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Cassini Plasma Spectrometer observations of bidirectional lobe electrons during the Earth flyby, August 18, 1999

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Abstract. Unlike previous missions to the magnetotail (IMP 6, ISEE 1, ISEE 3, and Geotail), which effectively made observations in the lobe at a single downtail distance, the Cassini Earth swingby allowed, for the first time, near-continuous observations covering a range of downtail distances. Bidirectional electrons are found in the northern lobe, consistent with previous studies. Enhancements in the electron fluxes are seen in a boundary layer between the lobe and sheath. These enhancements are accompanied by enhancements in ion fluxes traveling tailward. We also present what we believe to be the first observations of a returning electron population in the magnetosheath. Bidirectional electrons are observed upto 0.02 keV, while at higher energies only unidirectional electrons are observed. The low energy of the returning electrons arises as a result of the electron populations' passage through the magnetopause twice and losses due to precipitation.

1. Introduction

The first observations of bidirectional electrons made in the tail were those of IMP 6 [*Hada et al.*, 1981]. *Hada et al.* [1981] identified three types: distant magnetotail ($\sim$20 R_E downtail), near-nightside magnetopause ($\sim$20 R_E downtail), and near-Earth plasma sheet events ($\sim$10 R_E downtail). The distant magnetotail events were explained by Fermi acceleration. The near-Earth plasma sheet events were suggested to have originated in the ionosphere. They were thought to have been accelerated by electric fields and were likely to be the same phenomena as those seen by the Active Magnetospheric Particle Tracer Explorers (AMPTE)/CCE [*Klumpar et al.*, 1988] and the Combined Release and Radiation Effects Satellite (CRRES) spacecraft [*Johnstone et al.*, 1994; *Abel,* 1999]. The near nightside magnetopause events were seen until IMP 6 crossed the magnetopause and were not explained in the discussion.

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The origin of bidirectional electrons in the lobe (the events labeled near-nightside magnetopause in the above discussion) was first suggested by *Fairfield and Scudder* [1985], based on ISEE 1 observations ($\sim$10 R_E downtail). They found that bidirectional electrons in the lobe had the same dependence on the interplanetary magnetic field (IMF) direction as polar rain; that is, they both tended to occur in the northern(southern) polar cap/lobe when the IMF was in the away(toward) sector. On the basis of this fact, they suggested that the source of polar rain electrons is the Strahl component of the solar wind. This direct entry mechanism has remained largely unchallenged since.

Baker et al. [1986] made the first observations of bidirectional electrons in the deep tail (>20 R_E, sometimes >150 R_E) with ISEE 3. They found that bidirectional electrons are predominantly a feature of the lobes in the distant tail. These observations confirmed the findings and ideas put forward by *Fairfield and Scudder* [1985]. *Baker et al.* [1987] made a direct comparison between ISEE 3 observations of field aligned spectra made in the lobe and Defense Meteorological Satellite Program (DMSP) spectra of polar rain electrons. Ten periods of continuous counterstreaming lobe electrons were selected and compared to multiple passes of DMSP over both north and south polar caps. The suprathermal (>200 eV) components of the energy spectra at ISEE 3 and DMSP were generally found to have the same slope (with the absolute differences between spectra explained by a lack of intercalibration between instruments). The thermal component (<200 eV) was found to be much more intense at ISEE 3 than the similar component at DMSP. This difference was explained by the local entry of sheath plasma in the deep tail. *Greenspan et al.* [1986], in a similar study in the near tail using ISEE 1 data, did not find the low-energy population, suggesting that the near tail is relatively devoid of locally entered plasma (i.e., not that which crossed the magnetopause in the distant tail).

Geotail observations [*Baker et al.,* 1997] provided for the first time ion measurements at the time of bidirectional lobe electrons. *Baker et al.* [1997] found that enhancements in bidirectional electrons are accompanied by enhancements in the ion population. The ion population consisted of both magnetosheath origin ions and a ~10 keV O^+ ion population thought to be ionospheric in origin. All ions were observed to be moving tailward and roughly (though not exactly) field-aligned. The low-energy sheath ions are thought to enter the lobes in a similar way to the electrons; however, their high momentum stops them traveling back upstream to the Earth as electrons do. More recently, *Shirai et al.* [1998] have suggested that the direct entry mechanism is not the whole story. They found that both ion and electron fluxes are reduced as the spacecraft crosses the magnetopause, though the ions more so than the electrons.

What all of the observations discussed above share is the fact that they were all made on board spacecraft orbiting the Earth. At large orbital distances, spacecraft velocity is very low. Observations are made at an essentially stationary downtail distance, with motion in the *y-z* GSE plane, provided by the flapping motion of the tail itself. The Cassini flyby provides a unique view, with the spacecraft traveling ~9.1 R_E hour^{-1}, roughly downtail. The flyby has yielded near-continuous lobe observations covering downtail distances of ~30 - 60 R_E.

As well as the direct observations of bidirectional lobe electrons detailed above, there is also a body of work which compares observations of the solar wind and Strahl properties outside of the magnetosphere directly to polar rain observations at low altitudes. Recent work includes that of *Farrugia et al.* [2000] and *Ogilvie et al.* [2000] who showed intensifications in both the Strahl population and the polar rain in response to a very tenuous solar wind. While these observations help to support the direct entry of Strahl as the source of polar rain, they are not directly concerned with the intermediate processes and the exact nature of the entry of polar rain electrons into the magnetosphere.

2. Instrumentation

The Cassini Plasma Sspectrometer (CAPS) consists of three sensors: the ion beam spectrometer (IBS), the ion mass spectrometer (IMS) and the electron spectrometer (ELS). An overview of the instrument is given by *Young et al.* [1998]. The data presented here are taken from the latter two sensors. The IMS consists of a toroidal top-hat analyzer energy-per-charge and incident angle analysis section, in tandem with a three-dimensional linear electric field time-of-flight analyzer which provides mass discrimination with a resolution of $m/\Delta m$ of >50 for singly charged ions up to 15 keV (and $m/\Delta m$ of 8 above 15 keV). The angular acceptance is a fan 11° x 160° split into eight anodes each of 20°. The IMS covers the energy range 1-50,000 eV/q in 63 quasi-logarithmic steps with a complete energy sweep taking 4 s. Full details of the IMS are given by *Nordholt et al.* [1998]. The ELS is a hemispherical top-hat analyzer based on the High Energy Electron Analyzer (HEEA) of the Cluster Plasma Electron And Current Experiment (PEACE) [*Johnstone et al.,* 1997]. It has a 5° by 160° fan field of view (FOV), orientated similarly to that of the IMS. The ELS FOV is split into eight anodes each of 20°. ELS covers the energy range 0.6-27,000 eV in 63 quasi-logarithmic steps with a complete energy sweep taking 2 s. Full details of the ELS are given by *Linder et al.* [1998]. The CAPS sensors FOV and spacecraft coordinate system (X_s, Y_s, Z_s) are illustrated in Figure 1.

Cassini is not a spinning spacecraft, and so in order to increase the amount of the sky sampled by the CAPS instruments, the sensors are mounted on an actuator. This actuator rotates the sensors FOVs around Z_s. During the Earth flyby the actuator was sweeping between ± 60° around $-Y_s$ at ~1°s^{-1} (compared to a maximum operational range of ± 104°). The range of pitch angles observed by ELS depended on the relative orientation of the magnetic field to the spacecraft, with a minimum of 85° and a maximum of 180°.

3. Observations

An overview of the ELS observations can be found in the work of *Rymer et al.* [this issue]. This paper concentrates on the period ~2-8 hours after closest approach (which occurred at 0328 UT August 18, 1999). The position of the spacecraft during this period is shown in Figure 2. During these 6 hours, Cassini traveled from 20 R_E downtail to ~70 R_E downtail. Throughout the Earth flyby, Cassini is oriented such that the large antenna dish is directed at the Sun, so as to protect the instrumentation. This meant that Z_s (see Figure 1) was pointed downtail. Prior to 0600 UT on August 18, 1999, the spacecraft was orientated such that X_s was pointed roughly south and Y_s was pointed roughly east. Between 0600 and 0700 UT the spacecraft performed a roll such that X_s now pointed roughly east and Y_s now pointed roughly north. We will also present some supporting observations made by ELS when Cassini was located in the magnetosheath further downtail.

Plate 1 shows the electron data collected by the ELS during this interval. This figure is made up of 63 horizontal bands, separated by a white line, each relating to an individual energy level as indicated by the y axis. Within each band the pitch angle distribution is shown running from 0° at the bottom to 180° at the top of

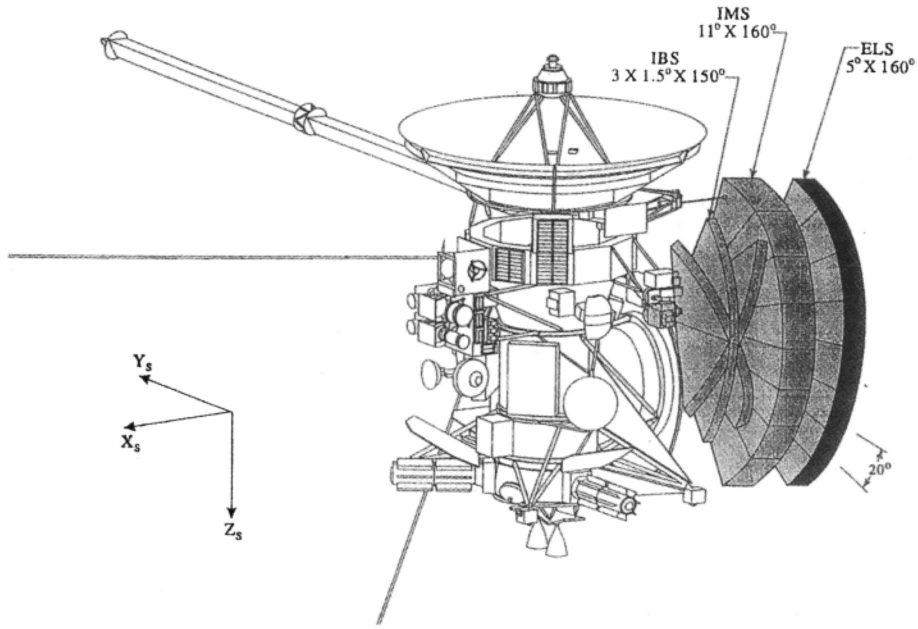

Figure 1. The Cassini spacecraft and Cassini Plasma Spectrometer (CAPS) instrument fields of view (FOVs). IBS, ion beam spectrometer; IMS ion mass spectrometer; ELS, electron spectrometer.

each band, with a time resolution of 128 s. The average counts per accumulation time (23.4375 ms) are indicated by the color scale, with gray indicating regions of pitch angle space not sampled by the instrument. Two-s magnetic field data from this interval are shown in Figure 3.

Each pitch angle distribution is calculated for data acquired over 64 energy sweeps (128 s). Fifteen 12° wide pitch angle bins are used covering the full pitch angle range from 0° to 180°. For each measurement the pitch angles covered by each anode are calculated using 2-s magnetic field measurements taken from the on-board magnetometer. The intensity in each pitch angle bin is then calculated by performing a weighted average of all the measurements in the averaging period according to the proportion of the anode looking at the relevant pitch angles at the time each measurement was made.

It must be remembered that the resultant pitch angle distribution is not necessarily true to life, and a number of factors must be considered. The basic resolution of the sensor is still 5° by 20°, and while the weighted average allows us to refine the resolution somewhat, it is still controlled by the basic resolution of the instrument. Firstly, if a very narrow feature (<1° wide in pitch angle) existed, its effect will be spread over the entire anode (up to 20° in pitch angle depending on

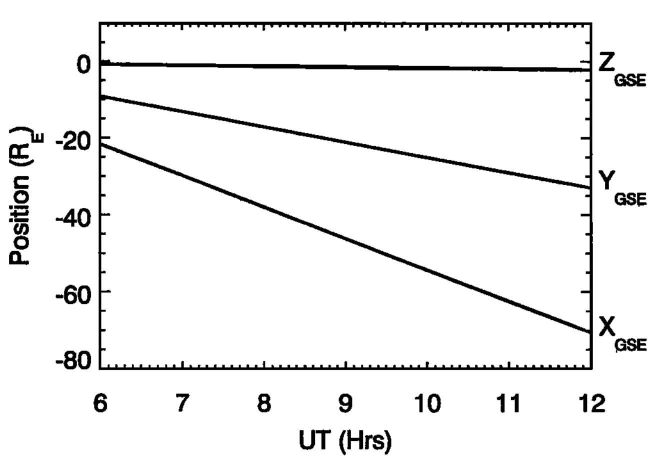

Figure 2. The position of the Cassini spacecraft between 0600 and 1200 UT, August 18, 1999, in GSE coordinates.

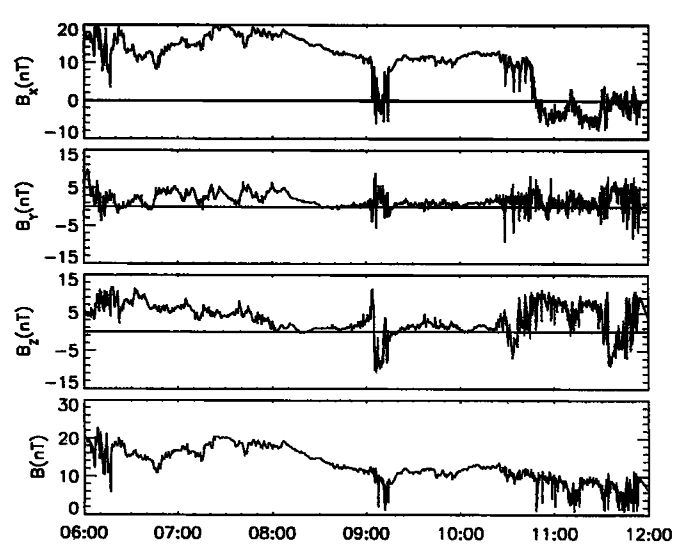

Figure 3. Two-s data from the Cassini magnetometer covering the period shown in Plate 1.

the orientation of the magnetic field). Secondly, we do not always measure all pitch angles represented in the defined pitch angle bins, and so we may miss narrow features at the extremes of our measured pitch angle range. Finally, it must be remembered that this averaging technique averages over all gyrophase seen. The amount and range of gyrophase seen will vary a great deal for the different pitch angle bins, owing to the way in which the sky is sampled. To clarify how features in this plot (and others of the same form) should be viewed the following points should be considered:

1. The width, in pitch angle, of any feature should be viewed as an upper limit. The width may, in extreme cases, be smoothed over as much as 20°.

2. The pitch angle bin at the edge of the FOV is suspect and may be ignored if it does not follow the general trend. However, the pitch angle bins at 0° and 180° are far more likely to contain realistic values.

3. Nongyrotropic features are not adequately represented. This does not appear to be of concern discussed in this paper (i.e., they are gyrotropic); however, there are features in the data set which are non-gyrotropic (e.g., the beam feature seen between 0400 and 0500 UT [*Rymer et al.*, this issue]).

Initially, Cassini is flying through the plasma sheet. Plasma sheet electrons are seen in Plate 1 at energies 0.1-10 keV peaked at 0° pitch angle. The positive B_x shown in Figure 3 indicates that the magnetic field is orientated toward the Earth (northern tail). The intense low-energy (<0.01 keV) electrons are photoelectrons, whose properties are seen to change throughout the flyby with the natural plasma environment. At around 0730 UT a substorm occurs [*Khan et al.*, this issue]. The resultant thinning of the plasma sheet finds Cassini in the northern lobe (we have identified this as the northern lobe due to the positive B_x component). Here we see bidirectional fluxes from 0.02 to 0.09 keV identified by the green stripes at the top and bottom of each band. At higher energies (>0.09 keV) the electrons are seen traveling earthward only. Above 0.3 keV no significant fluxes of electrons are seen. The bidirectional electrons seem to extend below 0.01 keV into the energy range dominated by the photoelectrons. The photoelectrons are almost certainly a nongyrotropic feature, and combining these two populations has resulted in some strange pitch angle structures, which should be disregarded.

After ~10 min, Cassini returns to the plasma sheet, where we again see predominantly earthward moving electrons. At 0800 UT, Cassini reenters the lobe, where it remains (with the exception of a short excursion into the magnetosheath at 0904 UT) until 1047 UT, after which Cassini enters the magnetosheath, never to return to the Earth's magnetosphere. The magnetopause crossings at 0904, 0914, and 1047 UT can be seen clearly in the magnetic field data (Figure 3) as a clear rotation of the field direction. The field rotations associated with Cassini's passages through the magnetopause have distinct signatures in Plate 1. Because of the operation of CAPS, the field rotation results in a change in the range of pitch angles sampled by ELS. This can be seen in Plate 1 as a change in pitch angle bins colored gray. Throughout the lobe observations, bidirectional electrons are seen in the energy range 0.01 to 0.2 keV. A number of intensifications of the field-aligned electron fluxes are seen. When the intensifications occur, the bidirectional fluxes are observed to extend to higher energies (>0.3 keV). It is likely that bidirectional electrons existed at higher energies but with flux levels below the sensitivity of the ELS. The intensification of such fluxes may have allowed them to be observed.

The ion data recorded by the IMS are shown in Plate 2. This plot is of the same format as Plate 1 but showing only 16 energy bins. Through the majority of the 0600-1200 UT period, IMS was operating in a mode such that the data telemetered to Earth were averaged over four adjacent energy channels. For the small time when IMS telemetered full energy resolution, we have performed a similar averaging. It is not strictly fair to represent the ion distribution in terms of pitch angle as often their velocities are dominated by the convection of the plasma (unlike electrons of similar energy, but much lower mass). However, this allows us to get some understanding as to what direction the ions are moving in. Unfortunately, the actuator motion during the Earth flyby does not allow a more traditional 360° cut through velocity space.

The most obvious feature in Plate 2 is that counts are very low (when present). This is because the IMS was not operating at full gain, in order to save the detector for use in the Saturnian system. The features seen in the IMS data map very well to those seen in the ELS data. Initially, we see plasma sheet ions moving earthward (0° pitch angle). While in the lobe we see, though not continuously, ions at 180°, i.e. moving tailward, with energies between 0.1 and 2 keV. When Cassini is traveling through the magnetosheath (clearly identified by the lack of coverage in pitch angle), we see ions at ~90°. This simply corresponds to ions moving tailward, convecting with the magnetic field.

Unfortunately, owing to the rotation of the field, and the FOV of ELS immediately after crossing the magnetopause, we cannot observe the 0° pitch angle particles, and a direct comparison between the sheath and lobe electrons is difficult. Plate 3 shows, in the same format as Plate 1, ELS data taken between 1800 and 2400 UT on the same day. Throughout this period, Cassini is located in the magnetosheath and presents a number of intervals during which both 0° and 180° pitch angle electrons are observed.

The interval shown in Plate 3 demonstrates that the sheath population is very varied, though this impression is compounded somewhat by the continual change of pitch angle coverage. However, a fairly consistent picture does emerge, which is best illustrated by the fairly steady interval between 1935 and 2010 UT, though the

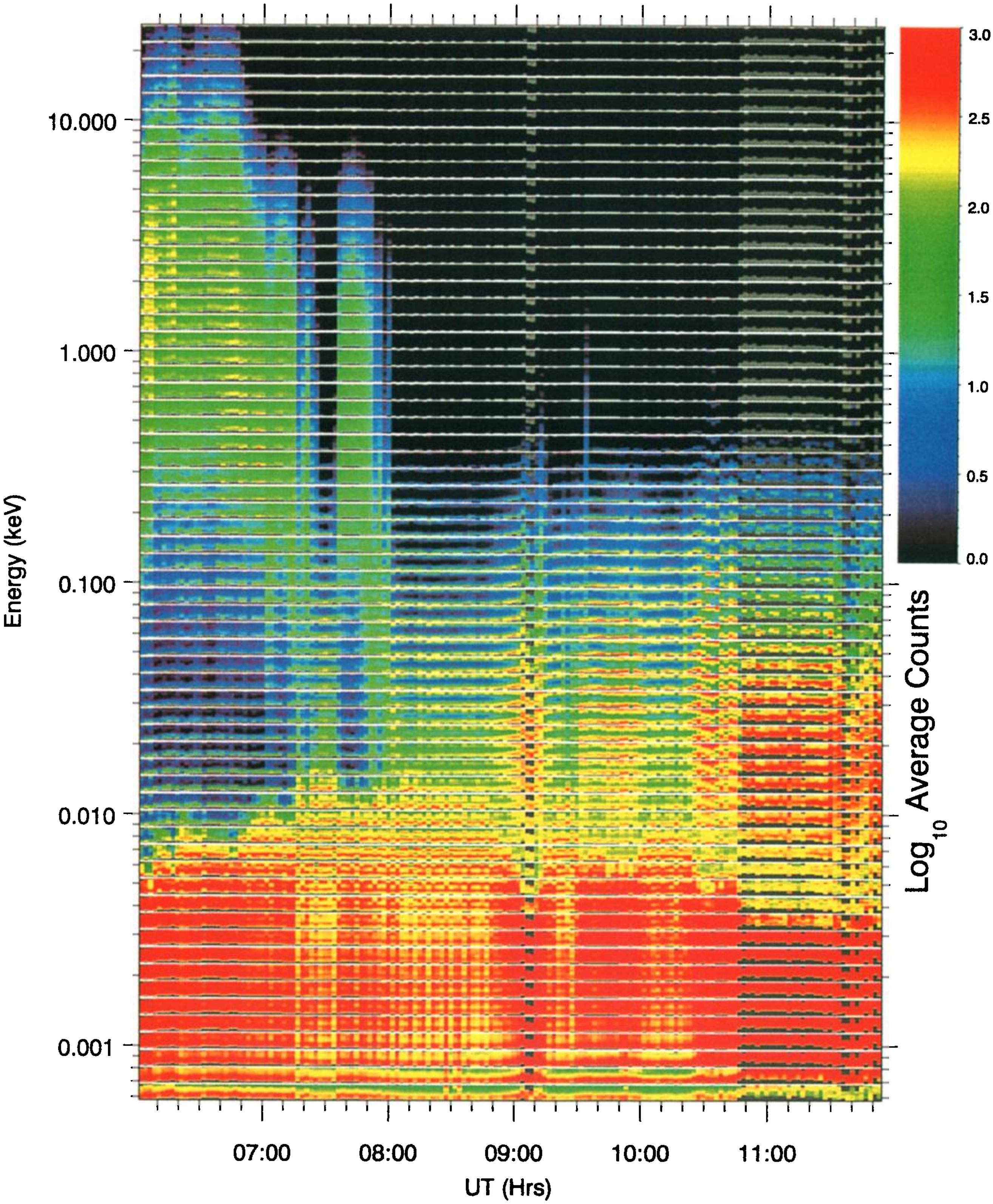

Plate 1. Data from the ELS from the period 0600 - 1200 UT, August 18, 1999. Full details of the plot are given in the text.

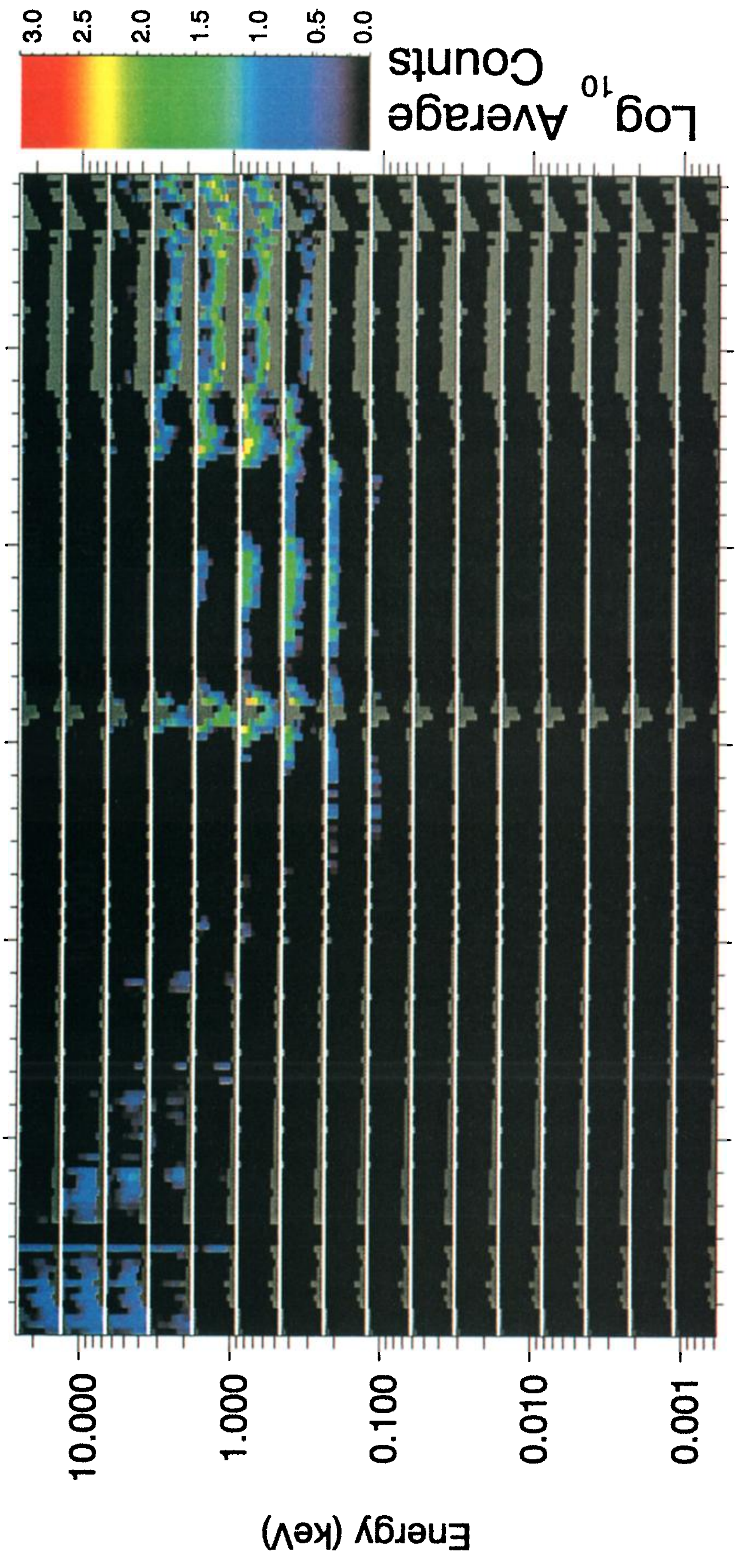

Plate 2. Data from the IMS from the period 0600 - 1200 UT, August 18, 1999. Full details of the plot are given in the text.

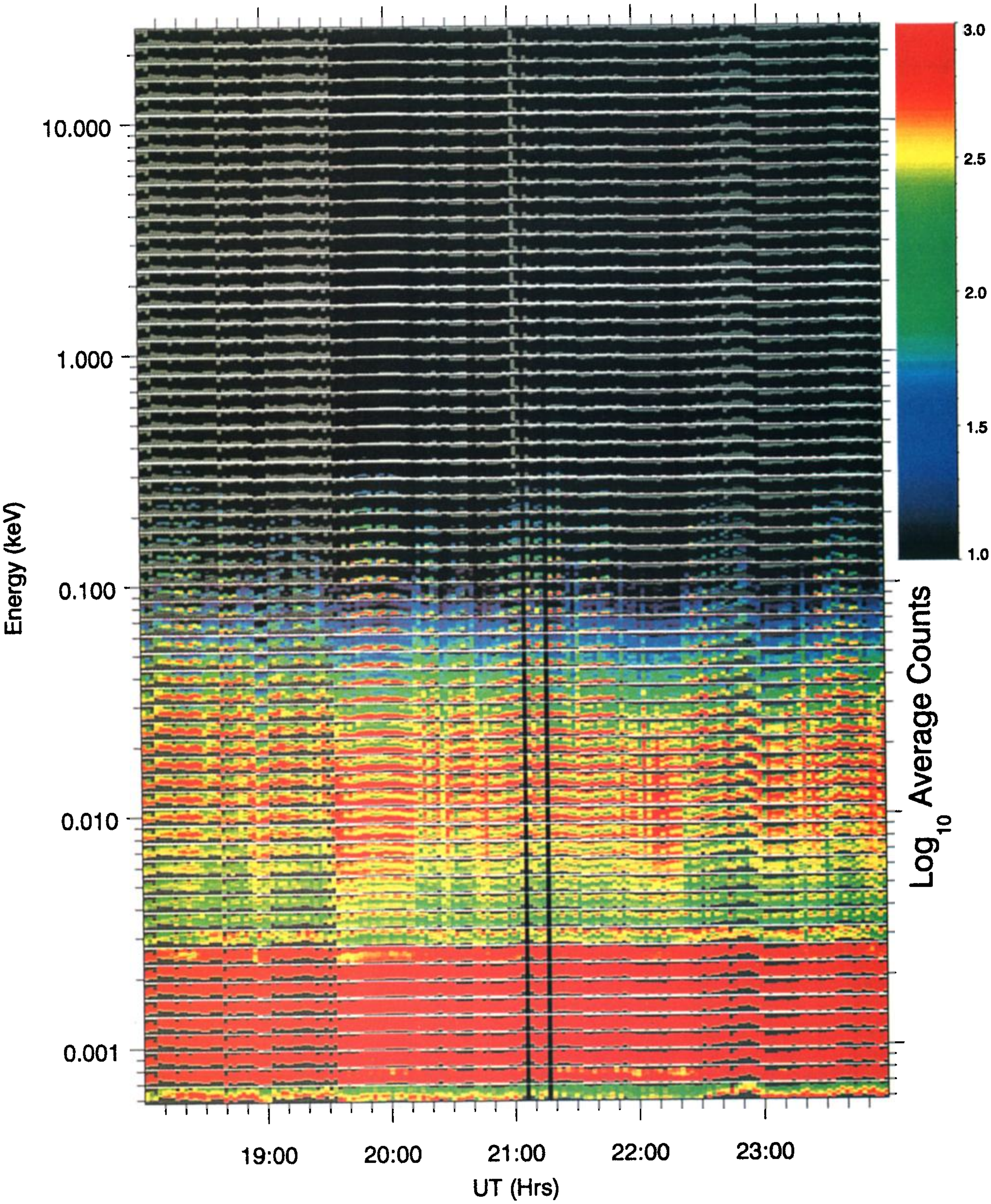

Plate 3. Data from the ELS from the period 1800 - 2400 UT, August 18, 1999. Full details of the plot are given in the text.

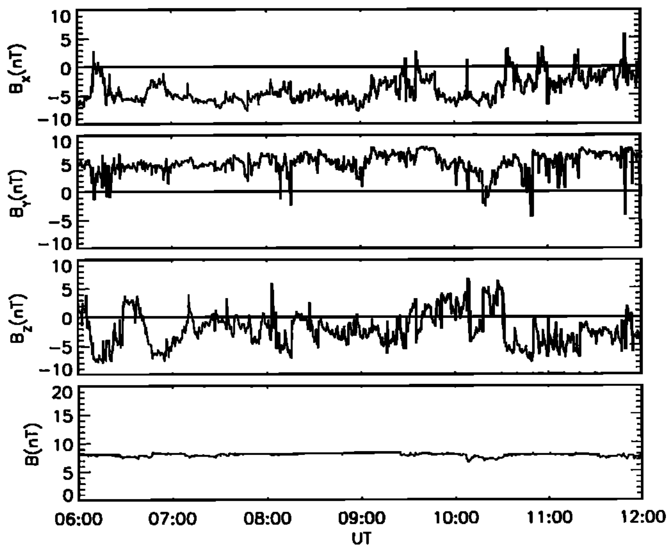

Figure 4. Interplanetary magnetic field (IMF) data from the ACE spacecraft covering the period 0600 - 1200 UT, August 18, 1999.

features can be seen at many other times (2020, 2030, 2050-2150, 2220, and 2320 UT). What we see are bidirectional electrons up to around 0.02 keV, with the 0° greater than the 180° fluxes (except at the lowest energies). Above 0.02 keV and up to $\sim$ 0.2 keV we see unidirectional electrons at 0° pitch angle.

4. Discussion

Figure 4 shows the IMF data from the Advanced Composition Explorer (ACE) spacecraft for the 0600-1200 UT period. During this period, ACE was situated in the solar wind upstream of the Earth. B_x is negative throughout this period. According to the arguments of *Fairfield and Scudder* [1985] and *Baker et al.* [1986], one would expect to see bidirectional electrons in the northern lobe, which is what we have presented here. Thus, initially, our results seem entirely consistent with previous models.

The final crossing of the magnetopause occurs at 1047 UT, being defined as the time when bidirectional electrons are no longer seen at 0.05 keV and the field rotation occurs. Looking at the magnetic field data in Figure 3, the field rotation can clearly be seen at 1047 UT as the x component of the field changes from positive to negative. However, the field becomes sheath like, in so far as it is more disturbed, some 20 min earlier. This period of disturbed field coincides with a period of enhanced bidirectional electrons and the appearance of tailward flowing ions. In fact, all periods of enhanced electron fluxes are seen when the field is disturbed such as in the sheath, while remaining oriented similarly to the field in the lobe. Also at these times we clearly see intensifications in the tailward moving ions, though the intensification in the ions is seen often as an appearance of ions; that is, the ion fluxes increased to a level that could be measured. It is possible that this enhancement of ion fluxes could simply be due to a change in flow direction which allows the particles to enter the detector. However, the simultaneous enhancement of electron and ion fluxes is in agreement with the previous findings of *Baker et al.* [1997]. How this fits in with the picture of restricted entry of electrons and ions at the magnetopause suggested by *Shirai et al.* [1998] is unclear; however, the enhancements are seen in the electrons traveling in both directions, indicating that these electrons have already mirrored at low altitudes. The field strength at the time of enhanced electron and ion fluxes is generally lower than at other times in the lobe, though by only 1 or 2 nT. It is hard to see how such a decrease in field strength could result in any real or perceived change in flux.

Both *Shirai et al.* [1998] and *Baker et al.* [1986] have shown clear examples of transitions from bidirectional to unidirectional electrons at the magnetopause. *Shirai et al.* [1998] classified these transitions into two types: the first showed rotational features in the magnetic field and the clear entry of the Strahl electron flux, and the second showed a tangential discontinuity and was interpreted as a locally closed magnetosphere. As we have mentioned, the orientation of the ELS FOV at the magnetopause crossing does not allow us to comment on the nature of the discontinuity in this case. We do, however, see bidirectional electrons at low energies (<0.02 keV) in the magnetosheath which have not previously been reported. Figure 5 shows the ACE magnetic field data for the period of ELS data shown in Plate 3. Again we see that B_x in the solar wind is negative throughout this period, and as such, we are in the same regime, as far as polar rain electrons are concerned, as we were when Cassini was in the lobe.

Our interpretation of the sheath observations is thus: The 0° electrons at energies less than 0.3 keV, extending

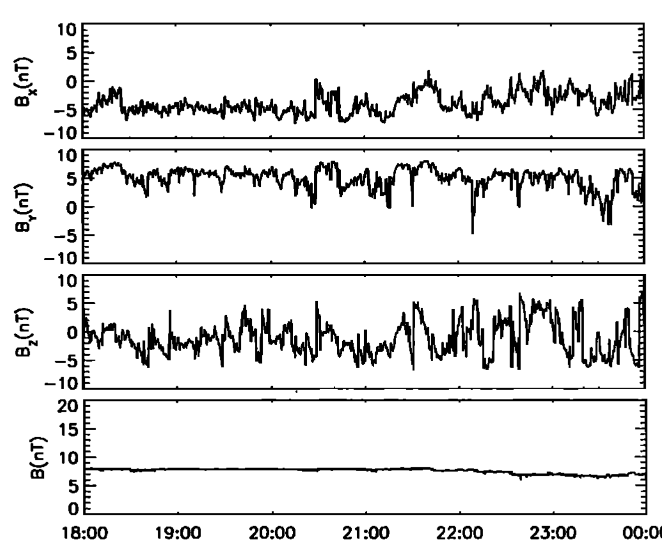

Figure 5. IMF data from the ACE spacecraft covering the period 1800 - 2400 UT, August 18, 1999.

into the photoelectrons, are the source of the polar rain electrons. The 180° electrons at energies less than 0.03 keV have passed through the magnetopause, mirrored at low altitudes, passed back through the magnetopause and are traveling up the field line. The reason that the returning electrons are seen only at much lower energies and at lower fluxes is likely to be due to their two passages through the magnetopause and losses due to precipitation. *Shirai et al.* [1998] found that the energy of electrons was reduced as they passed though the magnetopause from the sheath to the lobe. This was explained through the necessity to retain quasi-neutrality and the electrons entry into the magnetosphere being controlled by the ions. The electrons will then flow down the field line, mirror, and return. The most field-aligned electrons will be lost through precipitation. This will be more significant at higher energies as the source population is increasingly field-aligned at increasing energies. The precipitation of the most field-aligned electrons explains why in Plate 1, the lobe electrons above 0.09 keV are seen only traveling earthward. As the returning electrons again pass through the magnetopause, their energy is again reduced. As the mirrored electrons pass back through the magnetopause, we are presented with a situation where the returning electrons are flowing into a charge neutral plasma (i.e., the solar wind). Again, charge neutrality arguments may come into play. *Shirai et al.* [1998] suggested the reason that they did not observe any returning electrons in the sheath may have been due to a potential barrier such as that employed by *Lockwood and Hapgood* [1997] to explain the transition parameter at the dayside magnetopause and to maintain charge neutrality. We suggest that the returning electrons are present; it is simply that the sensor employed by *Shirai et al.* [1998] did not measure to low enough energies to observe them. However, the idea of a potential barrier could still apply. We have seen evidence in the ELS data set of the low-energy returning electrons in the magnetosheath at distances as far as 270 R_E downtail.

It is difficult to directly compare the sheath and lobe spectra to gain an understanding of exactly what is happening at the magnetopause in this example. Not only are the data we have presented here separated by a large downtail distance (~80 R_E) but also some 10 hours in time. An opportunity to resolve this dilemma may be presented with the Cluster spacecraft. The PEACE instrument is essentially the same in design as that of ELS and operates to energies of 1eV. The fact that there are four cluster spacecraft orbiting the Earth in formation intervals may arise when one spacecraft is located in the lobe, observing bidirectional electrons, while another is simultaneously located in the sheath measuring both the source and returning electron populations. During such intervals it may be possible to directly compare the sheath and lobe electrons.

5. Conclusions

We have presented here the first near-continuous observations of bidirectional lobe electrons, covering a wide range of downtail distances (X_{GSE} =20-60 R_E). These observations are consistent with previous findings regarding the orientation of the IMF X_{GSE} component. We also confirm that enhancements occur in tailward flowing ion fluxes concurrent with enhancements in bidirectional electron fluxes. Our new results can be summarized as follows.

1. We have observed the enhancements in electron and ion fluxes in a boundary layer where the field is sheath like in so far as it is disturbed, while being lobe like in its orientation.
2. We have presented the first observations of the returning electrons in the magnetosheath. These electrons are of a much lower energy than the source electrons, which we suggest is as a result of the electron populations' passage through the magnetopause twice and losses due to precipitation.

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