Cosmic electron gradients in the inner heliosphere

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[1] We report the first determination of the radial gradient of cosmic ray electrons in the inner heliosphere at rigidities of 1.2 and 2.5 GV from 1 to 5 AU. Since this determination was made during the A^+ solar polarity state, it also constitutes the only determination for particles in a polarity state opposite to their charge sign. We find that the radial gradient for electrons is indistinguishable from that for positive particles measured at the same time. We have found no significant latitude gradient in either 1.2 or 2.5 GeV electrons. Lack of the ability to study time evolution greatly hampers interpretation of our results. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2134 Interplanetary Physics: Interplanetary magnetic fields; 7859 Space Plasma Physics: Transport processes; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields. **Citation:** Clem, J., P. Evenson, and B. Heber, Cosmic electron gradients in the inner heliosphere, *Geophys. Res. Lett.*, *29*(23), 2096, doi:10.1029/2002GL015532, 2002.

1. Introduction

[2] Comparatively few observations of cosmic ray electrons in the inner heliosphere exist [*Evenson*, 1998]. It is therefore important to increase the existing data set and to ensure that new data can be properly compared to historical data. For decades the standard reference has been the payload LEE, developed at the University of Chicago in 1968 [*Hovestadt et al.*, 1970], and now maintained at the University of Delaware. We have recently embarked on a program to use this instrument, and other available data, to correct and validate data obtained with the Kiel Electron Telescope (KET) on the Ulysses spacecraft [*Simpson et al.*, 1992]. Most of the results of our work will be presented in papers now in preparation. In this Letter, we discuss one novel component of this work, namely the radial and latitudinal gradients of cosmic ray electrons in the inner heliosphere. While less statistically conclusive than one might desire, our analysis provides the only measurement ever made of these gradients. In this paper we consider electrons unresolved as to charge sign, that is we use the term electrons to include both negatrons and positrons. However, as summarized by *Clem and Evenson* [2002], electrons contained at most 20% positrons during the 1990's (a so-called A^+ solar polarity epoch.) Therefore this work also yields the first and only gradient measurement in the inner heliosphere for particles of a charge sign opposite to that of the solar polarity.

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2. Data and Analysis

[3] KET measures protons and helium in the energy range 6 MeV/n to above 2 GeV/n and electrons in the energy range from 3 MeV to a few GeV. Ulysses was launched on October 6, 1990, in the declining activity phase of solar cycle 22. A swing-by manoeuvre at Jupiter in February 1992 placed the spacecraft into a trajectory inclined by 80° with respect to the ecliptic plane. Ulysses completed its first out-of-ecliptic orbit in the beginning of 1998. The KET detector consists of an entrance telescope and a calorimeter surrounded by a guard counter. The entrance telescope comprises a silica-aerogel Cherenkov detector with an index of refraction of 1.066 inserted between semi-conductor detectors. It defines the geometry, selects particles with velocity $\beta > 0.938$ and determines the magnitude of the particle charge but not the sign of the charge. Below the entrance telescope is a 2.5 radiation length lead-fluoride (PbF2) crystal calorimeter located above a scintillator that counts the number of particles leaving the calorimeter. This part of the detector system characterizes electromagnetic showers. Based on measured signals, data from KET are classified into "channels" with a count rate available for each channel. Channel P4000 counts singly charged particles that do not interact in the calorimeter yet trigger the Cherenkov. These are nominally protons >2 GeV. Channel E300 counts singly charged particles that produce high signals in the calorimeter and also trigger the Cerenkov. Nominally these particles are energetic electrons. Additional criteria applied to the calorimeter subdivide E300 into E300A, corresponding to electrons with a mean energy of 1.2 GeV and E300B corresponding to 2.5 GeV electrons. These additional criteria are described in detail by *Rastoin* [1995].

[4] E300 counting rates cannot be used directly because they are contaminated by background resulting from proton interactions. Contamination of the E300B channel is not large, and electron data for 2.5 GeV have appeared in several papers [*Heber et al.*, 2002; *Clem et al.*, 2000]. Our current analysis yields a slightly better correction for E300B leading to a modulation amplitude enhanced by ≈10%. More significantly, we have generated a correction for the more difficult E300A. We are able to do this because the counting rate of the particles responsible for most of the contamination is measured directly at Ulysses as P4000. Thus the contamination and the normalization can be derived empirically by comparing the Ulysses data with other electron observations. For this purpose, we use previously unpublished data from LEE, as well as published observations from LEE and from the MEH electron detector on ICE [*Huber*, 1998]. To reduce potential systematic effects, var-

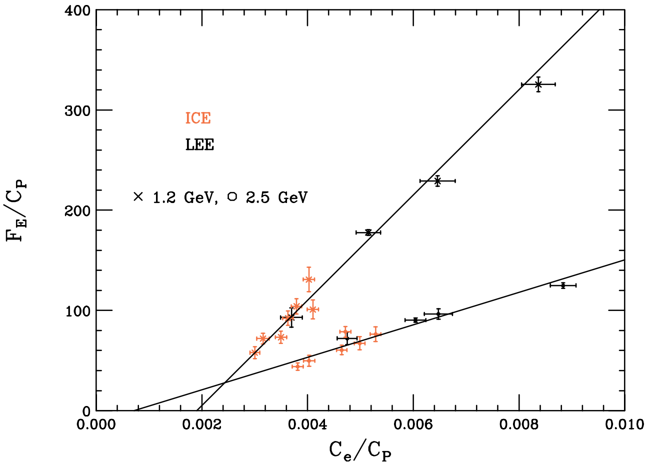

Figure 1. Relation of 1.2 GeV and 2.5 GeV electron fluxes observed at Earth by LEE and ICE to Ulysses electron channel counting rates. Solid lines are linear least squares fits to the data. Relative normalization of the LEE and ICE data sets was adjusted to minimize the chi square of the linear fits.

ious selection criteria and corrections were applied to the observations. ICE data were normalized by a uniform 5% at 1.2 GeV and 20% at 2.5 GeV to improve consistency with LEE observations since LEE features better electron energy resolution and stronger proton rejection. For the sake of brevity, we refer to any data taken near 1 AU in the ecliptic plane as taken "at Earth".

[5] Due to the orbit of Ulysses, a time offset was applied to the Ulysses data to reduce potential systematic effects caused by solar phenomena such as high-speed streams emanating from coronal holes. The offset was determined as the time difference between the intersection of Earth and Ulysses trajectories with Parker spiral field lines originating from the same longitude on the solar surface. The time offset marked the mid-point of a 27 day average of the Ulysses data.

[6] At first sight it seems to be a very difficult task to disentangle temporal and spatial effects. Fortunately, the changes caused by solar activity, latitude and radial distance do not occur in phase, so that careful selection from the nearly 11 years of observation available allows us to draw some conclusions about both the correction and the spatial gradients of electrons. To derive the correction and overall normalization we use observations when Ulysses was close to the ecliptic plane (<30 degree) and at radial distances between 4.4 and 5.4 AU. In this latitude range observed latitudinal gradients G_θ for protons and electrons are negligible [*Heber et al.*, 1996a, 1996b, 1999; *McKibben et al.*, 1996].

[7] If we assume that the proton contamination of the electron channels is linearly related to the counting rate of the proton channel, and is independent of modulation level, we can determine the true electron count rate C at Ulysses by subtracting the fraction of protons tagged as E300 events.

$$C = C_e - \beta \cdot C_p \tag{1}$$

where C_p is the observed counting rate in the P4000 channel and C_e is the observed counting rate in the E300A or E300B channel. We choose only measurements close to the ecliptic with a small radial variation, therefore the count rates at Ulysses and the flux at Earth should be linearly related

$$F_E = \alpha \cdot C = \alpha \cdot (C_e - \beta \cdot C_p) \tag{2}$$

where F_E is the electron flux at Earth. Note that the contamination correction is based on the P4000 counting rate observed at Ulysses only.

[8] The above equation can be re-written as

$$\frac{F_E}{C_p} = c_1 \frac{C_e}{C_p} + c_2 \tag{3}$$

where $\alpha = c_1$ and $\beta = -c_2/c_1$. Figure 1 shows a plot of $\frac{F_E}{C_p}$ against $\frac{C_e}{C_p}$. A linear least squares fit yields a β value of $(1.91 \pm 0.07) \times 10^{-3}$ for 1.2 GeV and $(7.2 \pm 1.0) \times 10^{-4}$ for 2.5 GeV. Figure 2 displays the derived contamination parameters graphically.

[9] Estimates of the contamination parameter can also be derived from Monte Carlo instrument simulations based on proton and electron spectra measured at Earth during periods of minimum and maximum modulation (Heber et al. manuscript in preparation, 2002). Results of the simulation, also shown in Figure 2, are systematically higher, but in good agreement with the empirical results. It is also interesting to note that (within errors) the values determined for different modulation epochs are consistent with each other, suggesting independence of the modulation level at the ≈5% level. The derived parameters can then be used to correct the Ulysses observations using equation 2. We refer to the corrected fluxes at Ulysses as F_U.

[10] We now proceed to incorporate other available data into the analysis to determine what might be learned about electron gradients. All available data are shown in Figure 3 (1.2 GeV) and Figure 4 (2.5 GeV). In addition to the data used in Figure 1, we include all available LEE and ICE data, as well as data from CAPRICE [*Boezio et al.*, 2000] and AMS [*Alcaraz et al.*, 2000]. For completeness we also show

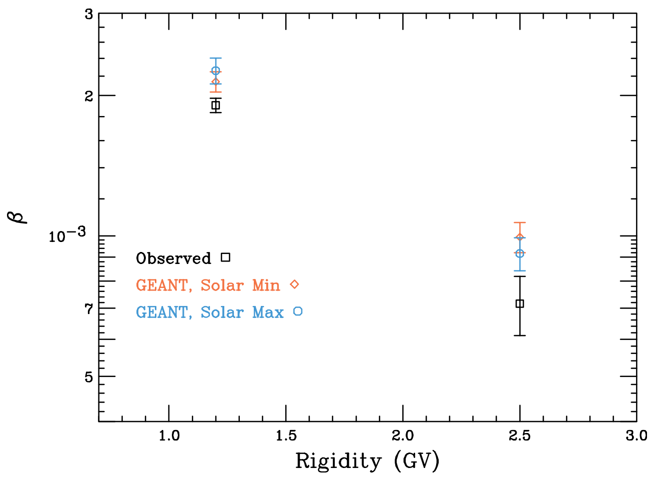

Figure 2. Proton contamination parameter β derived from simulation and observations. Blue circles represent simulations of solar maximum conditions while red diamonds were determined for solar minimum. Black squares represents observations.

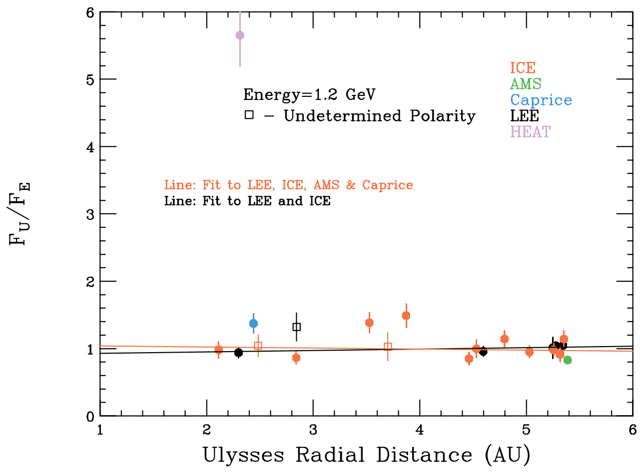

Figure 3. Ratio of corrected 1.2 GeV electron flux at Ulysses to observations at Earth as a function of Ulysses radial distance from the sun. The black line is a linear least squares fit to the solid LEE and ICE points. The red line represents the resulting fit to the data set that includes CAPRICE and AMS observations. The slope is a direct measurement of the radial gradient. The fits were restricted to data obtained when the heliosphere was clearly in the A^+ state.

data obtained from HEAT [*DuVernois et al.*, 2001]. However because the HEAT measurements seems so out of line with the rest of the data, we have not used the HEAT observations in our quantitative analysis. Because the normalization was derived from the cluster of points around 5 AU, the average value of the flux ratio at this distance is approximately one, as expected. Gradients would emerge as deviations from 1.0 as Ulysses moves about in the inner heliosphere. It is clear that the gradients are not large, but the scatter of points is large, particularly at 1.2 GV. This is highly reminiscent of the behavior of gradients inside 5 AU determined (for positive particles) by *Fujii and McDonald* [1997].

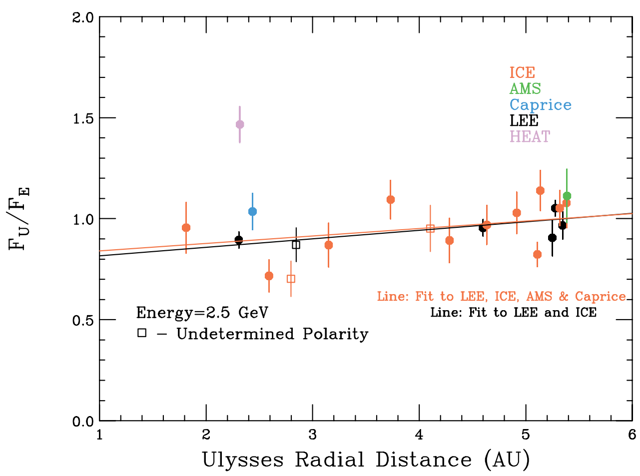

Figure 4. Ratio of corrected 2.5 GeV electron flux at Ulysses to observations at Earth as a function of Ulysses radial distance from the sun. The caption for Figure 3 gives a description of the fits.

[11] To put quantitative constraints on the gradient, we test specifically for a constant, nonlocal radial gradient in the electron flux, G_r, defined by

$$\frac{F_2}{F_1} = \exp\left(G_r(\mathrm{r}_2 - \mathrm{r}_1)\right) \tag{4}$$

where F_1 and F_2 are the fluxes two locations r_1 and r_2 from the sun and G_r is the nonlocal radial gradient.

[12] Since the normalization parameters for Ulysses electrons were determined at an average radial distance from the sun of 4.9AU it is straightforward to show that the relationship between the (possibly improperly) corrected flux at Ulysses and the flux at Earth is (if the gradient is assumed to be small)

$$\begin{aligned}\frac{F_U}{F_E} &\approx 1 + G_r \cdot (\mathrm{r}_U - 4.9) \\ &\approx G_r \cdot \mathrm{r}_U + 1 - 4.9 \cdot G_r \\ &\approx a \cdot \mathrm{r}_U + b\end{aligned} \tag{5}$$

where a and b may be derived from fits to the data and the relation inverted to yield estimates of the gradients.

3. Results and Conclusions

[13] Figures 3 and 4 display the ratio of corrected 1.2 GeV and 2.5 GeV electron flux at Ulysses to observations at Earth as a function of r_U. Black straight lines were fitted to the LEE and ICE data measured during the A^+ cycle. For comparison, the red lines were fitted to all observations (CAPRICE, AMS, LEE and ICE). These fits yield gradients that are consistent with those derived from the black lines. Gradients derived from LEE and ICE are compared to previous results in Figure 5. We find that the gradient for electrons is indistinguishable from that for positive particles measured at the same time and also in the 1970s. Since the electron gradients

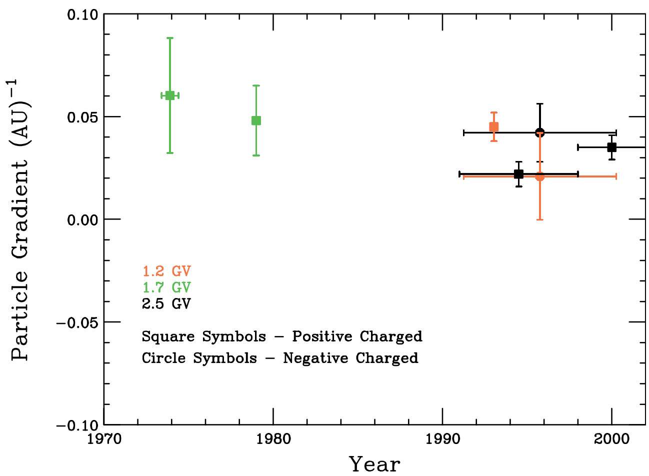

Figure 5. Summary of particle radial gradients determined from data obtained within 6AU of the sun from prior studies [*McDonald et al.*, 1997; *Fujii and McDonald*, 1997; *Heber et al.*, 2002] and the present analysis using only LEE and ICE data. Square symbols denote gradients of positive charged particles while circle symbols denote gradients of negative charged particles. Red indicates 1.2 GV, green 1.7 GV and black 2.5 GV.

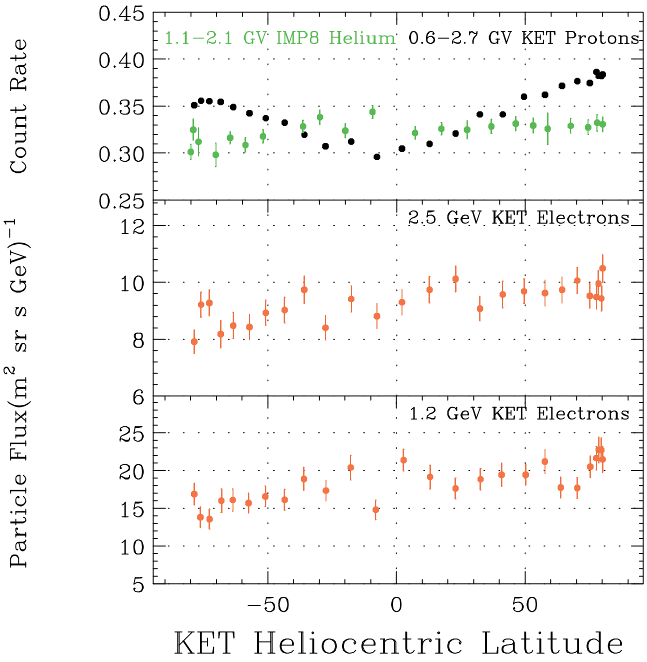

Figure 6. Dependence of particle fluxes on heliolatitude during the fast latitude scan of Ulysses. Proton and electron measurements were made at Ulysses, while the alpha particles were measured by IMP-8.

were measured during an A^+ solar polarity state this is also the first determination of inner heliosphere gradients for particles in a polarity state opposite to their charge sign. There were no spacecraft at appropriate distances to do the corresponding measurement for positive particles in the 1980s.

[14] We performed a similar analysis searching for latitude gradients in the electrons. For both energies the result was consistent with zero, but the statistics suffered from a lack of a time continuous reference at Earth. Fortunately the fast latitude scan of Ulysses provides a way to illustrate that the gradients are in fact consistent with zero without relying directly on a reference instrument. In Figure 6 we show the counting rate of 2.5 GV protons at Ulysses, together with the corrected fluxes of 1.2 and 2.5 GeV electrons from our analysis. For reference, we show the counting rate of alpha particles of similar rigidity measured by IMP-8. The Ulysses protons show a clear dependence on latitude, while the 2.5 GeV electrons show only the slow rise also seen in the alpha particles due to the general modulation recovery. At 2.5 GeV, these results are fully consistent with earlier publications [*Heber et al.*, 1996b]. Our current work has made slight improvements in the background correction, and has produced calibrated electron fluxes instead of counting rates, but the basic result has been reported for some time. The new aspect of the current work is the observation that there is no apparent gradient in the 1.2 GeV electrons either. One may have expected to see some difference in the gradient of 1.2 GeV electrons, because they have been observed to have much larger, and less regular temporal variations when compared with those of electrons at 2.5 GeV [*Clem et al.*, 2000]. There is some evidence of this tendency to larger fluctuations in Figure 6, and indeed even the hint that it may be more pronounced near the heliographic equator.

[15] In summary, we have made the first determination of the radial gradient of cosmic ray electrons in the heliosphere at rigidities of 1.2 and 2.5 GV from 1 to 5 AU. The electron radial gradients appears to be the same as those for positive particles of the same rigidity. Unfortunately, lack of the ability to study time evolution greatly hampers interpretation of our results. As with previous work on positive particles, electron radial gradients within 5 AU are not particularly well defined at a given time. Even though the radial gradients appear similar for positive and negative particles, there is no evidence for a latitude gradient in electrons, whereas protons of comparable rigidity exhibit a clear deficit of particles at the helioequator.

[16] **Acknowledgments.** B. Heber is grateful to the Deutsche Forschungsgemeinschaft for financial support. The ULYSSES/KET project is supported under grant No. 50 ON 9103 by the German Bundesminister für Bildung und Forschung (BMBF) through the Deutsches Zentrum für Luft- und Raumfahrt (DLR). Supported in part by NSF Grant ATM-0000745. IMP8 GME data were obtained from R.E. McGuire, Head, Space Physics Data Facility, NASA/Goddard Space Flight Center.

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