OBSERVATIONS OF A QUASI-STATIC PLASMA SHEET BOUNDARY

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Abstract. No high-speed flows or discernible counterstreaming ion beams were observed during a series of plasma sheet boundary encounters resulting from solar wind-driven plasma sheet motions. We conclude that the boundary may be active primarily during plasma sheet “recovery”. A temporal onset of flows in the inner plasma sheet (IPS) was associated with the appearance of counterstreaming beams embedded in an already isotropic plasma sheet distribution, suggesting that high speed flows at the plasma sheet boundary and close to the neutral sheet may have a common generation mechanism.

Introduction and Datasets Used

Substorm recoveries are often associated with entries of spacecraft from the lobes into the central plasma sheet (CPS) at distances > 10 R_E [Hones et al., 1967] though not always on a one-to-one basis [Lui et al., 1977]. Such entries, termed “plasma sheet recoveries”, appear to be expansions of the plasma sheet, characterized by sharp increases of the particle fluxes, high speed flows lasting 10-15 minutes, ion heating and magnetic field dipolarizations [Hones et al., 1971; Pytte et al., 1976; Lui et al., 1977; De Coster and Frank, 1979].

The outermost layers of the plasma sheet contain fast earthward ion beams [Lui et al., 1983; Takahashi and Hones, 1988]. Tailward beams appear as the distance from the boundary increases; eventually isotropic distributions dominate in the CPS. Plasma sheet boundary layer (PSBL) ion beams can be found for a wide range of geomagnetic activity and irrespective of substorm phase. Eastman et al. [1984] and Takahashi and Hones [1988] argued that such beams are nearly always present at the plasma sheet-lobe interface. However, PSBL ion flows remain below 100 km/s more than 60% of the time under all AE conditions (Baumjohann et al., 1988) Figure 9).

Since a small PSBL ion velocity may also result from a slight imbalance between counterstreaming beams [Eastman et al., 1984] the question whether ion beams represent a permanent feature of the PSBL remains unanswered.

Here we present a series of plasma sheet boundary crossings during which the plasma velocity was small and the ion distributions were essentially isotropic. We used data from the Los Alamos/MPI Fast Plasma Experiment [Bame et al., 1978a] and the UCLA magnetometer experiment [Russell, 1978] on ISEE 2. The time to measure an ion distribution function is 3 s (spin period) but the sampling interval is 12 s (at low data rate mode). The plasma moments were running-averaged with a 36 s window to reduce scatter; magnetic field data were running-averaged with a window of 12 s centered at the times of the plasma moments; magnetic field and plasma moments are plotted at 12 s resolution. The ion distribution functions were averaged at 2 min resolution to reduce noise, but they are qualitatively similar to the unaveraged ones. As a solar wind monitor, we used 64 s resolution data from the vector helium magnetometer [Fredsen et al., 1978] and 5 min resolution data from the LANL electrostatic analyzer [Bame et al., 1978b] on ISEE 3. IMP 8, closer to Earth, was used to establish the propagation of solar wind features from ISEE 3 to the near-earth environment, but was inappropriate as a principal solar wind monitor because its plasma data were sparse and noisy during this interval. We used 64 s resolution magnetic field data and 1 min resolution plasma data measured on IMP 8, after we running-averaged the data with a 10 min window. Ground magnetometer data from Alaskan and Western Canadian stations [Russell, 1987] at 1 min resolution were also used.

Magnetotail Observations

On March 16, 1979 at 0600 UT, ISEE 2 was in the northern tail lobe (Figure 1) at a large distance D_L from the expected position of the neutral sheet [Dandouras et al., 1988] but was closing upon it fairly quickly, mostly because the tilt angle of the Earth’s dipole (χ) was increasing. We identified the plasma sheet by requiring the ion pressure to exceed 10\(^{-2}\) nPa, the inner plasma sheet (IPS) by requiring that the ion beta, β_i, exceed 0.5 and the outer plasma sheet (OPS) by β_i < 0.5. The various regions are denoted by the grey-scale below the AE index in Figure 1; our definition of OPS is inclusive of the PSBL as defined by Baumjohann et al. [1988].

All boundary crossings took place at large D_L, given the < 3 R_E statistical plasma sheet half thickness near local midnight

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Fig. 1. Magnetic field and plasma moments measured on the ISEE 2 satellite. Position is also shown at the bottom. Coordinates: Magnetic field in GSM; Ion velocity in GSE. Units: Density N_i in cm\(^{-3}\); Temperature T_i in keV; Velocity V_x, V_y in km/s; Position in R_E. AE (nT) is at 1 min resolution. The bar indicates magnetotail regions: White is lobe, grey is OPS, and black is IPS. Dots above N_i indicate times for which distribution functions appear in Figure 2.
at downtail distances >15 R_E [Baurjohann and Paschmann, 1990], either unusual solar wind conditions or plasma sheet re-configurations must have caused these unusually high-latitude crossings. Features of the transient OPS encounters that preceded the more permanent entry in the IPS at ~1200 UT include: 1) The gradual (2–30 min) increase/decrease of the density from IPS levels; 2) The slow decrease of B_Z until 1010 UT to about ~10 nT followed by a slow increase until 1110 UT; 3) The relatively small (<100 km/s) ion flow velocity.

Distribution functions representative of the entries into the OPS and exits to the lobe are shown in Figure 2. The 0835 and 1100 UT transient OPS encounters and the 1200 UT permanent IPS entry exemplify the properties and evolution of the other ion distributions. At 0835 UT the fairly isotropic distributions upon OPS entry evolved smoothly to the high density plasma sheet distributions. Distributions at 0930 UT and 1000 UT, not shown in Figure 2, exhibit the same progression. The reverse sequence was observed during the outbound crossing at 1105 UT, shown in Figure 2, and outbound crossings at 0855 UT, 0945 UT and 1010 UT, not shown in Figure 2. In no case was there a progression from earthward beams to counterstreaming beams, to isotropic distributions, or vice-versa.

A flow enhancement did occur at ~1230 UT, after IPS entry. It was accompanied by magnetic field dipolarization, ion heating, and predominantly earthward flow velocity, features reminiscent of AMPTE/IRM Bursty Bulk Flow events [Angelopoulos et al., 1992]. An earthward beam was associated with this flow velocity increase (see bottom right panel of Figure 2), but the beam was already embedded in a fairly isotropic, hot plasma sheet ion population. A tailward moving beam was also seen at the same time; the imbalance between the two beams contributed to the observed earthward flow velocity at ~1239 UT. A tailward flow at ~1250 UT was also accompanied by two counterstreaming ion beams, with the tailward beam being faster and denser than the earthward one. At 12:55 the ion velocity switched back to earthward and was, again, accompanied by an earthward beam.

IMF and Ground Conditions

Data from ISEE 3, located at (243, -81, -14) R_E, and IMP 8, in the dawn magnetosheath at an average position of (-23, -31, 5) R_E during the 6-hr period of interest, are presented Figure 3 in GSM coordinates. The z component of the Interplanetary Magnetic Field (IMF) was predominantly northward from 0700 UT to 1300 UT on ISEE 3 (0800 UT to 1400 UT on IMP 8), but transient intervals of southward IMF can be seen both on ISEE 3 and on IMP 8; these were probably responsible for the relatively weak auroral electrojet activity in the plotted AE index.

A solar wind discontinuity was detected at ISEE 3 at 0700 UT. A decrease in ion density started at 0635 UT (line A). Given the observed velocity of 350 km/s and allowing for a 10 min delay downstream of the bow-shock, line A at ISEE 3 corresponds to the beginning of a decrease in the density at IMP 8, 90 minutes later. An anti-sunward rotation of the IMF at ISEE 3 started at 0640 UT and ended at 0700 UT (line B); line B corresponds to an anti-sunward re-orientation.

Fig. 3. Solar wind data from ISEE 3 at a position of (243, -81, -14) R_E and IMP 8 at a position of (-23, -31, 5) R_E. Coordinates: GSM Units: same as in Figure 1. The solar wind velocity elevation angle, λ, at ISEE 3 is shown grey-shaded.
of the IMF at IMP 8 80 minutes later, in accordance with the measured solar wind speed of 400 km/s. A time delay of 75 min is consistent with the measured solar wind speed of 450 km/s behind the discontinuity. Although few of the detailed magnetic field features behind the discontinuity on IMP 8 can be reproduced by a simple convection delay of the IMF measured on ISEE 3, there is an overall qualitative agreement of the magnetic field profiles at the two spacecraft. Thus, the gross characteristics of the fluctuations at ISEE 3 between 0750 UT and 1100 UT should influence the near-earth environment with a 75 minute delay. In particular, an increase of the solar wind velocity elevation angle, $\lambda$, by approximately five degrees at 0705 UT, followed by a decrease starting at 0740 UT, are features large enough to be reflected in the magnetotail's motion 75 min later.

The double southward turning seen at ISEE 3 between 1120 UT and 1300 UT was convected downstream from the Earth's bow shock almost unchanged. We extract a time delay of 60 min from the sharp northward turning at ISEE 3 at 1200 UT and at IMP 8 at 1300 UT. Thus, solar wind features seen on ISEE 3 between 1100 and 1300 UT should have influenced the magnetotail environment at the distance of ISEE 2 about 60 min later. In particular, the large increase of $\lambda$ starting around 1100 UT, peaking at 1140 UT and subsiding after 1300 UT should have influenced the magnetotail with a 60 min delay, i.e., from around 1200 UT to after 1400 UT.

A snapshot of the auroral oval at 1000 UT is shown in Figure 4, with a corrected geomagnetic (CGM) coordinate grid superimposed on it. The CGM midnight meridian is the vertical line that passes just west of Norman Wells (NOW). The auroral oval for the $K_p$ activity level of the time is superimposed in grey shading. Figure 5 presents ground magnetograms from the stations shown in Figure 4. At ~0950 UT a small activation was detected everywhere from Lynn Lake (LYN) in the east, to NOW in the west, thus extending over 2.5 hours of local time. (By "activation" we mean an increase of the AE or a decrease of the H component of the ground magnetograms; it may correspond to a substorm although we have not studied concurrent low latitude magnetograms, Pi2 data or other substorm diagnostics). A fairly large activation (300 nT) was seen at 1050 UT at College (CMO) but not to the east of CMO. Since the footpoint of ISEE 2 based on the T89 [Tsyganenko, 1989] model was ~2 hours east of CMO, the localized ground activity was confined to longitudes west of the spacecraft. Finally, another small activation at ~1125 UT was not detected at CMO but was seen at NOW, Inuvik (INK), Arctic Village (AVI) and Barrow (BW), all high latitude stations. If, therefore, extended over more than 2 hours of local time but was localized to higher latitudes.

**Synthesis**

On March 16, 1979 at 0830 UT, ISEE 2 was far from the expected neutral sheet position, yet it encountered the OPS; it exited to the lobe at 0855 UT. This transient plasma sheet encounter resulted from a change in the solar wind elevation angle, $\lambda$, seen 75 min earlier on ISEE 3. The entry into the plasma sheet was gradual, in accordance with the gradual increase of $\lambda$. The 0855 UT exit to the lobe may have been caused by the variations of $\lambda$ seen at 0750 UT on ISEE 3. The ion distribution functions were roughly isotropic at the lobe-plasma sheet interfaces with no evidence of beam structure. The elevation angle, $\lambda$, continued to increase at ISEE 3 until 0900 UT and then started to decrease. With a one hour delay, $B_z$ at ISEE 2 decreased until 1000 UT and then started increasing. This long term variation may have been due to the elevation angle increase, which probably caused the entire magnetotail to move northward. When $\lambda$ started to decrease, the distance to the expected neutral sheet position, $D_{ns}$, continued to decrease. Thus, the effect of decreasing $\lambda$ on the plasma sheet motion may have been counteracted by the decrease of the Earth's tilt angle $\chi$ (and consequently of $D_{ns}$). It is possible that the exits/entries into the plasma sheet between 0900 UT and 1120 UT were caused by motions of the tail due to fluctuations in $\lambda$.

At 0950 UT an intensification of the auroral electrojet with a large longitudinal extent occurred near the footpoint of ISEE 2. An ensuing gradual ISEE 2 entry to the OPS was followed by a slow ejection to the lobe. Neither crossing was accompanied by high speed flows or counterstreaming beams. Although we have no information about possible plasma sheet boundary activity during the onset of this activation (ISEE 2 was in the lobe at the time), it is noteworthy that during the recovery of the electrojet currents the boundary was inactive.

At 1050 UT a possible substorm onset was detected more than an hour in local time west of the expected footpoint of ISEE 2. The plasma sheet boundary, sampled twice during this period, had a small (<100 km/s) ion flow velocity and roughly isotropic distributions that evolved in the way shown in Figure 2.

At ~1125 UT, high latitude stations near the ISEE 2 footpoint detected a third electrojet intensification extending over more than 2 hours of local time. ISEE 2 was in the lobe at that time. The lobe field started to dipolarize at ~1130 UT. ISEE 2 was not in a position to detect any counterstreaming beams and high speed flows at the boundary during the initial phase of the magnetic field dipolarization. Only at 1145 UT did ISEE 2 encounter the OPS, possibly in response to
an increase in $\lambda$ at ISEE 3 60 min earlier. The plasma sheet — lobe interface passed over the spacecraft in a quasi-static state. There was no evidence of counterstreaming beams, the ion distributions were isotropic and became gradually more dense and hot as the spacecraft moved from the lobe to the OPS and into a dipolarized but slowly convecting IPS. The slow transition from the lobe to the plasma sheet differentiates this particular plasma sheet boundary entry from the typical plasma sheet expansions.

The dramatic increase in $\lambda$ seen at ISEE 3 at 1130 UT should have brought the neutral sheet closer to ISEE 2 about 60 min later. The above scenario may account for the fortuitous presence of ISEE 2 near the center of the plasma sheet when a high speed flow event started at 1225 UT. There is no evident ground magnetic signature associated with the fast flows at ISEE 2. The temporal onset of the high speed flows was accompanied by an onset of counterstreaming beams embedded within a fairly isotropic IPS distribution. The imbalance between the two beams is consistent with a net earthward or tailward flow velocity. The beams developed within an isotropic, hot ion population after an entry through a plasma sheet boundary that featured no ion beams.

Discussion and Conclusions

It is widely accepted that a recovering plasma sheet is accompanied by high speed flows and counterstreaming beams at its boundary, under a variety of geomagnetic conditions. However, it is not clear whether fast flows and/or ion beams are persistent features of the plasma sheet — lobe interface. Here we presented a series of plasma sheet boundary crossings which took place under AE conditions that varied from 50 nT to 300 nT. The boundary was devoid of fast flowing ions under quiet as well as moderately active conditions, i.e., during the subsidence of auroral electrojet intensifications at the footpoint of ISEE 2, and during the possible onset of a small substorm two hours of local time away from the footpoint of ISEE 2. Using ISEE 3 data we argued that the plasma sheet encounters were due to solar wind variations. In the cases presented, the ion distributions at the interface between lobe and plasma sheet were roughly isotropic. More case studies of such encounters and the conditions under which they occur are necessary to address the generality of the above statements. However, our counter-examples suggest that high speed flows and velocity filtered counterstreaming ion beams are not permanent characteristics of the plasma sheet boundary.

High speed flows in the CPS have been reported in the past. Huang et al. [1987] argued that during a geomagnetically active time event (AE > 500 nT) distributions of high speed flows in the neutral sheet were qualitatively similar to PSBL distributions. Angelopoulos et al. [1992] showed that CPS high speed flows can have the same properties (10 min time scale, are concurrent with magnetic field dipolarizations and ion heating, produce significant earthward transport even if they are spatially localized) as PSBL high speed flows [Lui et al., 1977; De Coster and Frank, 1979].

Here we also presented a near-neutral sheet fast flow event whose onset was probably due to the temporal onset of acceleration tailward of the spacecraft. The event took place during quiet to moderate geomagnetic activity (AE < 200 nT). Its ion distributions were reminiscent of previously reported PSBL high speed flows. This observation supports the suggestion of Huang et al. [1987] that CPS and PSBL high speed flows may be produced by the same acceleration processes. The lack of persistent beam structures at the plasma sheet boundary at all times and the temporal onset and subsidence of IPS high speed flows both suggest that such acceleration processes are inherently time dependent and are not always operating at a given local time.

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