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Multipoint Reconnection in the Near-Earth Magnetotail: CDAW 6 Observations of Energetic Particles and Magnetic Field

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The Coordinated Data Analysis Workshop (CDAW 6) substorm event at 1054 UT on March 22, 1979, is studied using energetic particle (> 20 keV) data from the medium-energy particle experiment of ISEE 1 as well as high-resolution magnetometer data of ISEE 1 and 2. These analyses cast new light on the structure and temporal evolution of the plasma sheet near 15 R_E during the substorm. These changes are generally consistent with predictions from the near-Earth reconnection model of substorms, modified to include subsidiary plasma and field structure on scales of a few Earth radii. In particular, the onset of streaming flow, nearly aligned with magnetic field lines, of energetic ions and electrons in all available energy channels and its reversal and subsidence are closely correlated with substorm phases. The energetic particles (which are isotropic during the growth phase) begin streaming tailward right after the expansion onset. They reverse their sense of flow in the midexpansion phase. The magnetic field variations suggest that two small magnetic island structures embedded within the plasma sheet moved tailward past the spacecraft shortly after the substorm expansion onset. These structures may be signatures of small-scale multisite reconnection associated with the formation of the near-Earth neutral line. Some magnetic and particle signatures not anticipated in the description of the substorm based on a two-dimensional model of the neutral line are discussed and shown to be reasonable for plausible extensions of the model.

INTRODUCTION

Dynamics of energetic particles in the magnetotail plays an important role in the substorm process. By establishing the relation between observed streaming of particles and substorm phases one may gain understanding of the onset and development of substorms. A substorm selected for intensive analysis in the Coordinated Data Analysis Workshop (CDAW 6) occurred at 1054 UT on March 22, 1979 (see the overview by *McPherron and Manka* [1985, and references therein]). Many characteristics of the event proved basically consistent with the near-Earth reconnection model of substorms [e.g., *McPherron and Manka*, 1985; *Paschmann et al.*, 1985; *Ipavich et al.*, 1985; *Baker*, 1984; *Fritz et al.*, 1984], although some features were difficult to interpret in terms of a single, two-dimensional X line model. By utilizing energetic particle data as well as high-resolution magnetic data which have not been used in previous studies of the event we have interpreted the event using a modified near-Earth reconnection model of substorms that gives plausible interpretations of some previously troublesome features observed in the substorm event.

The CDAW 6 substorm which occurred at the time of equinoctal symmetry is typical of isolated substorms following intervals of magnetic calm. As described in *McPherron and Manka* [1985], a large increase in solar wind velocity and an enhancement of the northward interplanetary magnetic field (IMF) initiated a storm sudden commencement at ~ 0826 UT. At ~ 1010 UT, following a long period of northward B_z, the IMF turned southward for more than 1 hour. About 10 min later (at ~ 1020 UT), the 57 station AE index began to increase. Although the IMF B_z turned southward at ~ 1010 UT [*Baker et al.*, 1985], implying an increase of energy input from the solar wind, a sharp increase in AE values was not seen for more than 40 min, when at about 1100 UT, AE rose from moderate values to more than 1000 nT. Using ground magnetometer measurements and the increase of electron fluxes observed at synchronous orbit, 1054 UT was identified as the onset of the expansion phase of the substorm [*McPherron and Manka*, 1985]. After reaching a peak at ~ 1140 UT the AE index decreased until 1300 UT when another substorm onset interrupted its recovery.

Overviews of plasma behavior in the magnetotail during this substorm have been provided in earlier papers. For example, ISEE 1 and 2 plasma observations of ions with energy below 40 keV and of electrons below 20 keV were reported by *Paschmann et al.* [1985]. *Ipavich et al.* [1985] reported the measurements of energetic protons (10 – 130 keV) and oxygen ions O^+ (~ 130 keV) using the ultralow energy charge analyzer (ULECA) on ISEE 1. *Fritz et al.* [1984] reported on the energetic electron and magnetic measurements from a set of four satellites located from 6.6 to 15 R_E along the 0200 LT meridian at the time of the 1054 UT substorm. These observations revealed flow patterns of charged particles which, if interpreted as temporal variations associated with the various phases of the substorm, are basically consistent with the presence of reconnection between the geosynchronous orbit and the ISEE 1 location (~ 15 R_E) near the 0200 LT meridian.

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During a substorm, magnetotail plasma is highly dynamic. In order to follow its time evolution one must examine measurements of particles over a wide energy range at high time resolution. The previously reported observations of energetic particles (> 30 keV) have rather poor time resolution or cover only a limited energy range. For example, the measurements of energetic ions H^+ and O^+ reported by *Ipavich et al.* [1985] were based on 512-s averages for particles with energy around 130 keV. These data are inadequate for studies of the motion of the particles on the less than 1 min time scales of significant variations of the magnetic field.

In this paper we investigate changes that occur on time scales of less than 1 min by using the medium-energy particle experiment (MEPE) of the ISEE 1 spacecraft which provides measurements of energetic ions and electrons with a time resolution of ~ 36 s for a full three-dimension scan and covers an energy range from 24 keV to 2 MeV for protons and from 22.5 keV to 1.2 MeV for electrons [*Williams et al.*, 1978]. We use these data in conjunction with detailed magnetic field measurements and other previous observations to better understand the CDAW 6 substorm.

Our observations show that prior to the expansion onset, while the particle distribution was isotropic at the spacecraft location, the magnetic field became increasingly taillike. We assume that this field configuration led to the onset of reconnection. We suggest that the neutral line formed on the earthward side of the spacecraft because we find ions and electrons streaming tailward after the expansion onset. Associated with strong tailward bursts of energetic particles, two bipolar signatures in B_z were observed. We interpret the two events as the signatures of two small-scale magnetic islands which were produced by multipoint reconnection in the plasma sheet and may have been associated with the formation of the near-Earth neutral line and the subsequent formation of a large-scale plasmoid. Part way through the expansion onset, the neutral line retreated tailward past the two ISEE spacecraft, and earthward streaming of particles was observed. Near the beginning of the recovery phase the streaming of particles subsided and the particle distribution became isotropic again. In the next section we present the detailed observations which led us to the interpretation sketched above. We elaborate on this interpretation of the observations in the discussion section.

Previous studies of this substorm [*Paschmann et al.*, 1985; *Eastman and Frank*, 1984] have encountered inconsistencies in relating certain details of the observations to the two-dimensional single X line reconnection model of substorm. In particular, the model places the ISEE spacecraft tailward of the neutral line, thus providing an interpretation of the period of about 20 min that is dominated by tailward flows, but the model does not account for a brief (about 2 min) period of earthward flow within the 20 min [*Paschmann et al.*, 1985]. As well, the subsequent flow reversal that is attributed to the tailward retreat of the neutral line is perplexing because it is observed earliest at the spacecraft further down to the tail [*Paschmann et al.*, 1985; *Eastman and Frank*, 1984]. Finally, the model does not explain why the field turns northward somewhat before the flow reverses [*McPherron and Manka*, 1985]. We will return to these points after examining the data and argue that the multiple island structure enables us to account for these anomalies.

OBSERVATIONS

The MEPE instrument measures fluxes of both ions and electrons. The data used in this study were acquired in the low bit rate mode which provides coverage of eight energy channels in eight azimuthal sectors (one sample per sector) for every spin. The detector continuously scans in polar angle relative to the ISEE 1 spin axis which is normal to the ecliptic plane. This scan is synchronized to the satellite spin rate (~ 3 s/spin) and covers a range of polar angles from 10° to 170° in 12 spin periods. A three-dimensional sampling of 96 points is made over the unit sphere every 12 spins (~ 36 s). Each of these samples contains eight simultaneously observed energy channels for ions and electrons.

During the CDAW 6 substorm (1000 UT to 1300 UT) the ISEE spacecraft were inbound near the 0200 LT meridian approximately 15 R_E behind the Earth and ~ 1 R_E below the magnetic equatorial plane. About 10 min before the expansion onset at 1054 UT, the magnetic field at the ISEE spacecraft became taillike. At about 1100 UT, both spacecraft observed very taillike fields; the field directions were antiparallel at ISEE 1 and ISEE 2 and directed 10° above and below the GSM equatorial plane, respectively. Such orientations cannot be attributed to flaring away from the center of the tail. Rather, it suggests that the neutral sheet was tilted 10° below the GSM equatorial plane at this time. The projection of the magnetic field into the GSM equatorial plane makes an angle of 15° with the x axis and the projected y components for ISEE 1 and 2 fields differ in sign. In order to better organize our data and to avoid changes in the sign of the y components caused only by crossing the neutral sheet we have transformed the magnetic data into a neutral sheet coordinate system by first rotating the coordinates 15° counterclockwise with respect to the GSM $+z$ axis, and then rotating them 10° clockwise with respect to the new $+y$ axis [*McPherron et al.*, 1987]. The neutral sheet coordinate system that we use for the magnetic data is illustrated in Figure 1.

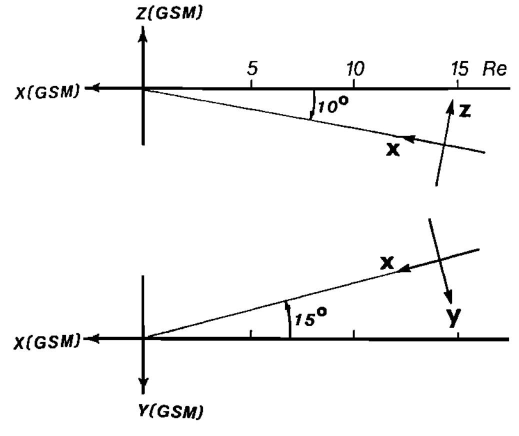


Fig. 1. Tilted neutral sheet coordinate system relative to the GSM coordinates.

Magnetic Data

Figure 2*a* shows the magnetic data in the neutral sheet coordinates. The figure exhibits the changes of magnetic configuration during the substorm event. In the early stage of the substorm (before ~ 1025 UT), ISEE 1 was south of the neutral sheet and observed B_z and B_x components of comparable size, implying a dipolelike field. Because of flapping of the magnetotail, ISEE 1 crossed the neutral sheet 3 times between 1025 and 1035 UT, shown by the changes of the sign of B_x. After 1040 UT the spacecraft was north of the neutral sheet and observed a large increase in B_x while B_z dropped to nearly zero, indicating a very taillike magnetic field. At about 1107 UT the neutral sheet passed upward over ISEE 1, and B_x changed direction, but the magnetic field remained taillike until ~ 1110 UT when B_z began to increase rapidly to a level comparable to B_x, indicating that the magnetic field at the spacecraft location was again dipolelike. The development of a taillike field was also observed by geostationary spacecraft near 0200 LT during the interval of southward turning of the IMF (1010 UT to 1110 UT) [*McPherron and Manka*, 1985; *Barfield et al.*, 1985; *Fritz et al.*, 1984]. The change of the magnetic field into a taillike configuration in this region is associated with energy accumulation during the growth phase of a substorm before the expansion onset [*McPherron*, 1972; *McPherron and Manka*, 1985]. The large increase in the magnitude of the total magnetic field after 1040 UT is regarded as both the signature of increasing storage of magnetic energy in the tail and the thinning of the current sheet during the growth phase of the substorm. The magnetic signature associated with the 1054 UT expansion onset at the ISEE 1 spacecraft is the commencement of magnetic fluctuations at ~ 1058 UT. As we will see later, a tailward streaming of energetic particles also starts at nearly this time at ISEE 1.

For comparison, the magnetic field observations from ISEE 2 are shown in Figure 2*b*. The separation vector pointing from ISEE 2 to ISEE 1 at 1100 UT is (−8800, 1200, 3700 km) in the tilted neutral sheet coordinates described above. The magnetic data of ISEE 2 exhibit variations similar to those of ISEE 1, except that the neutral sheet crossing of ISEE 2 after the expansion onset occurred at 1057:30 UT, about 10 min before the 1107 neutral sheet crossing of ISEE 1.

Ion Data

Figure 3 shows the ion fluxes averaged over 12 spin periods (~ 36 s) measured by the MEPE instrument on ISEE 1. A striking feature of these data is an abrupt increase of the ion intensities in all energy channels without detectable dispersion at ~ 1058 UT, about 4 min after the 1054 UT expansion onset. The largest flux increase of about 1 order of magnitude occurred in the first channel (24 to 44.5 keV). This is a spacecraft signature of the expansion onset. Before 1058 UT the ion intensity declined slightly. Although the spacecraft crossed the neutral sheet a few times between 1025 and 1035 UT, the ion fluxes were nearly constant, indicating that ISEE 1 was within the plasma sheet throughout the substorm growth phase. Electric field measurements [Pedersen et al., 1985] show that ISEE 1 was close to the northern edge of the plasma sheet at ~ 1059 UT. Earlier at 1040 UT the plasma density decreased slightly from ~ 0.3/cm^3 to ~ 0.1/cm^3 [*Paschmann et al.*, 1985], which suggests that the spacecraft entered the plasma sheet/lobe boundary layer.

Following the sudden increase at ~ 1058 UT, the ion intensities fluctuated rapidly with peak values gradually increasing, until ~ 1140 UT when the recovery phase of the substorm began on the ground. The fluxes remained high until after 1200 UT and then diminished to the preonset level by ~ 1300 UT. Note that at about 1125 UT

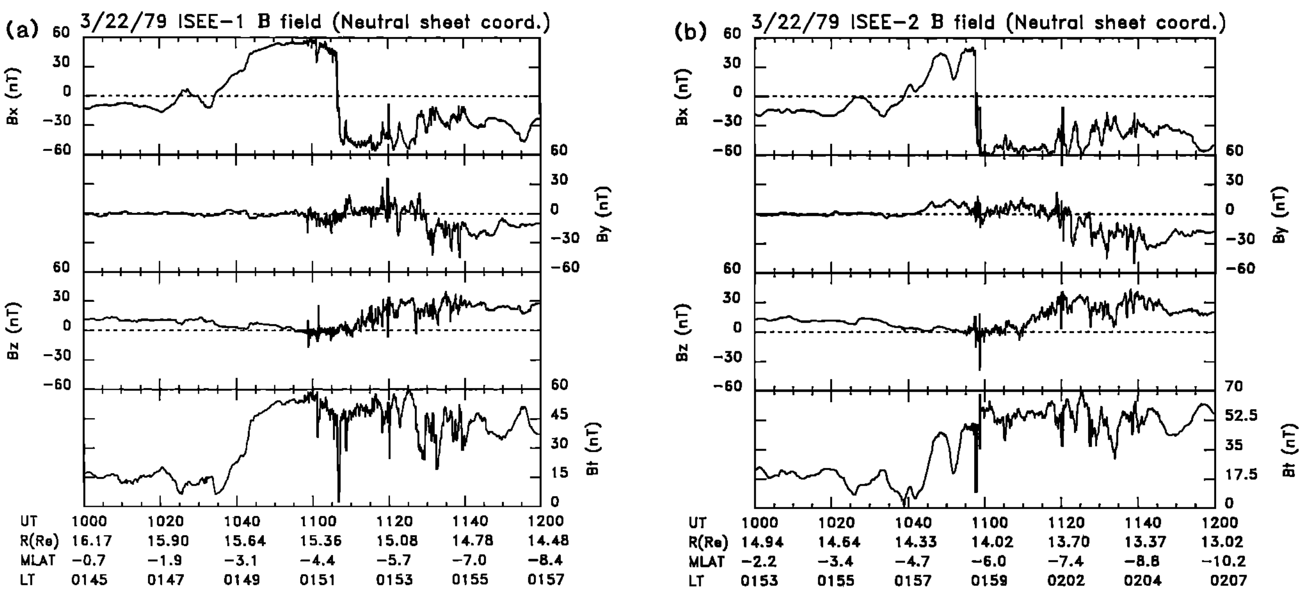


Fig. 2. (*a*) The ISEE 1 magnetic data in the neutral sheet coordinates defined in Figure 1. B_t is the total magnetic field. The spacecraft geocentric radial distance in Earth radii (R_e), the magnetic latitude, and the local time are provided. (*b*) ISEE 2 magnetic data in the neutral sheet coordinate system.

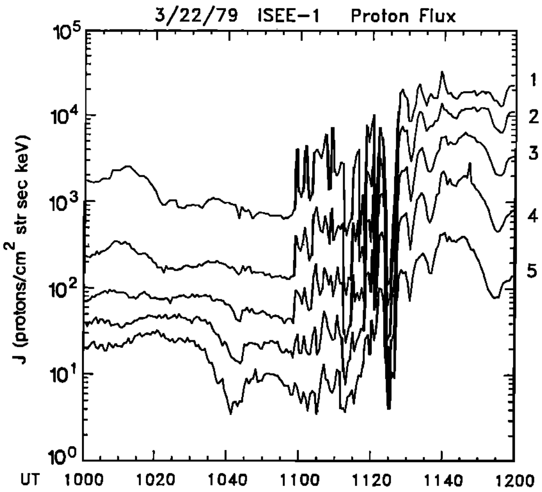


Fig. 3. Twelve-spin-averaged proton fluxes. Only data of the first five energy channels are shown. Channel numbers are shown at the right side of the panel: (1) 24−44.5 keV, (2) 44.5−65.3 keV, (3) 65.3−95.5 keV, (4) 45.5−142 keV, (5) 142−210 keV.

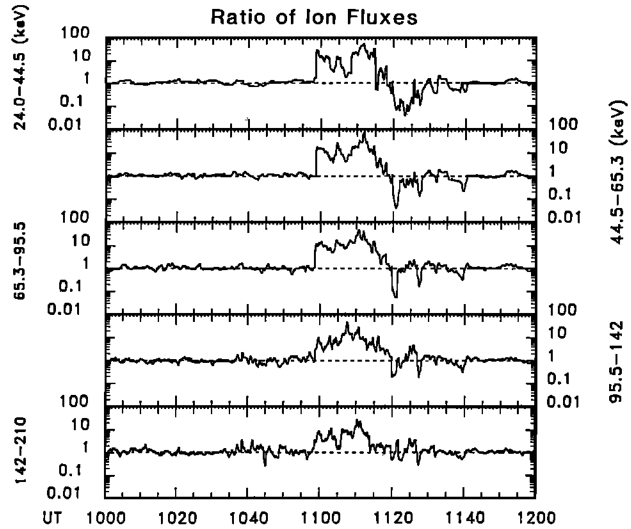


Fig. 4. The ratio of field-aligned tailward fluxes to earthward fluxes of ions for channels 1 to 5 of the ISEE 1 MEPE data.

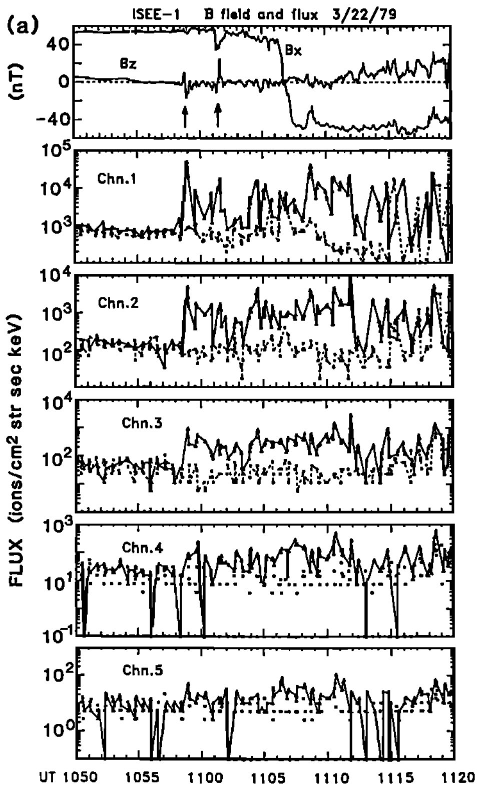
there was a sharp decrease of fluxes to a magnitude 1 order lower than the pre-onset level. Because the decrease in flux coincided with an increase of the total magnetic field, we attributed it to an excursion of ISEE 1 into the southern lobe. Our interpretation is supported by the analysis of energetic ion flux to be discussed later in relation to Figure 8. We find a strong net duskward directed ion flux at ~ 1125 UT. This flux anisotropy is consistent with a large northward pointing spatial gradient in the gyrocenter density. The interpretation is also consistent with ULECA observations [*Ipavich et al.*, 1985], which showed a large decrease in the H^+ intensity in all energy channels.

The sudden increase in the ion fluxes at ~ 1058 UT was accompanied by strong tailward streaming of energetic ions. In Figure 4 we display the ratio r of field-aligned fluxes directed away from the Earth (tailward) to field-aligned fluxes directed toward the Earth observed by ISEE 1. Values of $r > 1$ mean that the "tailward" fluxes exceed the earthward fluxes, while values of $r < 1$ mean that the earthward fluxes are larger. Included in the "tailward" flux are the averages of the fluxes of particles with pitch angle $\leq 30°$ (for $B_x < 0$) or $\geq 150°$ (for $B_x > 0$) measured in the three sectors around the GSE $+x$ axis. The "earthward" fluxes are the averages of fluxes of particles with pitch angle $\leq 30°$ (for $B_x > 0$) or $\geq 150°$ (for $B_x < 0$) in the three sectors around the GSE $-x$ axis. During the growth phase and the expansion phase of the substorm when the magnetic field became taillike (~ 1040 to ~ 1110 UT) these field-aligned fluxes may reveal tailward or earthward streaming of particles. We evaluate r for each spin period (~ 3 s) containing measurements of particles with the required pitch angles. There are some spin periods for which there were no measurements in the required pitch angle range, so the calculated r contains gaps. Examples that contain some gaps in the measurements can be seen in Figure 5a in which some of the data have been plotted at high time resolution. Because of the gaps, the data are not equispaced in time. To obtain Figure 4, we interpolated through the gaps and thus constructed a continuous record.

We should mention here that sunlight affected the MEPE detector response during the middle two spins of each 36-s data collection interval when the sectors of interest to us looked at the Sun (D. G. Mitchell, private communication, 1989). The effects of the sunlight have been removed from the data by making a quadratic fit to the data from the two spins before and after the ones oriented toward the Sun. In a few cases this interpolation produced zero values and was recorded as zero counts. In our analysis we have removed these zero counts from the first three channels since most of the count rates are relatively large, and thus the zero counts must represent missing data. But for the rest of higher-energy channels (channel 4 and above), all zero counts were kept since the count rates for those channels are frequently so small that it is not possible to attribute zeros exclusively to missing data.

Figure 4 shows that prior to the expansion onset, there was no field-aligned ion flow. At 1058 UT, sudden strong tailward streaming appeared simultaneously in all ion energy channels. We will argue later that this streaming is evidence of the formation of a neutral line earthward of the ISEE 1 location. The tailward streaming continued until ~ 1118 UT when r dropped below 1, corresponding to earthward streaming, and gradually decreased. The asymmetries of the field-aligned flux disappeared at ~ 1140 UT. The signatures of tailward followed by earthward streaming were similar for all energy channels. We notice that in the first channel (the top panel of Figure 4) the net tailward flux diminished markedly at about 1107 UT when ISEE 1 was crossing the neutral sheet. This reduction is most significant in the lowest-energy channel, while for the ions with energy > 44 keV (the second or higher channels) the tailward flows remained strong until the reversal at ~ 1118 UT.

During the period of earthward flow (~ 1118 to 1140 UT) an interval of tailward flow was observed around 1125 UT. This corresponds to the time when ISEE 1 en-



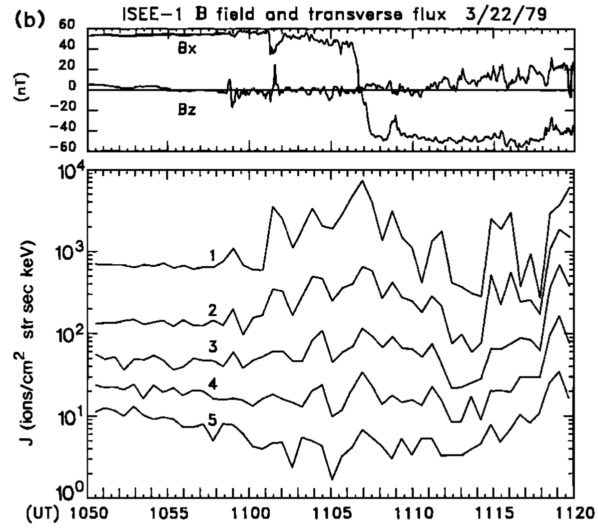


Fig. 5. (*a*) Top panel: The magnetic B_x and B_z components for the interval 1055–1120 UT. Panels 2 to 6: Field aligned tailward ion fluxes (triangles connected by solid lines) and earthward fluxes (squares, connected by dashed lines for channels 1 to 3) of channels 1 to 5 of the ISEE 1 MEPE data. (*b*) Twelve spin averages of differential fluxes of ions with $80^\circ - 100^\circ$ pitch angle. Magnetic B_x and B_z are plotted in the top panel.

tered the southern lobe. According to ULECA measurements [*Ipavich et al.*, 1985], during this short interval the tailward streaming O^+ ions ($\sim$ 130 keV) increased dramatically, producing differential flux intensity ratio $O^+/H^+ \sim 7 \pm 2$ in the tailward direction. Ipavich et al. attributed the tailward streaming to O^+ ions that were directly emitted from the southern auroral zone ionosphere, flowing away from the Earth. The ISEE 1 MEPE instrument cannot detect ion species, but the observed tailward streaming in this short period seems to be consistent with the ULECA observation. We note that Figure 3 shows that the flux in the lowest energy channel drops to about 100 (cm^2 str s keV)$^{-1}$ which is comparable to the fluxes reported by Ipavich et al.

Relation of Ion Streaming to Changes in the Magnetic Field

At 1058 UT, when strong tailward flow started abruptly, the magnetic structure also began to change. The relationship between the magnetic and particle data for the interval 1050 to 1120 UT can be seen in Figure 5*a* which displays the magnetic B_x and B_z components for ISEE 1, and the tailward and earthward directed ion fluxes used for determining the flux ratio plotted in Figure 4. Figure 5*b* shows the intensities of the ion fluxes transverse to the magnetic field.

The sudden increase in the tailward directed flux at $\sim$ 1058 UT, previously noted, is seen to coincide with a bipolar signature in B_z with a $+/-$ sense (marked by the first arrow in Figure 5*a*). This signature also was seen by ISEE 2, which at this time was on the opposite side of the plasma sheet. The timing of the magnetic variations can be analyzed from the plots of Figures 6*a* and 6*b* which present high resolution (0.25 s/sample) magnetic data for the interval 1058 to 1103 UT. The bipolar signature in B_z was observed by both spacecraft. As we show below, the variations are consistent with the signature of a looplike field structure moving tailward past the spacecraft. ISEE 1 may just have crossed the northern edge of the loop where B_x was almost constant while B_z changed from +10 to −20 nT. ISEE 2, penetrating deeper into the loop, saw B_z first increase to $\sim$ 30 nT and then decrease to $\sim$ −50 nT. There was a large $-B_y$ ($\sim$ −25 nT) excursion on ISEE 1 centered on the B_z signature while in ISEE 2 measurements, B_y signature was relatively insignificant.

The center (zero crossing) of the bipolar signature at ISEE 1 lagged behind that of ISEE 2 by about 15 s. Since ISEE 2 was $\sim$ 8800 km earthward of ISEE 1 on their inbound orbit, the tailward velocity of the loop structure may be estimated as $\sim$ 580 km/s. The bipolar B_z signature at ISEE 1 was well correlated with a bipolar signature (E_y) in the measured electric field ([*Pedersen et al.*, 1985], see the inset of their Figure 3). Northward B_z and dawnward E_y preceded southward B_z and duskward E_y. Thus the net $\mathbf{E} \times \mathbf{B}$ drift of the loop structure in the x direction was also consistent with tailward motion and the magnitude of the velocity was approximately $E/B \sim 5(\text{mV/m})/10(\text{nT}) = 500$ km/s, consistent with the value inferred from timing magnetic perturbations.

There is another notable magnetic signature in the ISEE 1 data between 1101 UT and 1102 UT (marked by the second arrow in Figure 5*a*) which in the lowest-energy channel is associated with a burst of strong tailward flow and also with a sharp peak of transverse ion fluxes (Figure 5*b*). This time the B_x component decreased significantly (by about 20 nT), while B_z showed

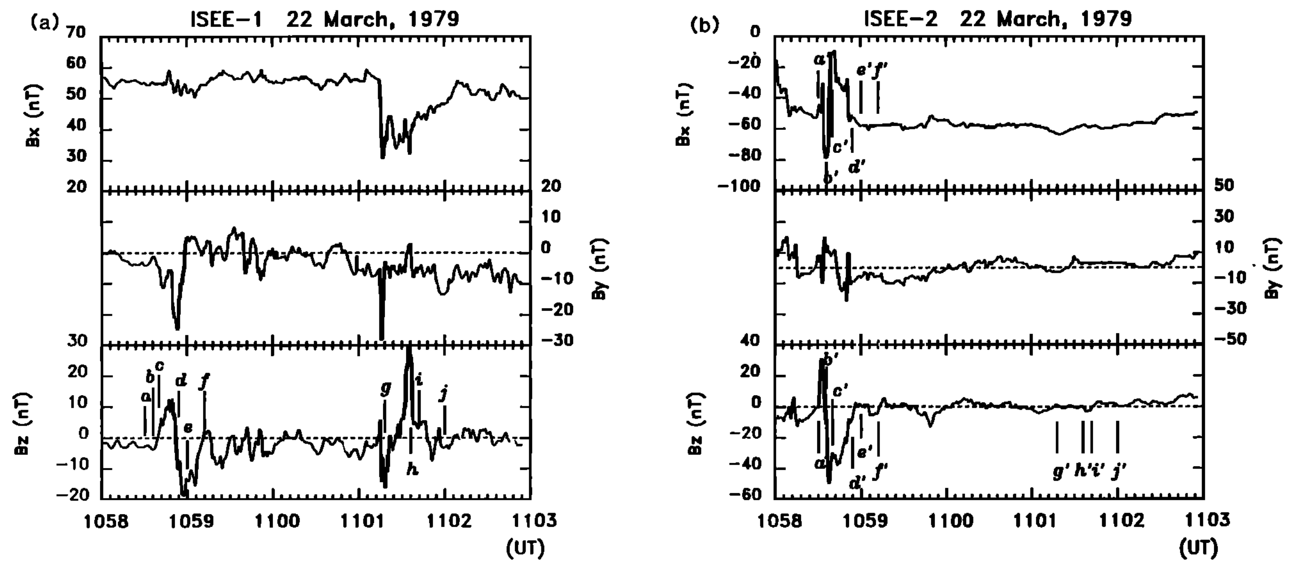


Fig. 6. (*a*) High-resolution (0.25 s/sample) magnetic data of ISEE 1 for the interval 1058 to 1103 UT. (*b*) Same as 6*a* but for ISEE 2. The labeled points correspond to points in a schematic interpretation illustrated by Figure 11 and are explained in the text.

another bipolar signature: first negative (~ −15 nT) then positive (~ +30 nT) (see the high time resolution magnetic field plot in Figure 6*a*). This signature can be interpreted as another loop structure moving tailward, but ISEE 2 recorded no evidence of this event at all (Figure 6*b*). This requires that the structure be small on the scale of the spacecraft separation. The separation in the dawn-dusk direction was only about 1200 km, and it seems unlikely that the spatial structure changed dramatically on such a small azimuthal scale. It seems more probable that the thickness of the loop was smaller than the ~ 3700 km N−S separation of the two spacecraft. The tailward convection of this loop or island structure is consistent with electric field observations as in the case of the first loop. Figure 3 of *Pedersen et al.* [1985] reveals a large negative (dawnward) E_y simultaneous with a peak of the northward B_z just before 1102 UT as required for a tailward $\mathbf{E} \times \mathbf{B}$ drift.

Transformation of Ion Streaming to Field-Aligned Coordinates

To examine the streaming motion of energetic ions with respect to the magnetic field, we have calculated the mean velocity of the energetic ions in the first six energy channels (24 to 333 keV):

$$< \mathbf{v} >= \frac{\int f \mathbf{v} \, d\mathbf{v}}{\int f \, d\mathbf{v}}$$

where f is the phase space density of ions which is derived from the measured differential flux and $\mathbf{v}$ is the ion velocity. As the MEPE instrument measured only the high-energy tail of the plasma distribution function, this calculated velocity is not the plasma bulk flow velocity, but it provides information on the direction and intensity of streaming of the energetic particles. We note that the transverse components of the calculated velocity can also be caused by finite gyroradii effects in the presence of a spatial density gradient. Since the detector requires 12 spins (~ 36 s) to complete a three-dimensional scan, the mean energetic ion velocity was calculated once for each 12 spin periods. Although the MEPE instrument cannot distinguish ion species, and in some special situations, energetic ions may be dominated by heavy ions (see the discussion above for the period around 1125 UT), we assume here that the ions measured by the detector are predominantly protons. This assumption may be justified by comparison of our observation with the O^+ and H^+ ion measurements of ULECA [*Ipavich et al.*, 1985]. O^+ ions (~ 130 keV) were first observed at ISEE 1 at 1040 UT, well before the expansion onset, and were streaming tailward, while H^+ ions showed a relatively isotropic distribution. During this time interval the O^+/H^+ intensity ratio at 130 keV was 0.6 measured in the tailward flow. The MEPE detectors did not reveal tailward streaming of ions in all channels until 1058 UT, the same time when ULECA observed H^+ ions begining to stream tailward.

A useful coordinate system in which to examine the flow is one aligned with the three principal magnetic field coordinates shown in Figure 7. The principal directions are given by the unit vectors $\hat{\mu}, \hat{\phi}, \hat{\nu}$. The vector $\hat{\mu}$ is parallel to the background magnetic field everywhere north of and at the neutral sheet, while it is antiparallel to the south. $\hat{\phi}$ is perpendicular to the magnetic meridian plane and points duskward, and the other transverse component $\hat{\nu} = \hat{\mu} \times \hat{\phi}$ completes the right-handed system. Thus in the case of a taillike magnetic configuration, $+\hat{\mu}$ always points earthward, $+\hat{\nu}$ northward, and

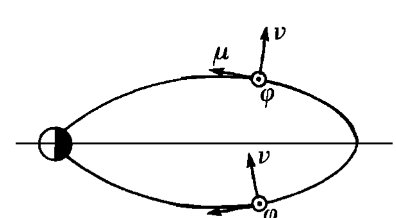


Fig. 7. The magnetic field directions $\hat{\mu}, \hat{\phi}, \hat{\nu}$.

$+\hat{\phi}$ duskward, as would GSM coordinate axes x, z, and y.

The components of the mean vector velocity of the energetic protons (24 to 333 keV) are shown in Figure 8. The figure shows that before 1058 UT the protons were isotropic (zero mean velocity in all components). At about 1058 UT there was an abrupt increase in negative parallel velocity V_μ implying tailward streaming of the energetic ions along field lines. The fluctuating tailward velocity persisted, reaching a maximum of ~ −2000 km/s, until ~ 1115 UT, when the fluctuation frequency and amplitude increased and the flow gradually changed direction becoming earthward (positive V_μ) after 1118 UT. The earthward velocity reached a maximum of ~ 1500 km/s at ~ 1120 UT and then decreased gradually until the distribution was again isotropic at about 1140 UT, i.e., near the beginning of the recovery phase. Note that the brief tailward flow around 1125 UT occurred during the ISEE 1 excursion into the lobe as explained above.

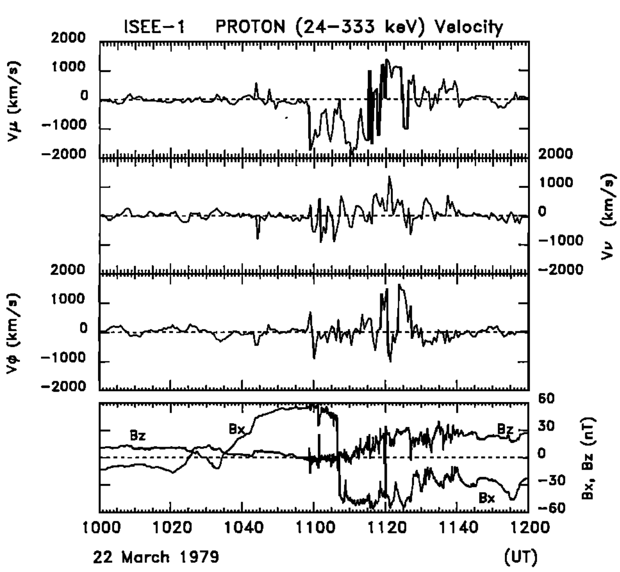


Fig. 8. Calculated mean velocity of the energetic ions for energies 24–333 keV in $\mu\phi\nu$ coordinates (see text). B_x and B_z are plotted in the last panel for comparison.

Coincident with the onset of tailward streaming, the fluctuations of the transverse velocity components V_ν and V_ϕ grew larger. The V_ν component was directed toward the central plasma sheet during the streaming flow period: between 1058 and 1107 UT, when the spacecraft was north of the neutral sheet, V_ν was on the average negative, while between 1107 and 1140 UT when the spacecraft was south of the neutral sheet, V_ν was mostly positive. This means that in the $\mu - \nu$ plane (nominal magnetic meridian plane) the motion of ions during the interval (1058 to 1140 UT) was essentially field aligned but there was an additional flow component transverse to the background field and pointing toward the central plasma sheet. This flow pattern is qualitatively consistent with that present inside the separatrix of reconnection regions predicted by theories [e.g., *Cowley*, 1985; *Walker and Sato*, 1984]. Considering the finite Larmor radius effect of energetic ions, we could alternatively interpret the V_ν component pointing toward the central plasma sheet as an asymmetric moment of the distribution arising from a spatial gradient of the ion flux in the dawn-dusk direction. However, we prefer the first interpretation because the onset of large fluctuations in V_ν is closely correlated with the onset of tailward streaming in the field-aligned component, and we saw no evidence of such a spatial gradient before 1058 UT. The azimuthal component V_ϕ is insignificant except for the period between 1115 and 1130 UT, when large fluctuations in the dawn-dusk direction were present. We have mentioned earlier that the finite average of V_ϕ at ~ 1125 UT corresponding to dominant duskward oriented flux was probably caused by the north-south gradient when ISEE 1 moved into the southern lobe for a few minutes.

Electron Data

Electron measurements during this substorm event show streaming patterns similar to that of ions. Unfortunately, meaningful electron data are available only for the lowest energy channel (22.5 − 39 keV) of the detector. For most of the interval of interest the flux in the higher channels was below the threshold of the instrument and hence could not be used.

In the bottom panel of Figure 9 we show the electron intensity from the first channel, while in the top panel we show the ratio of tailward flux to earthward flux for channel 1 electrons streaming along field lines. The intensity of the electron flux decreased significantly before the expansion onset. Two intervals of flux enhancement (1005 to 1010 UT and at 1025 to 1035 UT) preceded the substorm onset. They are associated with large increases in 90° pitch angle electrons (not shown) and are superimposed on an electron flux which declined from ~ 200 $(cm^2 \text{ str s keV})^{-1}$ at 0930 UT to ~ 8 $(cm^2 \text{ str s keV})^{-1}$ at 1054 UT. The flux then sharply increased and reached a maximum during the late expansion phase of the substorm. The second intensity enhancement may be associated with neutral sheet crossings between 1025 and 1035 UT, but the first enhancement was not associated with any magnetic signatures and is puzzling.

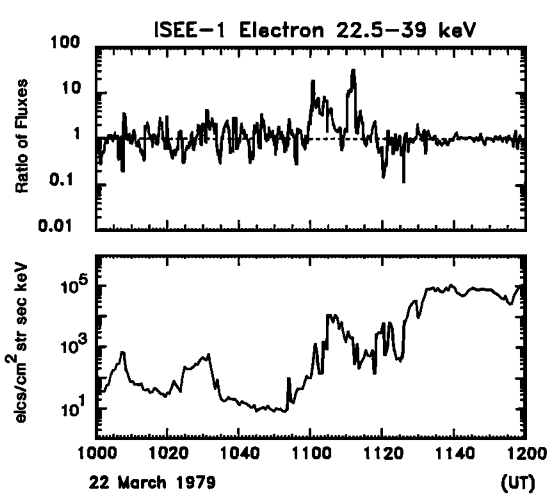


Fig. 9. The ratio of field-aligned tailward fluxes to earthward fluxes of electrons (22.5–39 keV) of the ISEE 1 MEPE data. The bottom panel shows the flux of electrons in the same channel.

Although the electron flux began to increase at ~ 1053 UT, persistent tailward streaming did not start until ~ 1059 UT (indicated in the first panel of Figure 9 by an increase in the ratio r to values much larger than one). The tailward streaming continued with fluctuations until about 1118 UT and was followed by a very weak earthward streaming. We noted that r decreases to somewhat less than one between ~ 1107 and 1109 UT. This feature is similar to that seen in Figure 4 for ions in the first channel.

The decrease of the electron intensity before 1054 UT may indicate that the spacecraft moved from deep within the central plasma sheet to the boundary layer. After the expansion onset when the plasma sheet moved up and the spacecraft crossed the putative separatrix of the reconnection region (discussed in the next section) at 1058 UT, streaming electrons were observed by the spacecraft.

Discussion

High time resolution data show similar responses for energetic protons and electrons for two hours during the CDAW 6 substorm event. Before the expansion onset the particle fluxes were quite isotropic and no streaming was observed in the different regions through which the ISEE spacecraft traveled, including the neutral sheet (between 1025 and 1035 UT) and the plasma sheet boundary layer (for example, after ~ 1040 UT). Strong tailward streaming was observed simultaneously for energetic ions and electrons in all available channels beginning a few min after the 1054 UT onset without detectable energy dispersion of ions. The tailward flow continued for about 20 min until a flow reversal was observed at ~ 1118 UT with relatively smaller velocities afterward. The earthward flow lasted for another 20 minutes and then subsided. The flux of energetic particles in the magnetotail increased markedly during the expansion phase. This streaming pattern of energetic particles is qualitatively the same as that of particles in the lower energy range (70 eV - 40 keV) [*Paschmann et al.*, 1985]. In general, the pattern of magnetic field and energetic particle observations in the previous section are consistent with the near-Earth reconnection model of substorms described by, for example, *Hones* [1979, 1984] and *McPherron* [1979].

A proposed scenario for this CDAW 6 event can now be outlined: a southward turning of the IMF at ~ 1010 UT increased energy input to the magnetosphere [*Baker et al.*, 1985; *Tsurutani et al.*, 1985]. As the magnetic stress built up, the near-Earth magnetotail became increasingly taillike. This was conducive to the onset of reconnection. The region of taillike field extended at least from 6.6 R_E [*Fritz et al.*, 1984; *McPherron and Manka*, 1985; *Barfield et al.*, 1985] to the ISEE 1 location at ~ 15 R_E. At geostationary orbit the dipolarization of the fields began between 1052 and 1054 UT and was associated with a recovery of synchronous particle fluxes. A particle injection at synchronous orbit occurred shortly after 1104 UT. At ISEE 1 the taillike magnetic configuration persisted at least until 1110 UT (Figure 2*a*), about 15 min after the expansion onset. A near-Earth neutral line formed between the geostationary orbit and the ISEE 1 location approximately at the time of expansion onset. After reconnection began the stressed magnetic field lines on the earthward side of the neutral line relaxed rapidly into a dipolar configuration, while field lines on the tailward side of the neutral line remained very taillike for another 15 min.

According to the model, a near-Earth X line produces fast jets of plasma directed earthward and tailward away from it, between separatrices and causes tailward ejection of a detached plasma sheet "plasmoid". ISEE 1 at ~ 15 R_E did not observe the passage of a large-scale plasmoid (which may form farther down the tail), but the signatures of plasma jetting are very evident in the strong tailward streaming starting at ~ 1058 UT (Figure 4) a few minutes after the presumed onset of near-Earth reconnection. The delay can be understood by reference to Figure 10 which schematically illustrates both the flow in relation to the magnetic configuration associated with near-Earth reconnection and the relative motion of the two ISEE spacecraft. There is a separatrix S between reconnected field lines and outer field lines which have not yet reconnected. This separatrix was still inside the plasma sheet at about 1058 UT (see also the schematic diagram in Figure 4 of *Lin et al.* [1990]), since the spacecraft observed streaming flow but did not enter the lobe at that time. As more and more field lines reconnect, this separatrix may become the "outer separatrix" defined by *Hones et al.* [1984], as the boundary between reconnected lobe field lines and field lines connected to the IMF (see Figure 3 of *Hones et al.* [1984]; and *Takahashi and Hones* [1988]). Figure 10 shows schematically the locations of the ISEE spacecraft at 3 times. At 1057 UT, both spacecraft were north of the neutral sheet and above the northern separatrix, and observed no streaming particles. Upward motion of the magnetotail caused ISEE 2 to cross the neutral sheet and ISEE 1 to approach the separatrix by 1057:30 UT. Thus ISEE 2 which was then located inside the separatrix and tailward of the substorm neutral line, began to observe ions streaming tailward [*Paschmann et al.*, 1985], while ISEE 1 which was still above the separatrix, saw no flow signature. At ~ 1058:40, ISEE 1 crossed the northern separatrix. The sudden appearance of tailward streaming of ions and electrons evident in Figures 4 and 9 marks the separatrix crossing. The lack of detectable dispersion in ion data implies that the source of the streaming energetic ions was close to the spacecraft.

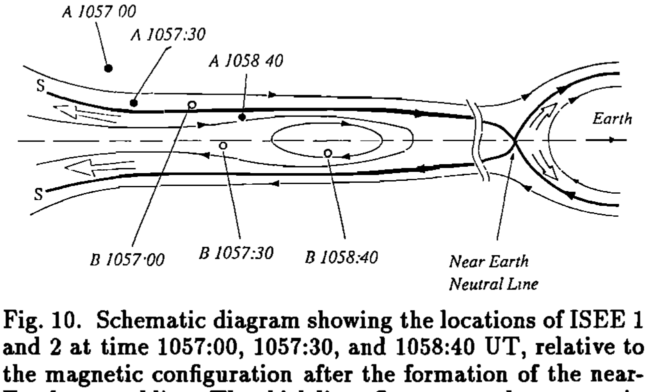


Fig. 10. Schematic diagram showing the locations of ISEE 1 and 2 at time 1057:00, 1057:30, and 1058:40 UT, relative to the magnetic configuration after the formation of the near-Earth neutral line. The thick lines S represent the separatrix (see text). Solid circles (marked A) represent the locations of ISEE 1, while open circles (marked B) are for ISEE 2. White arrows indicate the flow direction of particles.

The region inside the separatrix may correspond to the "postplasmoid plasma sheet" (PPPS) [*Richardson et al.*, 1987] (i.e., the plasma sheet region confined between the substorm neutral line and a large-scale plasmoid at some greater distance down the tail, which contains streaming energetic particles), The magnetic field at the two spacecraft locations in the PPPS region before 1110 UT was very taillike, almost parallel to the neutral sheet, so that the B_z component in the neutral sheet coordinates was almost zero (Figures 2*a* and 2*b*, also see the first panel of Figures 5*a* and 5*b* for ISEE 1 data). The tailward streaming of energetic particles in this region was burstlike as evident in Figure 5*a*. This may imply that the jetting of particles from the reconnection region is also burstlike. The decrease of the net tailward flux at about 1107 UT in the lowest-energy channels was caused by an increase in the earthward directed flux of ions in those channels. This is most clearly seen in the second panel of Figure 5*a* for ion data of channel 1: the earthward flux (dashed line) rose to the level of the tailward flux (solid line) between ~ 1106 and 1107 UT. The balance of earthward and tailward flux appears predominantly for ions with lower energy (< 20 keV). Measurements of the bulk velocity of low-energy protons (70 eV - 40 keV) by *Paschmann et al.* [1985] actually show a net earthward flow in this interval (1105 to 1107 UT). Below we will interpret this flow reversal in terms of multipoint reconnection in the plasma sheet.

Part way through the expansion phase, the neutral line apparently retreated tailward past the two ISEE spacecraft, placing them on the earthward side of the near Earth X line, where earthward streaming of particles was observed. For ISEE 1 this occurred at ~ 1118 UT as seen in Figure 4 and 8. The mean velocity of energetic particles (Figure 8) shows a large fluctuation in the field-aligned component V_μ just before the reversal time (1115 to 1118 UT) which may imply that the reconnection region is quite turbulent.

While the flow reversal is quite clear in the proton data, the earthward streaming of energetic electrons is almost not discernible (Figure 9). The reason is that the rapidly moving electrons, reflected back from their mirror points on the geomagnetic field lines, quickly develop counterstreaming distributions, thereby reducing the net earthward streaming. Energetic protons, which travel along field lines more slowly than electrons, drift onto field files not linked to their source before they are reflected at mirror points; thus counterstreaming does not occur.

The 20-min duration (~ 1059 – 1118 UT, Figure 9) of the burst of tailward streaming energetic electrons is unexpected, since the energetic electron boundary layer is expected to be extremely thin. If we assume that the source of the streaming electrons (the reconnection region) was about 5 R_E earthward of ISEE 1 and that E_y = 5 mV/m and B_x = 50 nT, electrons of 30 keV, traveling tailward from the source to the spacecraft will drift across field lines under the $\mathbf{E} \times \mathbf{B}$ drift for about 50 km in the N-S direction, while ISEE 1 has moves southward ~ 800 km. This means that the streaming electrons were present in a region that extended at least about 800 km in the z direction at the ISEE 1 location. A flux tube of this N-S extent maps to a source region in the equatorial plane that may extend in x direction for a few thousand kilometers. This is a reasonable size for reconnected flux tubes. For instance, flux tubes reconnected on the dayside magnetopause which have been interpreted as FTE's usually have a scale size of about one R_E.

We have pointed out in the discussion of Figure 5 that there are two distinct magnetic events at 1058:30 to 1059 UT and 1101 UT to 1102 UT, each of which is associated with a strong tailward burst of energetic protons. The second is also associated with an enhancement in the transverse flux. In Figure 11 we present a schematic view of a double magnetic loop structure (magnetic island) which provides a possible interpretation of these events. The suggested paths of ISEE 1 and 2 with respect to the magnetic islands are plotted in the figure with dashed lines, and critical times are marked a to j, corresponding to the labels in Figure 6. The diagram does not show the large scale plasmoid that we believe was retreating down the plasma sheet to the left of the diagram.

The first event was observed right after the spacecraft crossed the separatrix (S in Figure 10). ISEE 2, which was south of ISEE 1, crossed the central plasma sheet at 1057:30 UT and encountered a tailward moving magnetic island at 1058:30 UT (seen as a bipolar signature in B_z, points a′ to e′ in Figures 11 and 6*b*), while ISEE 1 passing only the edge of the loop, observed a weaker but still clear bipolar signature in B_z (points a to e in Figure 11 and 6*a*). Since the tailward velocity of the island is estimated to be about 580 km/s, the length of the loop must have been ~ $2-3$ R_E. We noted that the electron streaming at ISEE 1 peaked between ~ 1100 and 1101 UT (Figure 9), while at ~ 1059 UT when the first loop accompanied by proton streaming was seen, there was little electron streaming. This pattern suggests that the spacecraft was on closed field lines between 1058 and 1059 UT, since electron streaming occurs principally on open field lines.

About 2 min later, ISEE 1 encountered another possible loop structure. At 1101:18 it was at position g (near a suggested $X-$ type neutral line between two loops) where B_x decreased and B_z pointed southward. Then it went deeper into the structure (point h) where B_z

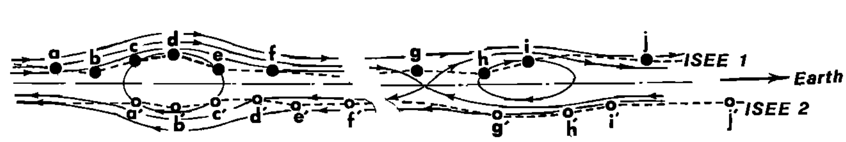


Fig. 11. Schematic diagram of the loop structures observed by the ISEE 1 and 2 spacecraft. Dashed curves illustrate the proposed spacecraft trajectories relative to the loop structures. This schematic does not show the large-scale plasmoid that we believe was retreating down the plasma sheet in the region to the left of the diagram.

turned north and the particle intensity increased (e.g., see Figure 5*b*, particularly the lowest-energy channel). The electron flux (lower panel of Figure 9) also exhibited a remarkable peak between 1101 and 1102 UT. Unlike the first event, the ratio of tailward to earthward electron fluxes did not vanish. This may imply that ISEE 1 was passing the edge of the second loop, where field lines were open or newly closed. We also note that at the same time (between 1101 and 1102 UT) the proton density (see Figure 1 of *Paschmann et al.* [1985]) attained a local maximum which is consistent with our interpretation. ISEE 1 did not remain within the second loop during its passage but rather emerged through the northern edge of the loop (points i, j) into a region where B_z went to almost zero and B_x increased to the previous high level. The second island must have been thinner than the first one, or its center higher, since ISEE 2 $\sim$ 3700 km to the south of ISEE 1 did not observe the second signature at all.

To better illustrate the magnetic evidence for the two magnetic islands, we have plotted (Figure 12) magnetic vectors measured at ISEE 1 and ISEE 2 as projected onto the $X-Z$ plane. In creating the diagrams it was assumed that static structures moved tailward past the spacecraft at a uniform velocity of 580 km/s. Vectors of ISEE 1 are plotted for the interval 1058:30 to 1059 UT (Figure 12*a*) and 1101 to 1102 UT (Figure 12*b*). ISEE 2 vectors are plotted for intervals 15 s earlier than the above intervals, i.e., 1058:15 to 1058:45 UT and 1100:45 to 1101:45 UT. The lengths of the vectors for measurements of each spacecraft in each interval have been normalized to the maximum vector length in the interval. The vector pattern in each interval is consistent with looplike magnetic field lines which are overplotted

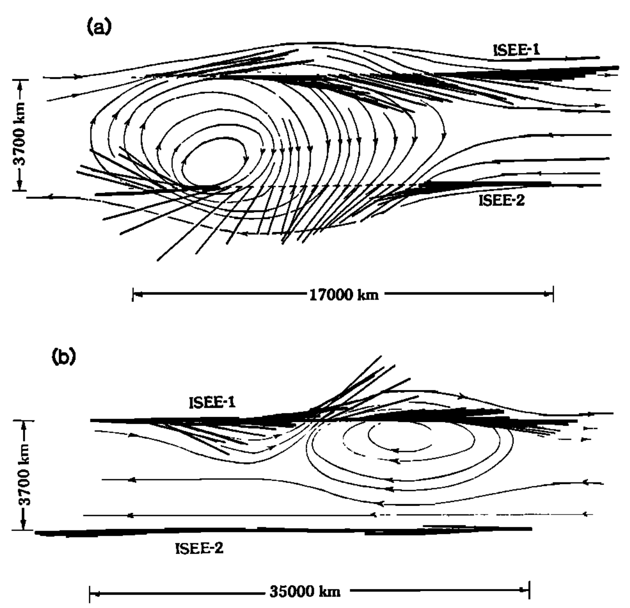


Fig. 12. Magnetic vectors (thick lines) measured at ISEE 1 and 2 projected onto the $X-Z$ plane to visualize the two loop structures: (*a*) the first loop observed between 1058:30 and 1059 UT by ISEE 1 and (*b*) the second loop observed between 1101 and 1102 UT by ISEE 1. Schematic magnetic field lines (thin lines) are overplotted on each vector plot. Vectors are plotted every 0.75 s.

schematically on the same diagrams. Since the B_y component in the two events was not zero, the magnetic field lines do not actually close in the $X-Z$ plane.

A significant B_y component (Figure 6*a*) present in ISEE 1 magnetic data during the first event calls to mind the signature of flux ropes oriented east-west across the tail discussed by *Elphic et al.* [1986] and *Hughes and Sibeck*, [1987]. However, for a flux rope one would expect B_y to increase toward the center of the rope, yet ISEE 2 which was deeper within the structure did not observed a larger B_y. Most likely these events are small magnetic bubbles.

The second loop appeared 2 min after the first. Thus by the time the second loop was observed the first one would have been $\sim 10\ R_E$ further down the tail. Since we estimate that the near-Earth neutral line was only $\sim 5\ R_E$ earthward of the spacecraft, both loops could not have existed simultaneously earthward of the ISEE spacecraft. Instead, the second loop must have been generated later than the first.

The observation of the loop structures suggests that multipoint reconnection occurred intermitently in the magnetotail during this substorm. After the magnetic field became extremely taillike between the geostationary orbit and the ISEE locations, reconnection occurred at several locations at different times. At the expansion onset a neutral line formed near to the Earth, coincident with the tailward jetting of plasma observed by ISEE 1. While the magnetic field lines tailward of the neutral line remained very tail like, new $X-$ type neutral lines and island structures were generated and subsequently moved tailward. The possibility of occurrence of the multiple X line reconnection (MXR) process in the tail associated with substorms has been noted by *Lee* [1988] and related to the time-dependent magnetic reconnection. MXR forms magnetic islands. In this event, we may have observed two of the islands produced by multipoint reconnection. The size of the islands observed was only $\sim 2-3\ R_E$ and their vertical thickness may have been $\sim 0.5 R_E$ or less. As the two ISEE spacecraft were within the plasma sheet when they observed the islands and the thickness of the islands was of the order of the vertical separation of the two spacecraft, the islands must have been embedded within the plasma sheet.

Observations of magnetic islands on scales much smaller than that of the plasmoids suggested by *Hones* [1979] and $X-$ type neutral lines implied by negative B_z near the neutral sheet have been reported previously [e.g., *Schindler and Ness*, 1972; *Bowling*, 1975; *Lui and Meng*, 1979; *Nishida et al.*, 1981; *Nishida*, 1984]. *Bowling* [1975] reported that the looplike structures observed in the magnetotail were associated with enhanced geomagnetic activity ($K_p \geq 3$). *Lui and Meng* [1979] reported that the magnetic bubbles in the neutral sheet were observed both during substorms and during quiet geomagnetic conditions. *Nishida et al.* [1981] in their statistical study have shown evidence of the occurrence of reconnection at radial distances less than 33 R_E.

The mechanisms that allow magnetic islands in the magnetotail to form have been discussed by several authors. *Schindler* [1974] suggested that magnetic islands are generated by the ion-tearing mode when the plasma sheet is sufficiently thin and/or the normal magnetic field component is sufficiently reduced, which is the case in the CDAW 6 event. Simulations by *Sato and Walker* [1982] show that the tearing mode is excited much more violently in the presence of parallel plasma flow in the plasma sheet than in the case with no flow. *Bhattacharjee* [1987] presented a quasi-thermodynamic model for the relaxation of magnetotail plasmas during substorms and pointed out that the presence of a chain of magnetic islands along the tail axis is a universal feature of the relaxed state. Thus it is very likely in our event that magnetic islands were produced in the near-Earth magnetotail after the expansion onset, while the magnetic field was still very taillike with plasma streaming nearly along the tail axis.

Recently, *Richard et al.* [1989] have studied the magnetic island coalescence instability for magnetotail reconnection, a process wherein small islands coalesce to form a large magnetic island which moves down the tail. They pointed out that reconnection in the tail could be a two-step process: small-scale island formation followed by the rapid coalescence of small islands into larger ones. There is no evidence that we were observing a two-step process, but the occurrence of the small loop structures inside of 15 R_E may be evidence of small spatial scale reconnection in the near-Earth magnetotail.

The occurrence of small-scale islands and $X-$type structures may provide an interpretation of the brief flow reversal during the period dominated by tailward flows between 1058 and 1118 UT, mentioned in the introduction section. As reported earlier, at about the time of the ISEE 1 neutral sheet crossing at 1107 UT, the Fast Plasma Experiment (FPE) on ISEE 1 measured earthward flow for a brief interval between 1105 and 1107 UT during the period of generally tailward streaming of plasma [*Paschmann et al.*, 1985]. The energetic particle data show a significant reduction in the net tailward flux during that interval ($\sim$ 1106 UT), but only in the lowest-energy channel. Counterstreaming of H^+ ions from 1105 to 1107 UT was also reported by *Ipavich et al.* [1985]: earthward flow at $\sim$ 12 keV and tailward flow above $\sim$ 30 keV. At the same time, ISEE 2 which was in the southern lobe/sheet boundary also observed earthward flow of protons (< 40 keV) for about 1 min (see Figure 1 of *Paschmann et al.* [1985]). Between 1105 and 1107 UT, the two ISEE spacecraft moved through the northern plasma sheet boundary layer, the central plasma sheet, and the southern plasma sheet boundary layer. The fact that the brief flow reversal was observed simultaneously at ISEE 1 and ISEE 2 suggests a common source of flowing ions. The spacecraft may have entered a region containing plasma flowing from a newly formed $X-$ type structure tailward of the spacecraft. As flows jetted away from the reconnection region, the spacecraft earthward of the $X-$ type magnetic field thus observed earthward flow. The newly formed $X-$ type structure may have accelerated particles only to relatively low kinetic energy so that only low-energy particles revealed net earthward streaming and high-energy channels were dominated by tailward streaming particles which may have been accelerated effectively by sources earthward of the spacecraft. We do not have direct evidence for the above conjecture, but it seems plausible. *Eastman and Frank* [1984] have also mentioned the idea of multiple X line reconnection in interpreting the flow reversals in this event. They found that while the reversal at $\sim$ 1105 to 1107 UT could be explained reasonably well by multiple X line reconnection, the reversal at $\sim$ 1116 to 1118 UT could not. Here we have interpreted the later reversal as a signature of tailward motion of the near-Earth neutral line.

As mention in the introduction section, the FPE data [*Paschmann et al.*, 1985] show that ISEE 1, which was travelling inbound behind ISEE 2, observed the flow reversal (at $\sim$ 1116 UT) 1 to 2 min earlier than ISEE 2 did (at $\sim$ 1118 UT). To interpret this observation, we have made use of a three-dimensional reconnection simulation by *Birn and Hones* [1981]. In Figure 13 we have reproduced one of the panels in their Figure 2 showing the flow pattern around the reconnection region in the xy plane. The figure shows that the earthward flow region (left part of the panel) is surrounded by regions of tailward flow. It is possible that as ISEE 1 traveled through the outer portion of the earthward flow region, ISEE 2 was just outside the region of earthward flow and continued to observe tailward flow for some time. The two circles in Figure 13 indicate schematically the proposed locations of the two ISEE spacecraft at the time of the observed flow reversal.

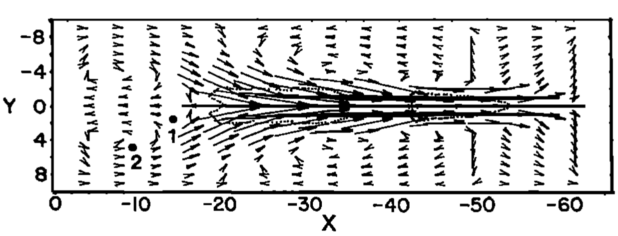


Fig. 13. Flow vectors and magnetic neutral lines (dotted lines) in the xy plane from the computer simulation by *Birn and Hones* [1981].

Another problem to be explained is that after 1110 UT, while tailward streaming flow was still observed, B_z turned northward (Figure 2). If the spacecraft was tailward of the near-Earth X line as implied by the tailward streaming particles, the B_z component should have been negative, or near zero in the case of taillike field configuration. The northward turning of B_z after 1110 UT may be interpreted in terms of a finite longitudinal extent of the X line. The near-Earth reconnection region where B_z is negative may be localized in the y direction. On either side (in the y direction) of the reconnection region magnetic field lines are closed (thus B_z is positive), but the plasma is still streaming tailward. When the ISEE spacecraft moved earthward and toward later local time, they left the reconnection region and entered the surrounding region with closed field lines. Thus the spacecraft observed northward turning of B_z but continued to observe tailward streaming particles. The possibility of such a situation is also demonstrated clearly in Figure 13 which shows that the region of negative B_z (the reconnection region enclosed by dotted lines) was more restricted than that of strong tailward flow. As pointed out by *Birn and Hones* [1981], negative B_z does not prevail throughout the entire region of tailward flowing plasma. Thus observations of tailward flowing plasma threaded with northward field do not rule out the existence of reconnection.

An alternative interpretation of the positive B_z with tailward flow after 1110 UT is that the ISEE spacecraft were observing the high-speed ion beam which characterizes the plasma sheet boundary layer, since after 1110 UT both ISEE 1 and 2 were probably in the sheet/lobe boundary layer (with magnetic field strength of 50 to 60 nT and plasma density about $\sim 0.3/\text{cm}^3$ to $\sim 0.1/\text{cm}^3$). As described by, for example, *Eastman and Frank* [1984], signatures of this region include enhanced anisotropies of the particle distribution functions and high-energy ion beams. The high-speed ion beams observed in the plasma sheet boundary layer are dominantly field-aligned and flowing sunward but they may occasionally be antisunward or counterstreaming. A statistical study by *Baumjohann et al.* [1988] also shows that high-speed flow is a characteristic of the plasma sheet boundary layer, but all of the high-speed flow they observed were field-aligned and directed toward the Earth. From 1110 UT until 1200 UT, both of the ISEE spacecraft were in the plasma sheet boundary layer, except for the short interval around 1125 UT when ISEE 1 went into the lobe. During this period each spacecraft moved only $\sim$ 900 km in the $-z$ direction, but three different streaming patterns were observed. The streaming was tailward before $\sim$ 1116 UT on ISEE 1 and before $\sim$ 1118 UT on ISEE 2. Then it turned earthward, and the streaming ended after 1140 UT (see Figure 4 of this paper and Figure 1 of *Paschmann et al.* [1985]). It is unlikely that one of the two spacecraft traversed three different layers in 900 km, and the other, separated by 2000 to 3000 km, traversed the same three layers in another 900 km. Thus we believe that the changes in particle streaming were caused by temporal variations.

Summary

During the 2-hour interval (1000 to 1200 UT) of the CDAW 6 event the ISEE 1 and 2 spacecraft, traveling inbound, traversed various regions of the magnetotail including the central plasma sheet and plasma sheet/lobe boundary layer. Observations of energetic ions and electrons from ISEE 1 show that the particle dynamics are closely correlated with substorm phases. We have interpreted our observations in the framework of the near-Earth neutral line model of substorms, to which we have added a detailed description of small-scale structure and temporal variation.

In the growth phase of the substorm (before 1058 UT) the energetic particles were isotropic in both the plasma sheet boundary layer and the central plasma sheet near the neutral sheet. After the expansion onset, strong tailward streaming particles were observed in all channels suggesting that a neutral line formed on the earthward side of the spacecraft. We have demonstrated the possible presence of several island structures, and shown that the assumption of small-scale $O-$ type and $X-$ type field structures can explain the brief flow reversal around 1106 UT seen in low-energy particle data. In the midexpansion phase the flow direction reversed and earthward streaming particles were observed, implying that the substorm neutral line retreated tailward of the spacecraft. The streaming of particles subsided near the beginning of the recovery phase and the flux of energetic particles increased to a level a few orders of magnitude higher than that before the expansion onset, which is evidence of conversion of magnetic energy accumulated during the growth phase into particle kinetic energy.

We have considered the possibility of the phenomena we observed, such as the streaming pattern of energetic particles, being the result of the spacecraft traversing different regions, for example, the central plasma sheet and the plasma sheet/lobe boundary layer. But the onset of the particle streaming, its reversal and subsidence were observed by two ISEE spacecraft (with a small time shift) when the two spacecraft were obviously traveling in different regions for some period. A similar streaming pattern observed by the two spacecraft located in the different regions is best interpreted as phenomena associated with a common particle source which is suggested as the near-Earth reconnection region.

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