively stable throughout the decade of the 1990s, while the 2000, 2002 and 2005 BESS flights [2] have shown a transition for anti-protons as predicted by drift models. These results are generally consistent with models that predict charge sign effects of solar modulation resulting from a magnetic polarity transition.

Although the primary focus of recent electron observations has been on charge sign it is important to remember that, owing to their low mass, electrons provide a unique look at low rigidity heliospheric phenomena that are largely inaccessible to instruments that measure only ions. The most puzzling observation, illustrated in Figure 1, is a negative spectral index below 200 MeV [3,4,5,6]. For some time, this turn up in the spectrum had only a phenomenological interpretation, namely that that the electron mean free path increases dramatically at low rigidity. This inference was at odds with the predictions of scattering theory and was typically viewed with some suspicion until Potgieter [7], taking into account the work of Bieber [8] and Achatz [9] showed that dynamical and dissipation effects could produce exactly this behavior.

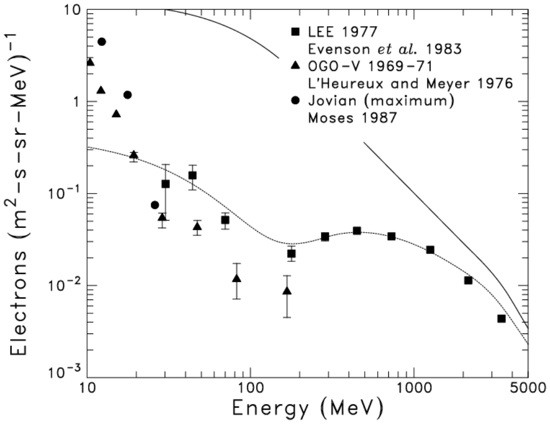

Figure 1: The cosmic ray electron spectrum has an upturn below 200 MeV that is distinct from the spectrum of Jovian electrons [4,5,6]. Estimated local interstellar spectrum (solid line) and a phenomenological fit to the data (dashed line) are also shown.

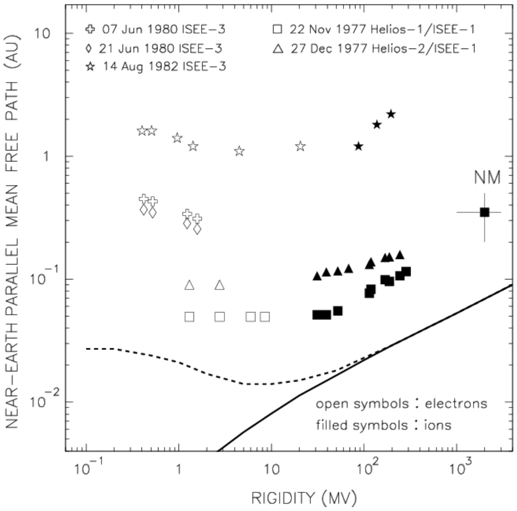

Figure 2: The parallel mean free path for solar particle events has a rigidity dependence that is nearly the same for most events, but the magnitude shifts up and down over two orders of magnitude[12].

Huber [10] completed a thorough review of the literature, and added new data from original analysis of balloon and spacecraft measurements, to examine the evolution of low energy electron fluxes from 1964 to 1994. He was able to draw only tentative conclusions because of large uncertainties in the data, namely that the electron spectrum from approximately 50 to 200 MeV consistently displays a negative spectral index and that there is no evidence for direct Jovian origin of these electrons. The spectrum undergoes modulation, but the amplitude of the modulation is less than that of higher rigidity electrons and nuclei and it may or may not depend on solar polarity state. The latter observation is reminiscent of the work of Moraal [11] who noted that charge sign effects could be masked if electrons contained a large enough positron abundance. This has proved not to be the case at higher energies but the possibility of a large positron component remains entirely open at low energy.

New observational insights were presented by Droege [12], who determined parallel mean free paths in a number of solar particle events over a range of three decades in rigidity. The key result of his work, shown in Figure2, is that a similar rigidity dependence of the mean free path is observed in every event analyzed, but that the level of this universal trend varies greatly (two orders of magnitude) from event to event. In all events, the mean free path of electrons decreases with rigidity up to ~ 2 MV and then is rigidity independent up to ~ 30 MV. Above 30 MV, only proton measurements are available, and the mean free path increases slowly with rigidity. While this work certainly suggests a large diffusion coefficient for cosmic electrons as well it is far from proof that this is the origin of the turn-up. Other explanations are quite plausible.

Jupiter's magnetosphere produces electrons (5-25 MeV) which fill both the inner and outer heliosphere. But the near power law rise in the electron spectrum (Figure 1) extends up to over 100 MeV, well above the maximum energy of electrons observed on spacecraft near Jupiter. Time structure associated with Jovian emission is not observed in the inner heliosphere above about 30 MeV [5]. Electrons in the turn-up may originate in the outer heliosphere. The termination shock region accelerates anomalous component nuclei (He, N, O, Ne, Ar, etc.) from atoms in the interstellar medium that enter the heliosphere as neutrals that are ionized within the heliosphere and picked up by the solar wind. The solar wind then transports them to the termination shock region for acceleration [13]. A similar process could accelerate electrons from the Jovian seed population. The energy gain, in terms of energy per charge, required to produce electrons in the power law region is comparable to that observed in anomalous nuclei. Such a Jovian seed population would consist only of negatrons and would be characteristic of this process if this part of the spectrum is ever resolved by charge sign. Confirming electron

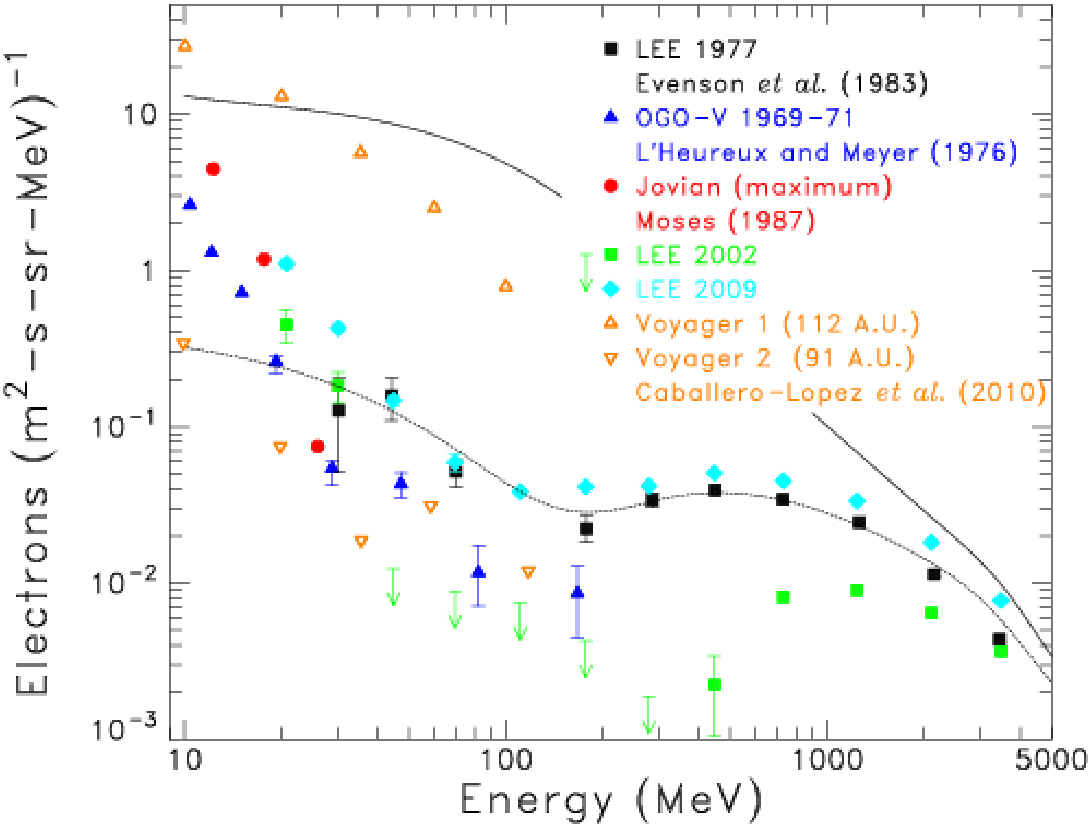

Figure 3. Figure 1 with LEE 2002 measurement (solid, gray squares) and 2009 measurement (diamonds) plus recently published Voyager 1(open triangles) and Voyager 2 observations (inverted open triangles) [14].

acceleration in a standing, heliospheric shock structureewould provide an important model for similar, more energetic processes in supernova shocks.

Alternatively, low energy electrons could come from an additional component in interstellar space. Even at high energy, radio waves and gamma rays only provide averages over a large volume of the galaxy, and may not represent local conditions. The interstellar electron spectrum at low energy is not particularly well constrained by these observations.

LEE 2009 Balloon Exposure

The 2009 flight of LEE returned a truly exciting result. Although it only reached about 141,000 feet, the extremely low modulation level allowed the complete electron spectrum from 20 MeV to 5 GeV to be observed for the very first time. The 1977 LEE flight (on a lighter balloon to approximately 145,000 feet) came close, but did not cover all of the energies. Even the record setting flight in 2002 to 161,000 feet did not observe the whole range due to greater modulation. As might be expected the electron fluxes above 200 MeV are significantly higher in 2009 (because this was an A^{neg} solar year) than in 1977 (which was an A^{pos} year). However the really new and interesting observations are at 100 MeV and below. The nearly power law behavior of the spectrum now stands clearly distinct from the Jovian spectrum. The possibility that these electrons come from Jupiter via simple diffusion in the interplanetary magnetic field is now essentially eliminated. The general shape of the spectrum is also consistent with the most definitive previous determination, that for 1969-1971 [3]. The three main conclusions of Huber [10] – none of which could formerly be made truly quantitative – are thus all confirmed:

- The spectrum exhibits a persistent, negative slope
- Sensitivity to modulation is much less than might be expected by extrapolation from higher energy electrons and comparison with similar energy nucleons
- There is little or no evidence for charge sign dependence of the behavior.

Voyager Data

We also have, for the first time, direct measurements of the electron spectrum in the outer heliosphere from the Voyager spacecraft, also included in Figure 3 [14]. The Voyager 1 data suggest significant disagreement with the estimated "interstellar" electron spectrum heretofore used in our analysis (the solid line in Figures 1 and 3). Whether this is a problem with the construction of the spectrum or an indication that the particles are accelerated in the heliosphere remains to be determined.

Considering only the Voyager 1 data and the 1 AU data one could form a nice picture, in that the 1 AU spectrum is lower and softer (i.e. more steeply negative). Lower is easy to understand as a radial gradient, and softer makes sense because as the energy increases one approaches the region of extreme electron modulation (200 – 800 MeV). The spectrum at 1 AU in 2002 is also both lower and softer than the spectrum in 2009, consistent with this qualitative picture. The amazing thing is not only the great difference in the fluxes of electrons measured by the two Voyagers, attributed [14] to a large north - south asymmetry in the properties of the heliosheath, but that Voyager 2 measures a spectrum that is below that of the electrons at 1 AU. The relation between the two Voyager spectra also violates the "lower – softer" pattern, as the Voyager 2 spectrum is lower than the other spectra but also harder.

Conclusions

Definitive observations of low energy electrons both in the inner and outer heliosphere simultaneously now pose two intriguing questions.

1. What causes the negative slope of the spectrum?
2. Why is the spectrum so variable within the outer heliosphere while it is apparently rather stable at 1 AU?

Indeed these two questions lead to a third, possibly more fundamental, namely

3. Just where are these things really coming from anyway?

Measurement of the positron abundance would discriminate among different models for the turn-up. Any positrons will be undeniably galactic. Positron abundance higher than predicted by secondary production would constitute a discovery of primary cosmic ray positrons, presumably accelerated from ambient supernova material. This would add a significant dimension to the discussion of a possible excess in positrons at high energy and the attendant concern with, e.g., a "dark matter" origin. A deficit of positrons would point to acceleration in the heliosphere. If the low energy electrons contain a typical galactic abundance of positrons the answer to the turn-up must lie in transport theory. Unfortunately we are unlikely to have positron abundance measurements in this energy range in the near future, but getting them should receive high priority.

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