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Email: gdz@sub.uni-goettingen.de

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Motion of Flux Transfer Events on 10 November 1977 Determined by Energetic Particles on ISEE 2*

P.W. Daly and E. Keppler
Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau 3, Federal Republic of Germany

Abstract. The medium energy particle spectrometer on board ISEE 2 has been used to measure the orientation and motion of the flux transfer events (FTEs) seen at the inbound magnetopause crossing on 10 November 1977. The method used is a simple version of the remote sensing technique using azimuthal asymmetries of ion intensities, that has previously been used to sound the magnetopause. During these events, the particle intensity was high enough that the secondary detectors, looking out of the ecliptic plane, could also be used, in spite of their much lower geometry factors. Only ions with pitch angles near 90° were employed, which eliminates some of the uncertainties of the method. The FTEs are seen to approach the spacecraft from the magnetopause side, with a northward component of velocity, and to retreat towards the magnetopause, also with a northward component. This is consistent with the picture of FTEs as isolated flux tubes in the magnetosheath connected to the magnetosphere which then move poleward to release magnetic tension. The northward motion has earlier been deduced only from the magnetic signature and is observed here directly for the first time. The speed of the FTEs is of the order of 100 km/s, and the size is of the order of an earth radius.

Key words: Magnetopause – Flux transfer event – Energetic particles – Remote sensing

Introduction

Flux transfer events (FTEs) were discovered by Russell and Elphic (1979) in the magnetic data from the ISEE spacecraft during dayside magnetopause crossings. They were first observed in the magnetosheath, near the magnetopause, and were interpreted from the magnetic signature as a localised flux tube connected to the magnetosphere, being pulled poleward (northward in these cases) by the magnetic tension of the bent field line. That FTEs were indeed interconnected to the magnetosheath was confirmed by Daly et al. (1981) who showed that they were accompanied by streaming magnetospheric ions. The direction of streaming indicated connection to the northern hemisphere, consistent with the deduced northward motion. FTEs have since been discovered inside the magnetopause (Daly and Keppler, 1982) and with so-called 'reverse' magnetic signatures, indicative of southward motion (Rijnbeek et al., 1982). Further energetic particle data have been presented by Scholer et al. (1982), as well as plasma and magnetic data (Paschmann et al., 1982), and plasma wave data (Anderson et al., 1982). Modelling of the events by tracing ion trajectories through the magnetopause has been carried out by Speiser et al. (1981) and by Speiser and Williams (1982).

In this work two FTEs from the 10 November 1977 inbound magnetopause crossing are analysed to determine the orientation and motion of the energetic particle boundaries. The method used is that of remote sensing by means of azimuthal asymmetries in the energetic ion intensities. This technique, based on the finite gyro-radii of the particles, was introduced by Kaufman and Konradi (1969) to sound the magnetopause and was first employed using the particle spectrometer on board ISEE 1 by Williams (1979). Further work has been published by Williams et al. (1979) and Williams (1980). Fritz and Fahnenstiel (1982) and Fritz et al. (1982) have used the ISEE 2 instrument to probe the magnetopause, while Andrews et al. (1981) have used the same device to measure plasma sheet motions. Daly (1982) has presented a critique of how the method should be employed at different types of boundaries, using more than one gyro-radius. These criticisms do not apply to the present work, since only ions at pitch angle 90°, and thus at only one gyro-radius, will be analysed.

Instrumentation

The medium energy particle spectrometer on board the ISEE spacecraft is described elsewhere (Williams et al., 1978), but the main points will be summarised here. The primary instrument on ISEE 2 (WAPS, Wide Angle Particle Spectrometer) consists of a silicon surface barrier detector with a geometry factor of 0.01 cm^2 sr to detect ions, looking at a direction 82° to the spin axis. A magnetic field sweeps electrons into separate detectors. The energy threshold for protons is 25 keV, for electrons 20 keV. Four secondary sets of detectors with lower geometry factors (factor of 80) are mounted at 10°, 44°, 136°, and 170° to the spin axis. These detectors are designated NAPS (Narrow Angle Particle Spectrometer) 1, 2, 3, and 4 respectively. Normally the NAPS detectors have too low a count rate to be useful at the outer magnetosphere, but since the events to be discussed here have unusually high intensities, measurements from these detectors will be included in this analysis.

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Offprint requests to: P.W. Daly

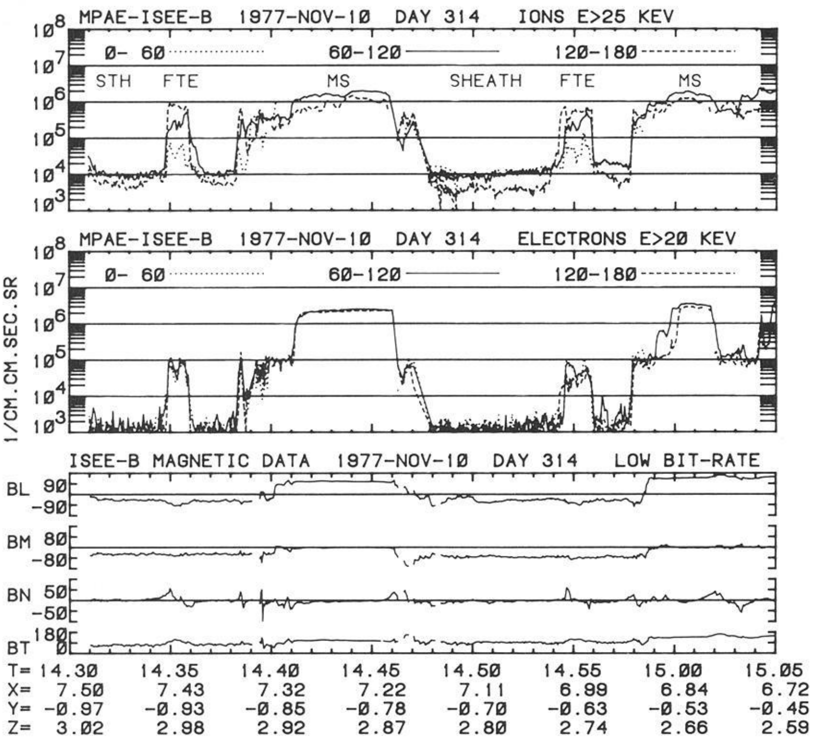

Fig. 1. Ion and electron intensities, in three pitch angle ranges, from the WAPS detector on ISEE 2, plotted against time from UT 1430 to 1505 on 10 November 1977, during an inbound pass of the magnetopause. Also included are the magnetometer data in the boundary normal coordinate system (LMN). *BT* is the magnitude of the magnetic field; *T* is the universal time; *X, Y, Z* are the satellite's GSE coordinates in earth radii

Directional information is obtained by sorting the count rates during one spin (3 s) into sectors, the number of which depends on data format and bit-rate. The number of sectors for the WAPS during the events in this paper is 8. This directional resolution within the spin plane (which is also the plane of the ecliptic) is supplemented by use of the NAPS detectors looking out of the spin plane. The NAPS detectors are not sectored at this time, that is, they yield only one measurement averaged over the entire spin.

Data

Figure 1 shows ion and electron data on 10 November 1977 from UT 1430 to 1505, during an inbound pass of the ISEE 2 satellite. Also shown are the magnetic field data from the U.C.L.A. magnetometers, plotted in the boundary normal coordinate system (LMN) of Russell and Elphic (1979). The spacecraft is in the magnetosheath until UT 1440 ($BL < 0$, marked *STH*), in the magnetosphere until 1447 ($BL > 0$, marked *MS*), is again in the magnetosheath until 1459, when it enters the magnetosphere for the final time. The particle data are from the WAPS detector only, and are divided into 3 pitch angle ranges of width 60° each, plotted as dotted, solid, and dashed lines. The FTEs at UT 1435 and 1455 have the characteristic magnetic signature, where the component normal to the magnetopause, *BN*, goes first positive then negative before returning to zero. There are several other FTEs during this time interval, including one inside the magnetosphere at UT 1502, but only the first two mentioned will be treated in this work. These two events are accompanied by increases in the ion and electron intensities. The ion intensities are close to their magnetospheric values and are greatest in the direction antiparallel to the magnetic field (dashed line highest in upper panel of Fig. 1). The electrons are fairly isotropic and of much lower intensity than in the magnetosphere. They presumably escape from the opened field line much more quickly than the ions, leaving an isotropic background population.

Remote Sensing

What is not shown in Fig. 1 are the azimuthal asymmetries about the magnetic field. That is, at two different directions making the same angle to the magnetic field there can be different intensities observed. This effect is caused by the particle's finite gyro-radius plus a density gradient. As explained by Daly (1982), the particle intensity should be a function only of pitch angle and position of the gyro-center. Particles detected at the spacecraft at constant pitch angle but different gyro-phase angles have different gyro-center locations and can therefore have different intensities. For this work we consider the intensity to be a step function, to be either high or low. Different sectors can switch at different times, allowing us to determine the orientation, and thus direction of motion, of the particle boundary of the FTE.

The direction of the magnetic field in the magnetosheath is essentially along the geocentric solar ecliptic (GSE) *Y* axis, with a small inclination (17°) towards $-Z$ and $+X$. Thus sector 1 of the ISEE 2 WAPS instrument, which looks towards $+X$, sector 5, which looks towards $-X$, the NAPS 1 detector, which looks along $+Z$, and NAPS 4, which looks along $-Z$, are all close to 90° to the field line. The intensities of the ions in these four directions are shown in Figs. 2 and 4, for 5 min intervals covering the FTEs at UT 1435 and 1455, respectively. The various curves have been shifted vertically to separate them, and have been labelled with arrows according to the flow direction of the corresponding particles in the GSE *XZ* plane. With *Z* upwards and *X* to the right, then NAPS 4 detects upward moving particles, WAPS sector 1 observes those moving to the left, WAPS sector 5 those to the right, and NAPS 1 sees those going downwards.

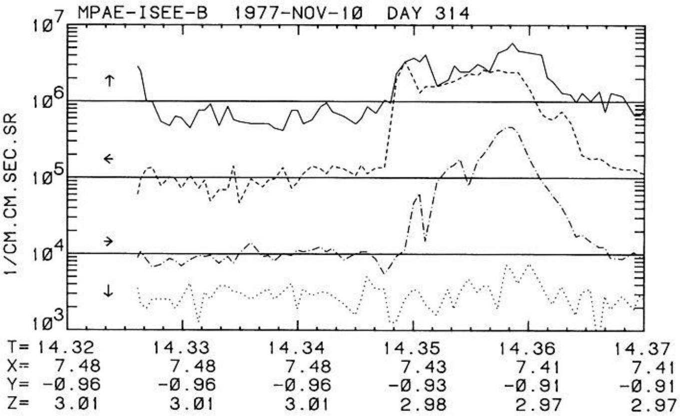

Fig. 2. Ion intensities in four directional channels which look perpendicular to the magnetic field, plotted against time for 5 minutes containing the FTE at UT 1435. The channels are shifted vertically to separate them

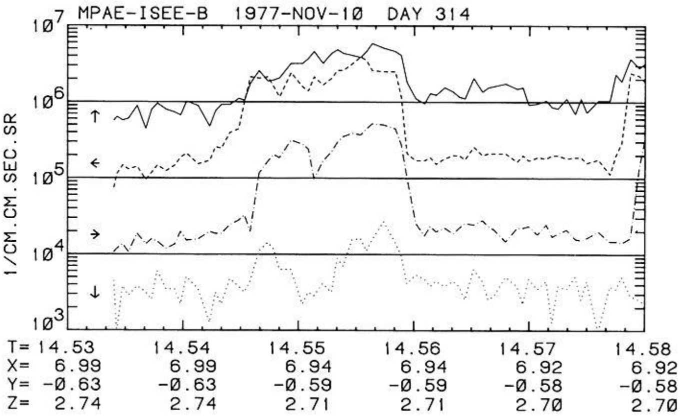

Fig. 4. The same as Fig. 2, but for the 5 minute period containing the FTE at UT 1455

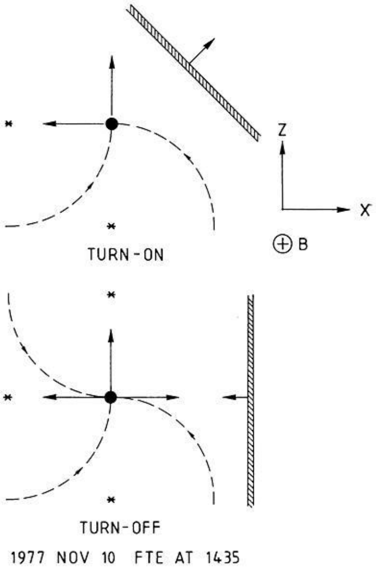

Fig. 3. Representation in the GSE *XZ* plane of those channels which have high intensities at the beginning and end of the FTE at UT 1435, showing also the deduced orientation of the particle boundary

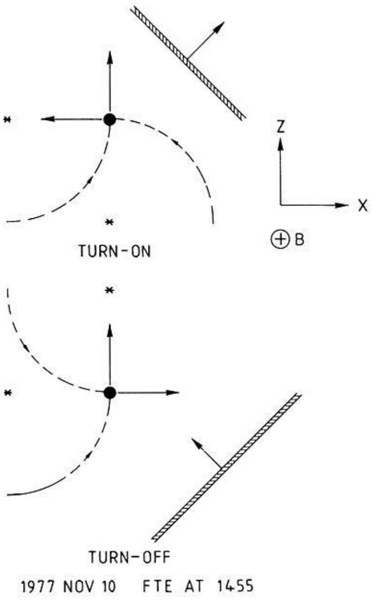

Fig. 5. The same as Fig. 3, but for the FTE at UT 1455

From Fig. 2 it can be seen that for the FTE at UT 1435 the upward and leftward moving ions switch from low to high before the those in the other directions. At the end of the event the upward particles remain high longer, while the left and rightward particles decrease together. These two situations are illustrated in the *XZ* plane in Fig. 3. In the upper part of the diagram the beginning of the FTE is shown, with ions moving upwards and to the left. A quarter of each gyro-orbit is plotted as a dashed line, and the corresponding gyro-centers are marked with a star. The event turns on with particles whose gyro-centers are located below and to the left of the spacecraft; that is, the particle boundary must be oriented from lower right to upper left, as indicated by the shaded bar, and is moving towards the upper right. At the end of the event, the lower part of Fig. 3, the upward moving particles, those with their gyrocenter to the left, persist longest, and those moving left and right, with centers below and above, are lost together. The boundary is vertical, as shown, and moves to the left.

A similar analysis can be performed for the FTE at UT 1455. Figure 4 shows the plot against time of the intensities of the four directions perpendicular to the magnetic field. Again those moving upwards and to the left turn on before the others, and the upward moving particles turn off last. This time, however, the rightward moving ions tend to last one spin longer than the leftward ones. The representation in the *XZ* plane is given is Fig. 5. The upper part is the same as in Fig. 3, but the lower part, the end of the event, has been drawn to reflect the asymmetry between the rightward and leftward moving ions: the boundary is oriented from lower left to upper right and moves to the upper left. The inclination from vertical is perhaps exaggerated.

Discussion

The four directional channels of the ISEE 2 ion detector which are perpendicular to the magnetic field see the onset and end of the flux transfer events at different times, allowing one to determine the orientation of the particle boundary. The determination is very rough, to within half a quadrant in the plane normal to the field, in this case the GSE *XZ* plane. In both cases the event begins with the particle boundary moving along the positive *X* and *Z* axes, that is coming from the magnetopause and from the south. Both events end with the boundary moving along the negative *X* axis (towards the magnetopause), and in the second case at 1455, also along the positive *Z* axis. The *L* axis of the LMN coordinate system (Russell and Elphic, 1979), which is identified as north, is inclined 21° to the left of the *Z* axis. Thus all the boundary motions in Figs. 3 and 5 have a northward component.

Paschmann et al. (1982) have classified both these FTEs as their type A, meaning the field is more southwards during them than in the magnetosheath, contrary to the predictions of the simple picture. Their explanation is that these are shallow penetrations of the events, seeing only the draping of the ambient field outside the reconnected flux tube itself. They point out that this is not consistent with the observation of magnetospheric particles unless these can leak outside. Such a leakage is postulated for the remote sensing method, but such particles must exhibit gyro-phase asymmetries. That particle distributions without such asymmetries are observed at some time during each FTE demonstrates that the reconnected flux tube must have been encountered. For the FTE at 1435, this encounter is about 20 s long, whereas for the one at 1455 it is 60 s. We conclude that the reconnected flux tube was fully penetrated, at least briefly, and that the magnetic field in these events is more complicated than that derived from simple pictures. Certainly the field aligned current which is required to explain the normal component signature (Paschmann et al., 1982; Rijnbeek et al., 1982) would also produce a southward component even fully inside the FTE.

An estimate of the velocity of the events can be made from the size of the gyro-radius and the time of passage of the particle boundary. The average energy of the ions (assuming protons) in the >25 keV integral channel is 37 keV (spectral index during the FTEs is 4, Daly et al., 1981) and the field is 100 nT, which makes the gyro-radius 275 km. From Figs. 2 and 4 one sees that the particle boundary takes roughly 10 s to cross all the channels, a distance of two gyro-radii. The velocity is then of the order of 55 km/s. This however is the velocity along the normal of the boundary surface. If the FTE is moving in the plane of the magnetopause and the particle boundary is inclined 45° to the real direction of motion, then the velocity of the FTE is $55/\sin(45)=78$ km/s. The duration of the FTE is about 2 min, which would mean its physical size is 9,400 km. These calculations are order of magnitude only.

Summary and Conclusions

The particle boundaries of the flux transfer events are seen to sweep over the spacecraft with a velocity of the order of 100 km/s, from the magnetopause and the south, and to retreat towards the magnetopause and to the north. The size of the event is of the order of an earth radius. The original picture of Russell and Elphic (1979), in which FTEs were bloated flux tubes moving northward on the outer surface of the magnetopause, is confirmed by this direct observation of the motion of the associated particle boundaries. This analysis is made possible for the events at the crossing of 10 November 1977 because the ion intensities were high enough for the NAPS detectors to be useful, and because the magnetic field was so oriented that four directional sectors could be found looking perpendicular to it.

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