

# Plasma Flow Reversals at the Dayside Magnetopause and the Origin of Asymmetric Polar Cap Convection

J. T. GOSLING, M. F. THOMSEN, S. J. BAME, AND R. C. ELPIC

*Los Alamos National Laboratory, Los Alamos, New Mexico*

C. T. RUSSELL

*University of California, Los Angeles, California*

A number of events have been observed in the Los Alamos/Garching fast plasma experiment data from ISEE 2 within  $\pm 3$  hours of noon wherein the  $y$  component of the plasma flow within the low latitude boundary layer and magnetopause current layer is oppositely directed to that in the adjacent magnetosheath. When the  $y$  component,  $B_y$ , of the local magnetosheath magnetic field is positive, events of this nature are found preferentially in the northern dusk and southern dawn quadrants, and when  $B_y$  is negative, they are found preferentially in the opposite two quadrants. Plasma flows in these events are always also poleward, that is they are always directed away from the GSE equatorial plane. The observations are qualitatively and quantitatively consistent with previous observations of accelerated flows at the magnetopause and with models of magnetic reconnection, with the reconnection occurring at low latitudes near the GSE XY plane independent of the magnitude or the sign of the  $y$  component of the local magnetosheath magnetic field. Local magnetic shears at the magnetopause for these events range from 60 to 180 degs, which, together with the occurrence of these events at low latitudes, does not tend to support the antiparallel merging hypothesis. These observations of  $B_y$ -dependent flow reversals provide a graphic demonstration of how asymmetric polar cap convection and related phenomena, such as the Svalgaard-Mansurov effect, originate in magnetic reconnection at the dayside magnetopause.

## INTRODUCTION

Electric field measurements made by satellites at high geomagnetic latitudes reveal that the pattern of magnetic field line convection in the Earth's polar caps depends strongly on the sign of the  $y$  component of the interplanetary magnetic field, IMF [e.g., Heppner, 1972; Heppner and Maynard, 1987]. When the IMF  $B_x$  is negative (southward) and  $B_y$  is positive (duskward), antisunward convection is concentrated on the dawnside of the northern polar cap and on the duskside of the southern polar cap. On the other hand, when  $B_y$  is negative the antisunward convection is concentrated on the duskside of the northern polar cap and on the dawnside of the southern polar cap. This asymmetric polar cap convection produces characteristic patterns in the daily variation of the geomagnetic field observed on the ground at high latitudes which depend upon the sign of the  $y$  component of the external magnetic field [Svalgaard, 1968; Mansurov, 1969]. Indeed, the Svalgaard-Mansurov effect is commonly used to infer the polarity of the IMF (pointed away from or toward the Sun along the Archimedean spiral) in the absence of direct measurements thereof. Plasma entry from the solar wind into the geomagnetic tail lobes exhibits a similar dependence on the sign of the  $y$  component

of the IMF [e.g., Hardy *et al.*, 1976; Gosling *et al.*, 1985]. In particular, the plasma mantle in the distant tail is found preferentially in the northern dawn and southern dusk lobes when  $B_y$  is positive, and in the opposite quadrants when  $B_y$  is negative.

It has been suggested that the  $B_y$ -dependence of polar cap convection, the Svalgaard-Mansurov effect, and the  $B_y$ -dependence of plasma entry into the distant tail lobes are all consequences of asymmetries associated with the reconnection (or interconnection) of interplanetary and terrestrial field lines at the dayside magnetopause [e.g., Jorgensen *et al.*, 1972; Russell and Atkinson, 1973; Cowley, 1982]. As illustrated in Figure 1, the field line tension in recently reconnected field lines should be oppositely directed in the northern and southern hemispheres and should depend upon the sign of  $B_y$ . For the case of positive  $B_y$  illustrated in the upper portion of the figure, reconnected field lines in the northern hemisphere should be pulled toward the dawnside of the polar cap as they are dragged tailward by the magnetosheath flow, and reconnected field lines in the southern hemisphere should be pulled toward the duskside of the polar cap. When  $B_y$  is negative, as in the lower portion of the figure, the forces associated with field line tension should reverse in each hemisphere.

In the reconnection scenario sketched in Figure 1, magnetosheath plasma crossing the magnetopause into the low latitude boundary layer should experience an acceleration in the direction of the large arrows drawn. As the plasma flow in the magnetosheath generally diverges from the stagnation point near the nose of the magnetopause, this acceleration is such as to tend to reverse the  $y$  component of the flow

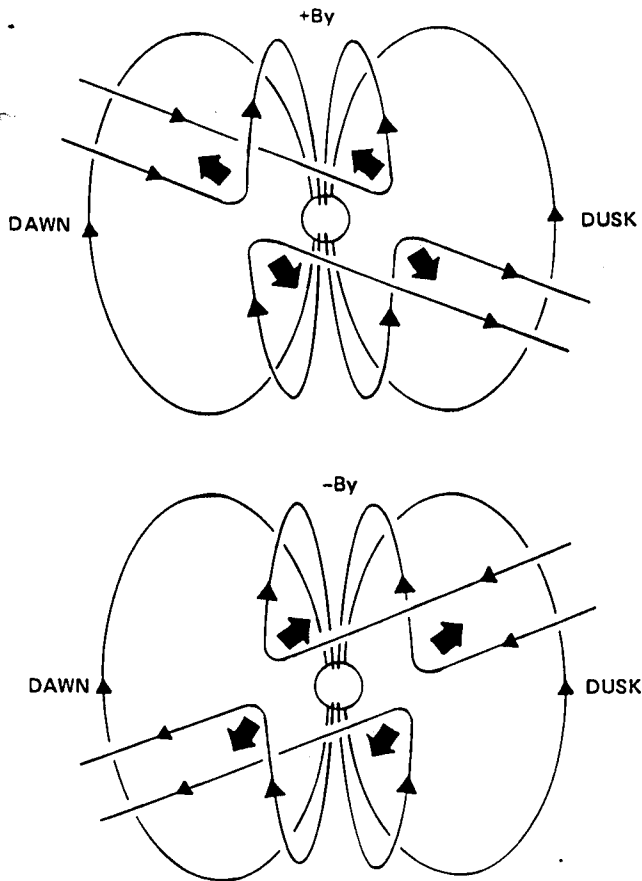


Fig. 1. Schematic drawings of reconnection at the dayside magnetopause as viewed from the Sun. The large arrows indicate the direction of the forces associated with magnetic tension on recently reconnected field lines. When the  $y$  component of the interplanetary magnetic field is positive (upper drawing), these forces pull the recently reconnected field lines toward the dawnside of the northern polar cap and the duskside of the southern polar cap as the field lines are dragged tailward by the flow of the solar wind. Similarly, when the interplanetary magnetic field is negative (lower drawing), the reconnected field lines are pulled toward the duskside of the northern polar cap and the dawnside of the southern polar cap. Such effects are believed to be the origin of asymmetric polar cap convection and related phenomena.

in the northern dusk and southern dawn quadrants when  $B_y$  is positive and in the northern dawn and southern dusk quadrants when  $B_y$  is negative. Whether or not the flow actually reverses direction there will depend upon the magnitude of the acceleration experienced and the flow speed in the adjacent magnetosheath [e.g., Scudder, 1984; Aggson *et al.*, 1984]. In general, actual reversals in the  $y$  component of the flow should be more common near noon where the field is relatively strong and where the  $y$  component of the magnetosheath flow is relatively small than near the dawn and dusk terminators where the field is generally weaker and the external flow stronger.

Using data obtained from the fast plasma experiment, FPE, on ISEE 2, a number of events have been observed where the  $y$  component of the plasma flow within the dayside low latitude boundary layer is oppositely directed to that within the adjacent magnetosheath. As would be expected on the basis of Figure 1 and the above discussion, events of this nature occur preferentially in the prenoon southern hemisphere and in the postnoon northern hemi-

sphere when the magnetosheath  $B_y$  is positive, and in the opposite quadrants when  $B_y$  is negative. Further, the flow changes observed at the magnetopause in these events are in reasonable quantitative accord with the predictions of reconnection models. These observations, documented in this paper, thus provide a graphic demonstration of how asymmetric polar cap convection and related phenomena originate in reconnection at the dayside magnetopause. Cowley *et al.* [1983] have previously discussed two such events found in the ISEE FPE data, including one of the events included in the present study (event 10 - Sept. 11, 1979).

Before proceeding to the observations, we should note that there is nothing fundamentally different about magnetopause reconnection events where a flow reversal is present as opposed to reconnection events where no flow reversal occurs. Events of the latter sort, commonly characterized by plasma flows considerably higher than in the adjacent magnetosheath but directed roughly in the same direction as the magnetosheath flow, have been documented in a number of papers [e.g., Paschmann *et al.*, 1979, 1985, 1986, 1989; Sonnerup *et al.*, 1981; Gosling *et al.*, 1982, 1986] and have firmly established that quasi-stationary reconnection commonly occurs at the magnetopause, both at the dayside and along the near-tail flanks. The particular merit of the present set of observations is that it explicitly demonstrates how asymmetric polar cap convection and related effects originate in reconnection at the dayside magnetopause. Further, as noted elsewhere [Cowley *et al.*, 1983; Paschmann, 1984], the reverse flow signature is unique to reconnection models of the magnetopause and can not be an element of diffusive entry [e.g., Gary and Eastman, 1979] or impulsive penetration [e.g., Lemaire, 1979; Lemaire and Roth, 1978] models of the low latitude boundary layer.

## INSTRUMENTATION

The plasma measurements reported here were made with the joint Los Alamos/Garching fast plasma experiment on ISEE 2 [Bame *et al.*, 1978]. The experiment consists of three 90 deg spherical section electrostatic analyzers capable of making rapid two- and three-dimensional measurements of ion and electron velocity distribution functions. Two-dimensional measurements of ions and electrons are made with an azimuthal resolution of 6 deg at 16 energies at each of 16 azimuths, integrated over  $\pm 55$  deg of elevation angle relative to the ecliptic, in one satellite rotation of 3 s. The measurement cycle is repeated every spin in high data rate, and every fourth spin in low data rate. This extremely good temporal resolution allows the experiment to resolve the structure of narrow boundary layers such as the Earth's magnetopause and bow shock. Three-dimensional measurements are made much more slowly (repetition time 24 s in high data rate) with 27.5 deg angular resolution in polar angle. The magnetic field data were obtained by the University of California at Los Angeles flux gate magnetometer on ISEE 2 [Russell, 1978]. In high (low) data rate the experiment returns a measurement of the field vector every 62.5 (250) ms. For the most part this paper utilizes 12-s averages of the field on sliding 4-s centers.

## OBSERVATIONS

### *An Individual Event*

Figure 2 presents selected ion moments and the  $z$  component of the magnetic field in GSE coordinates from ISEE

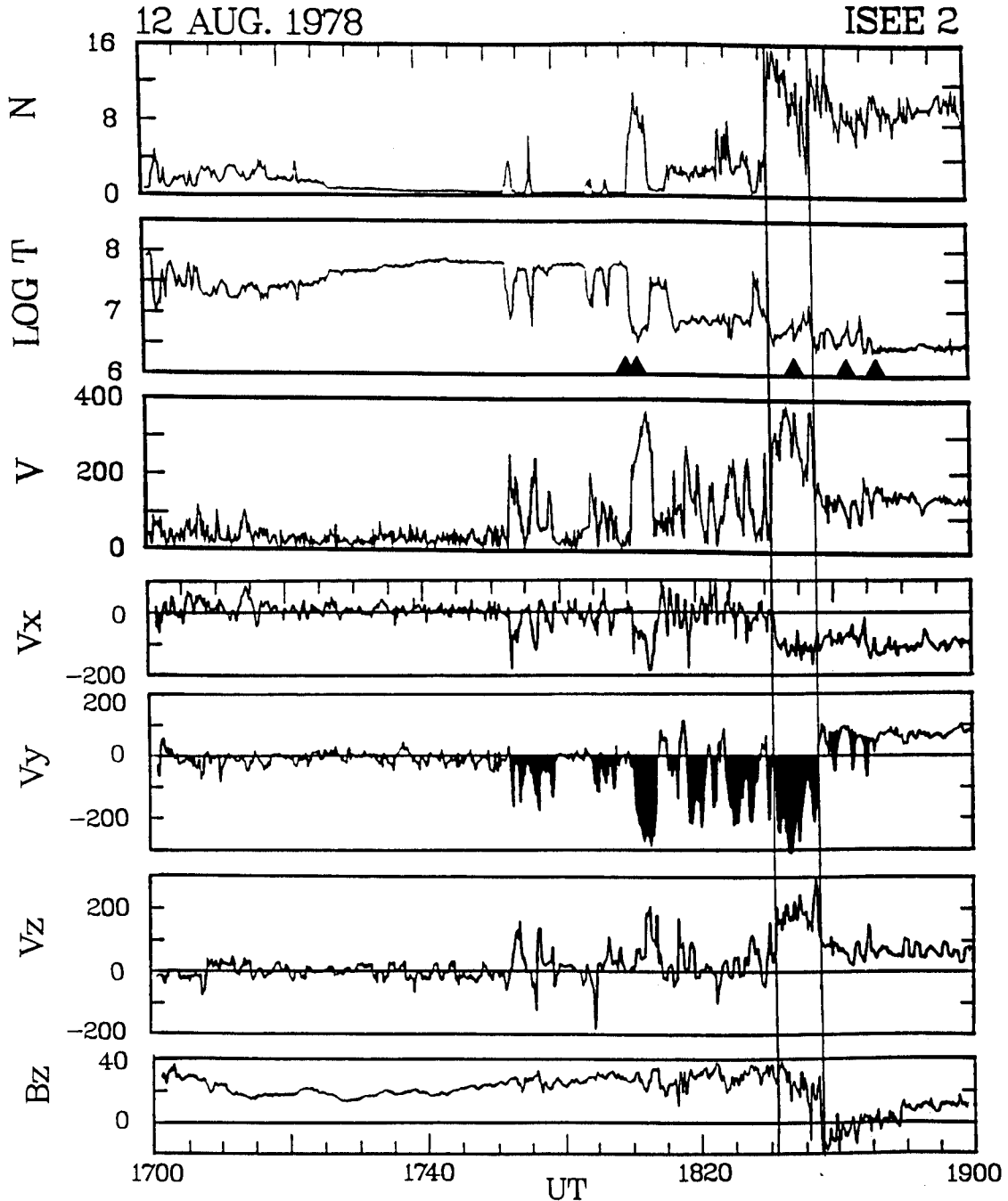


Fig. 2. Plasma and magnetic field data from ISEE 2 surrounding an outward crossing of the Earth's magnetopause on August 12, 1978. From top to bottom the quantities plotted are the ion density ( $\text{cm}^{-3}$ ), the ion temperature (K), the bulk flow speed (km/s), the GSE X, Y, and Z components of the bulk flow speed (km/s), and the GSE Z component of the magnetic field. The shading emphasizes where  $V_y$  is oppositely directed to the flow prevailing in the adjacent magnetosheath. Vertical lines bracket the actual magnetopause traversal.

2 for an outbound crossing of the magnetopause on August 12, 1978. The spacecraft GSE coordinates at the time of the magnetopause crossing, bracketed by the vertical lines in Figure 2, were (8.3, 2.4, 3.8)  $R_E$ . Thus the crossing occurred in the postnoon sector at a northern GSE latitude. Figure 3 shows the complete magnetic field data for this same time interval, also in GSE coordinates. As would be expected for this spatial location the magnetosheath flow sunward of the magnetopause, that is after 1837 UT, was

predominantly antisunward ( $-V_x$ ), duskward ( $+V_y$ ), and northward ( $+V_z$ ).

Intermittently, from about 1753 UT until the magnetopause crossing beginning at about 1831 UT, the spacecraft was in the low latitude boundary layer, distinguished by a magnetospheric field orientation, ion densities and temperatures intermediate between those of the adjacent magnetosphere and magnetosheath, and, in this case, bulk flow speeds greater than or comparable to those in the magne-

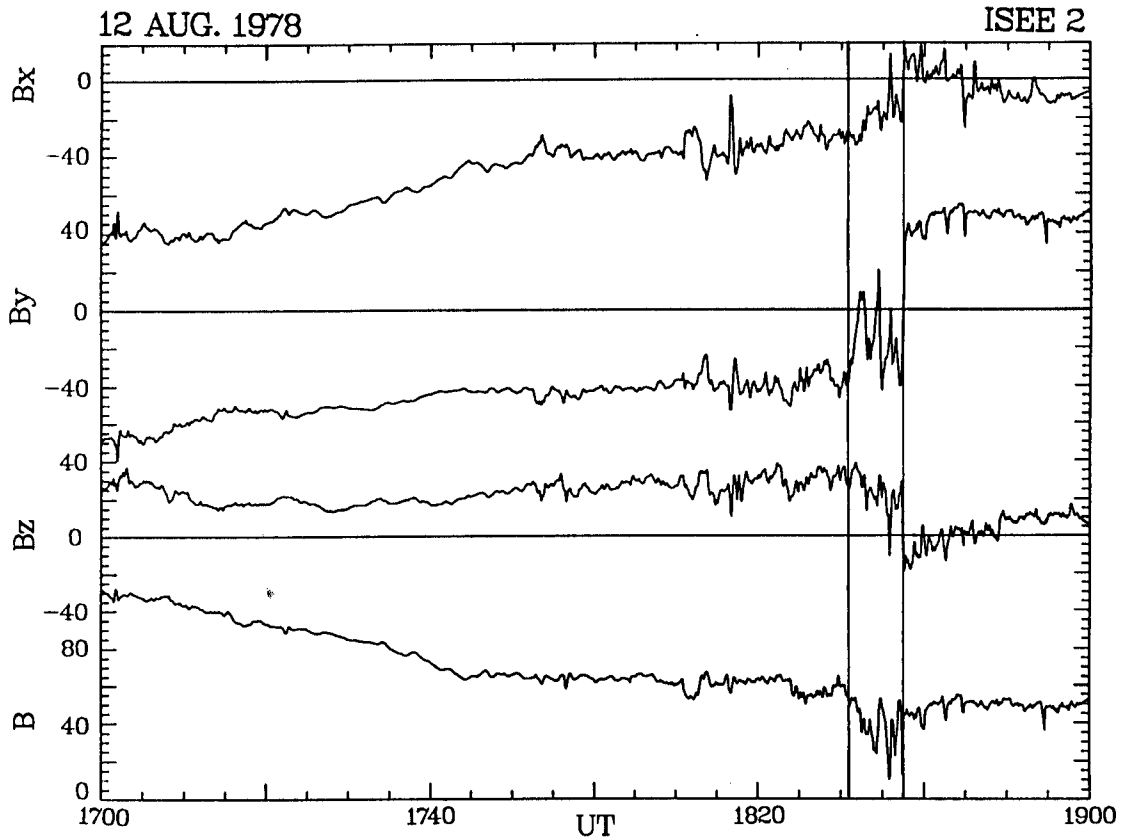


Fig. 3. Magnetic field data (in nT) from ISEE 2 in GSE coordinates for the 1700 - 1900 UT interval on August 12, 1978. Vertical lines bracket the traversal of the magnetopause.

tosheath. Of particular importance to the present paper, the  $y$  component of the flow within the boundary layer was directed downward ( $-V_y$ ) for the most part, i.e., opposite to the  $y$  component of the flow in the magnetosheath. The flow in the boundary layer was also predominantly northward, as in the magnetosheath.

Similar downward and northward flow, as well as antisunward flow, was also present within the magnetopause current layer encountered in the interval from about 1831 to 1837 UT. The current layer is identified as the region where the field executes the major portion of its rotation from its magnetospheric to its magnetosheath orientation or visa versa. From Figure 3 it is apparent that in this case the field rotation within the current layer was not monotonic as observed by ISEE 2. It is also obvious that the total field magnitude within the current layer was depressed. Such field depressions are commonly observed within the current layer when accelerated flows are present [e.g., Sonnerup, 1984; Gosling et al. 1986], and were present in approximately half of the events considered in the present study. Ion densities at the earthward edge of the current layer for the event shown in Figure 2 were actually higher than in the adjacent magnetosheath and at the sunward edge were lower than in the magnetosheath. Ion temperatures within the current layer were comparable to or slightly lower than those in the boundary layer.

The essential point of the above observations is that the  $y$  component of the flow within both the low latitude bound-

ary layer and the magnetopause current layer predominantly had the opposite sign from that within the adjacent magnetosheath. As the crossing occurred postnoon at northern latitudes and as the magnetosheath field (Figure 3) had a positive  $y$  component, the flow reversal was as predicted by the schematic drawing shown in the upper portion of Figure 1, with the actual point of reconnection lying below the spacecraft location and duskward of it. It is worth emphasizing that in this example, as in most other observations of dayside reconnection, the accelerated plasma was found both in the current layer and in the boundary layer. This contrasts with the situation along the tail flanks where the accelerated plasma in magnetopause reconnection events is almost always confined to the current layer, and there is generally no boundary layer immediately earthward of the current layer at such times [Gosling et al., 1986].

Figure 4 displays the flow and field data in boundary normal coordinates, with the N-direction being parallel to the magnetopause normal and directed outward, the L-direction being along the projection of the magnetospheric field onto a plane perpendicular to the normal, and the M-direction completing a right-handed orthogonal system. The boundary normal vector  $\mathbf{N}$  was obtained using the tangential discontinuity assumption and is (0.711, 0.014, 0.703) GSE. A minimum variance analysis on either the field or the flow vector yields nearly the same normal. In LMN coordinates the flow reversal is evident as a change in the sign of  $V_M$  at the magnetopause. In contrast to the reversal in  $V_y$ , which

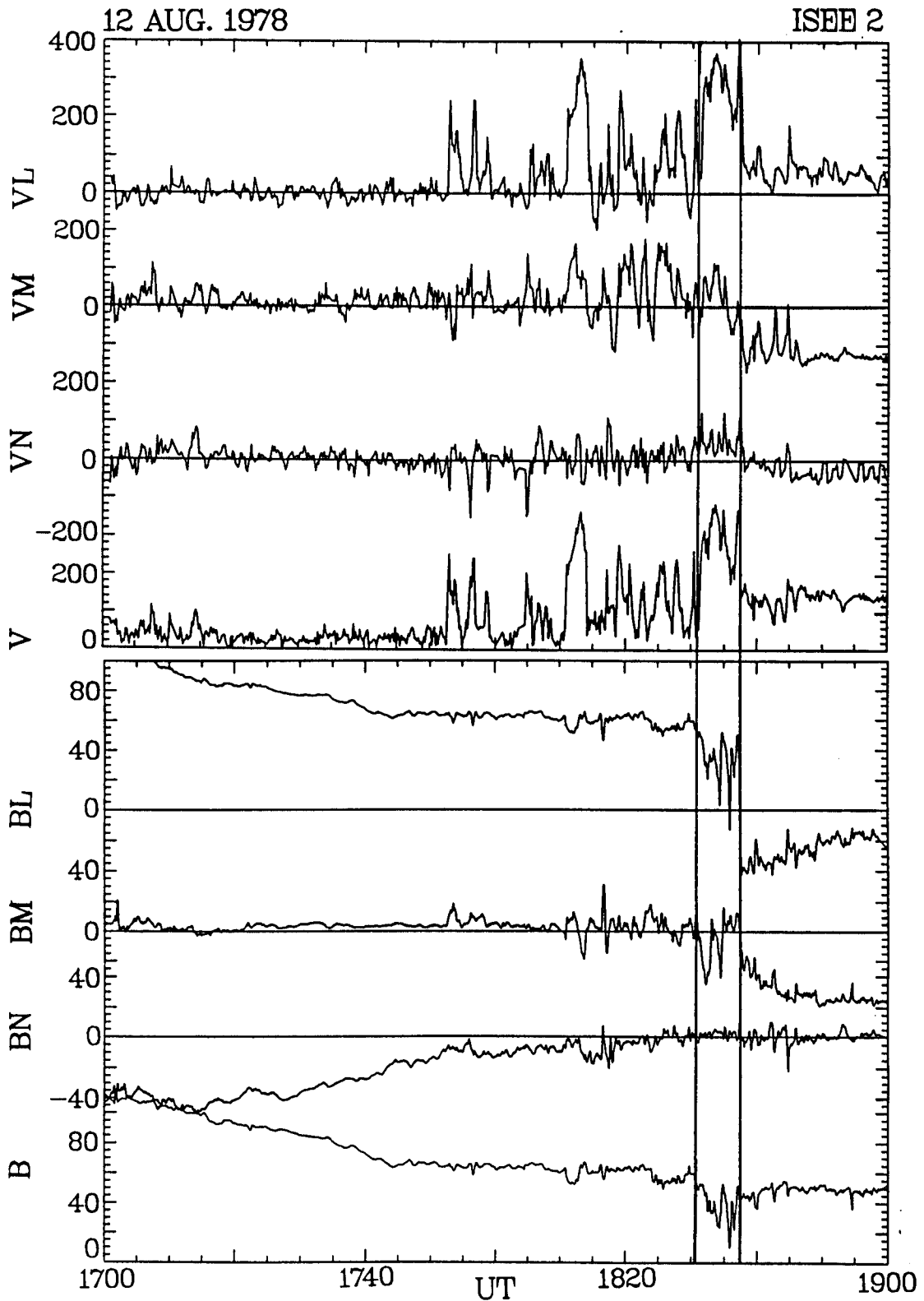


Fig. 4. Plasma flow (km/s) and magnetic field (nT) data from ISEE 2 on August 12, 1978, plotted in boundary normal coordinates. Vertical lines bracket the traversal of the magnetopause.

occurred at the outer edge of the current layer, the full reversal in  $V_M$  did not occur until approximately midway through the current layer. Further, in this coordinate system it is clear that the magnetosheath field had a substantial component antiparallel to the magnetospheric field, as well as a strong component transverse to it.

Three short-lived and small depressions in the total magnetic field are evident in both Figure 3 and Figure 4, centered approximately at 1840, 1842, and 1845 UT, shortly after the magnetopause crossing. The normal field component for each of these events exhibited the  $\pm$  signature characteristic of flux transfer events, FTEs, [Russell and Elphic, 1979], although the signature was considerably clearer for the events at 1842 and 1845 UT than for the one at 1840 UT. These events were thus "crater" FTEs as discussed, for example, by LaBelle *et al.* [1987]. Associated with each of these crater events was a significant perturbation in  $V_M$  (or  $V_y$ ), and the ion temperature was somewhat enhanced (see Figure 2). We show below that these characteristics within the crater FTEs were caused primarily by the presence of ion populations counterstreaming along  $B$  relative to the resident magnetosheath ion population.

Figure 5 shows a series of 3-s snapshots of two-dimensional ion velocity distributions,  $f(v)$ , obtained at the times indicated by the small triangles on the log  $T$  panel in Figure 2. They correspond respectively to the magnetosphere proper, the low latitude boundary layer, the magnetopause current layer, one of the magnetosheath FTEs, and finally the upstream magnetosheath. From these snapshots the following is apparent:

1. A hot magnetospheric population was not generally present in the magnetosheath.
2. Three different populations of ions were present within the FTEs: the ordinary magnetosheath population flowing roughly in the  $+y$  direction, a warmer population of ions counterstreaming along  $B$  in the  $-y$  direction, and a much hotter population of ions also counterstreaming along  $B$  in the  $-y$  direction. The presence of the latter 2 populations was primarily responsible both for the apparent deflection of the flow within the FTEs and for the somewhat higher temperatures observed there. The cooler of these populations probably consists of magnetosheath ions "reflected" at the magnetopause back along  $B$  (see, for example, Sonnerup *et al.* [1981] and Cowley, [1982]), while the hotter popula-

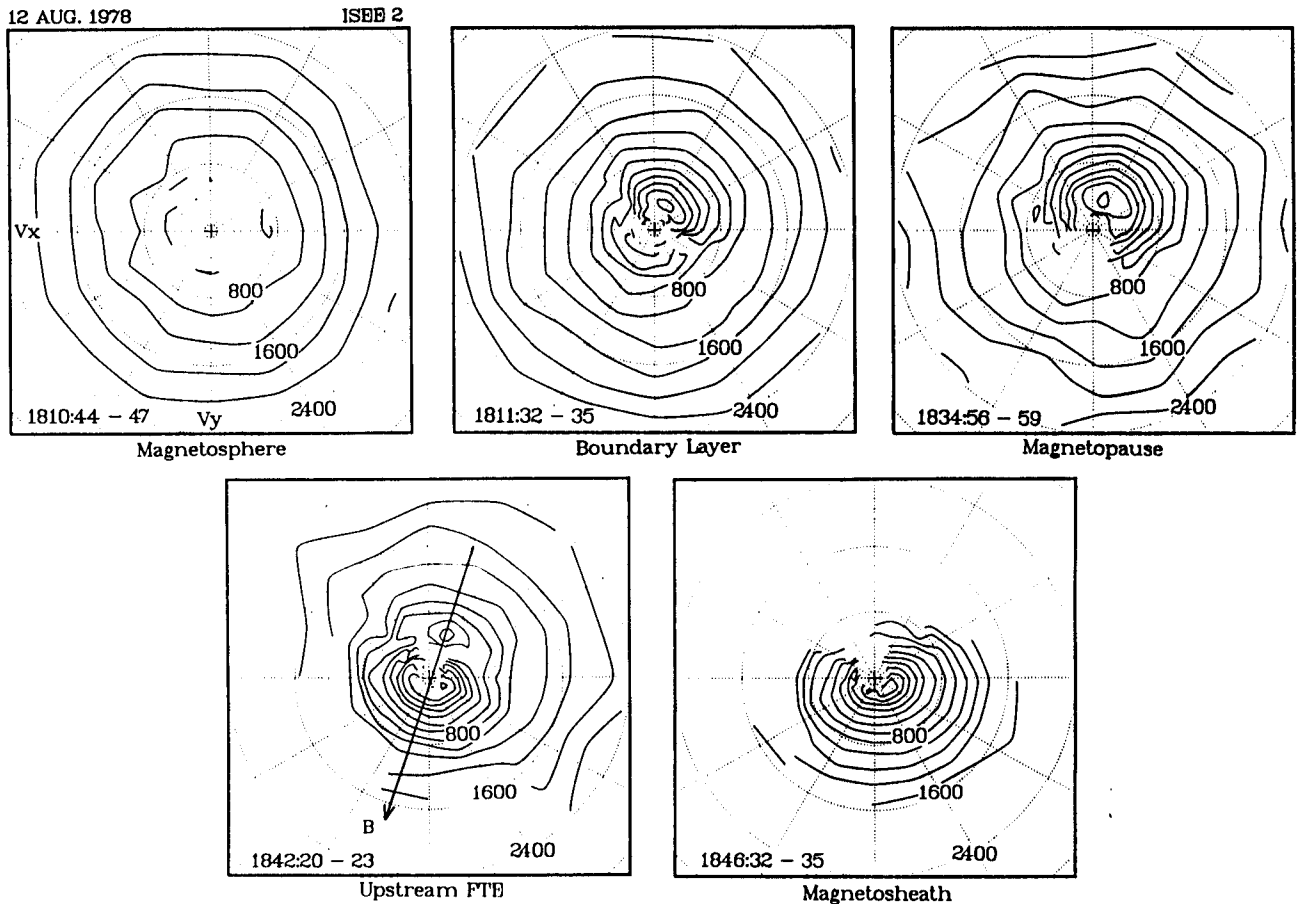


Fig. 5. Three-second snapshots of 2-dimensional ion velocity distribution functions obtained in the vicinity of the magnetopause by the fast plasma experiment on ISEE 2 on August 12, 1978. The distributions are shown as contours of constant phase-space density separated logarithmically (two contours per decade). The sunward direction is to the left and the duskward direction is to the bottom. In constructing these contours we have assumed that all of the ions present are protons and that they uniformly fill the  $\pm 55$  deg acceptance fan of the instrument. The plus symbol at the center of the plot indicates zero speed in the spacecraft reference frame, and the numbers on the dotted circles indicate the velocity scale in km/s. Successively in time (upper left to lower right), the snapshots were obtained in the magnetosphere proper, in the low latitude boundary layer, in the magnetopause current layer, in one of the upstream FTEs, and in the magnetosheath proper.

tion of ions almost certainly consists of magnetospheric ring current ions which had leaked out of the magnetosphere on reconnected field lines into the magnetosheath (see, for example, *Sonnerup et al.* [1981], *Daly et al.* [1981], and *Thomson et al.* [1987]). The dawnward direction of flow of these two additional populations was consistent with a reconnection site duskward and south of the satellite location, as has been inferred independently from the observed flows within the boundary layer and current layer.

3. Both relatively cool ions of magnetosheath origin and hot ions characteristic of the ring current were present in the boundary layer and current layer. The cooler magnetosheath-like ions were flowing in the  $-y$  direction, i.e. opposite to their  $y$  motion in the magnetosheath itself, while the hotter ions were roughly isotropic.

4. As is evident by the relative spacing between adjacent contours of  $f(v)$ , both the reflected magnetosheath ions and the transmitted magnetosheath ions were hotter than the parent magnetosheath ion population. This indicates that the higher ion temperatures of the current layer and boundary layer result not just from a superposition of magnetosheath and magnetospheric populations, but also arise from the presence of a dissipation process which heats the relatively cold magnetosheath ions entering the magnetopause current layer (see, for example, *Gosling et al.* [1986]).

#### Event Statistics

We have surveyed the ISEE 2 FPE and magnetic field data for the interval from launch in late October 1977 through January 1980 for flow reversal events at the magnetopause similar to that of August 12, 1978. The survey encompassed local times ranging from about 0400 to 2000. The second column of Table 1 contains the dates for 17 flow reversal events identified in this survey. (Subsequent to the original submission of this paper we identified several additional events, but have not included these additional events in the study.) Fifteen of the events included in the study (events 3 - 17 in the table) exhibited reversals in  $V_y$  while two (events 1 and 2) exhibited reversals in  $V_x$ . The lat-

ter two events are interesting examples of flow reversals at the magnetopause but do not relate directly to asymmetric polar cap convection and related effects. Column 3 of Table 1 contains the times bracketing the interval in which reversed flow was observed in the boundary layer and current layer. Since the presence of magnetosheath-like plasma and reversed flow within these layers was often intermittent and variable, as in the August 12 event already illustrated, the reversed flow was usually not continuously observed for the entire intervals listed. Columns 4-6 give GSE coordinates of the satellite position in  $R_E$ , while columns 5-7 provide respectively, in degs, the tilt ( $\psi$ ) of the dipole axis projected onto the GSE YZ plane, the tilt ( $T$ ) of the dipole axis perpendicular to the GSE YZ plane, and the solar magnetic latitude (MLAT) of the satellite at the time of the magnetopause crossing. We have chosen to display our data in GSE coordinates; however, the data provided in Table 1 allow the interested reader to convert the measurements to GSM or SM coordinates if so desired.

Using the data listed in Table 1, Figure 6 shows the positions of the 17 magnetopause crossings in GSE latitude and longitude. Owing to the inclination of the ISEE 2 orbit to the XY plane, the crossings shown in Figure 6 scatter across two latitude bands, one at about  $+20$  degs and the other at about  $-10$  degs. All of the data points above the XY plane correspond to outward crossings of the magnetopause while all of the points below it correspond to inward crossings. Note that all of the  $V_y$  reversal events occurred at longitudes within  $\pm 40$  degs of the noon meridian. Although both of the  $V_x$  reversal events occurred at relatively high GSE latitudes, Table 1 reveals that both events occurred at low solar magnetic latitudes.

Table 2 provides information on conditions in the magnetosheath just adjacent to the magnetopause for each of the 17 events. From left to right the various columns list the event number, the sheath ion density ( $\text{cm}^{-3}$ ), ion temperature (K), electron temperature (K), GSE X, Y, and Z components of the flow (km/s), GSE X, Y, and Z components of the sheath magnetic field (nT), the sheath plasma beta, the Alfvén flow Mach number, and the hourly-averaged value of the Z component of the interplanetary magnetic field (nT)

TABLE 1. Magnetopause Flow Reversal Events: Dates, Times, Coordinates, and Geomagnetic Dipole Orientations

Event	Date	Time	GSE			$\psi$	$T$	MLAT
			$x$	$y$	$z$			
1	12/4/77	0808-0813	8.7	-8.4	5.1	18.7	-28.5	10.8
2	1/2/78	0310-0316	4.0	-8.3	3.3	-10.0	-33.8	-4.3
3	7/31/78	2028-2116	8.9	5.8	4.5	3.0	22.9	39.5
4	8/12/78	1753-1837	8.3	2.4	3.8	12.4	25.6	43.6
5	9/8/78	0020-0040	7.6	-1.6	3.5	12.4	0.1	26.2
6	11/25/78	1414-1422	6.5	-1.3	-0.6	17.3	-10.6	-11.4
7	8/3/79	2258-2300	9.0	5.8	4.0	3.6	16.2	31.7
8	8/8/79	1711-1728	9.3	4.9	4.0	15.6	27.8	36.5
9	9/8/79	1802-1830	9.5	-0.7	3.7	16.8	16.0	37.6
10	9/11/79	0409-0411	9.8	-0.9	3.8	21.8	-6.9	14.5
11	10/14/79	0306-0324	11.7	3.3	-1.6	18.6	-19.2	-31.1
12	10/14/79	1422-1427	7.1	-5.9	3.6	27.8	2.3	38.8
13	11/21/79	1023-1032	10.4	-3.6	-1.9	25.2	-19.2	-18.8
14	11/23/79	1815-1822	11.5	-5.4	-1.8	6.1	-10.0	-14.2
15	11/28/79	1211-1212	11.6	-7.3	-1.7	21.1	-15.6	-8.6
16	12/3/79	0929-0930	9.5	-5.8	-2.0	20.7	-24.9	-19.8
17	12/15/79	0925-0928	7.3	-5.9	-2.1	15.7	26.1	-21.9

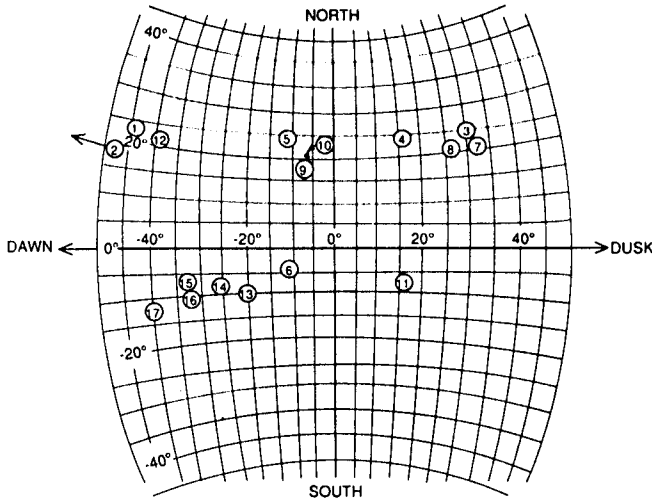


Fig. 6. GSE latitude and longitude for the 17 magnetopause events (circled numbers) discussed in this paper. Event 2 lies to the left of the plot at a longitude of 64.2 deg and a latitude of 19.7 deg; events 9 and 10 occurred at nearly the same latitude and longitude.

from either IMP 8 or ISEE 3 in GSM coordinates. Examination of the table reveals that the flow reversal events occurred preferentially for local magnetosheath conditions characterized by strong  $B_y$  and by values of beta and  $M_A$  less than 1.0, although there were some notable exceptions to this rule. Further, 12 out of 13 events for which interplanetary data are available occurred when the hourly-averaged value of the interplanetary  $B_z$  (GSM) was negative. However, the local sheath orientation of the field would seem to be the more pertinent quantity. Owing to changes in the field at the bow shock and draping of the field about the magnetopause within the magnetosheath, the local field orientation is only indirectly related to the IMF orientation upstream. On the other hand, the local field orientation is also possibly different from that at the actual reconnection site.

Table 3 presents the data on the actual flow reversals observed,  $\Delta V_o$ , as well as information on the flow reversals predicted on the basis of stress balance ( $\Delta V_p = \pm \Delta B / (4\pi\rho)^{1/2}$  where  $\Delta V_p$  is the vector change in velocity predicted,  $\Delta B$  is the observed vector change in magnetic field across the magnetopause,  $\rho$  is the plasma mass density in the magnetosheath, the plasma is assumed to consist entirely of protons and electrons and to be isotropic, and the sign depends on whether the point of reconnection lies above or below the observation point). In practice, the field and flow were variable within both the current layer and the boundary layer for all of the events studied, just as for the August 12, 1978, event shown in Figure 2; the values given in the table refer to the position where the flow speed maximized within the boundary layer or current layer. From left to right the quantities listed in Table 3 are the event number, the GSE components and the magnitude of the observed velocity change (km/s) across the magnetopause, the GSE components of the observed magnetic field change (nT) across the magnetopause, the GSE components and the magnitude of the predicted velocity change (km/s) across the magnetopause, and the angle (deg) between the predicted velocity change and that actually observed.

Figure 7 shows GSE YZ projections of the observed flow velocities in the boundary/current layer for each of the 15  $V_y$  flow reversal events, normalized to the magnitude of the flow velocity in the adjacent magnetosheath,  $V_s$ . Events for which the sheath  $B_y$  was positive are shown above, and events where  $B_y$  was negative are shown below. For  $B_y$  positive the  $V_y$  flow reversals occurred preferentially in the northern dusk and southern dawn sectors, and for  $B_y$  negative they occurred in the northern dawn and southern dusk sectors, as expected from Figure 1. Although three of the  $+B_y$  events (5, 9, and 10) occurred in the northern dawn sector just before noon, the sheath flows there had  $+V_y$  (zero  $V_y$  in the case of event 10) as noted in Table 2. Presumably this is a consequence both of the aberration of the upstream solar wind flow caused by the Earth's motion about the Sun and a transverse acceleration of the solar wind plasma at the shock as predicted by the Rankine-Hugoniot relations [Russell et al., 1981; Crooker et al., 1984].

TABLE 2. Magnetopause Flow Reversal Events: Magnetosheath Parameters

Event	n	$T_i$ ( $\times 10^6$ )	$T_e$ ( $\times 10^5$ )	GSE			GSE			$\beta$	$M_A$	IMF $B_z$ (GSM)
				$V_s$	$V_y$	$V_z$	$B_x$	$B_y$	$B_z$			
1	12	1.8	4.0	-105	-89	116	-12	-30	-19	0.67	0.77	
2	18	2.5	4.0	-173	-100	115	-30	-32	-17	0.54	0.99	-6.9
3	20	1.5	3.0	-70	70	69	-2	16	-3	4.30	1.33	
4	12	3.2	5.0	-92	92	75	10	40	-17	0.76	0.39	
5	15	2.0	8.0	-53	45	40	22	41	-18	0.58	0.28	-11.0
6	18	5.0	6.0	-50	-87	0	0	30	-100	0.32	0.15	-13.9
7	8	2.5	8.0	-78	111	63	-6	22	-7	1.59	0.76	-2.1
8	20	2.5	5.0	-70	70	46	3	18	-20	2.85	0.83	-4.9
9	20	2.4	5.0	-83	39	77	4	32	0	1.96	0.64	-1.2
10	22	2.0	4.0	-64	0	64	10	40	-16	0.95	0.49	-3.8
11	5	2.0	7.0	-44	63	-64	11	-30	10	0.43	0.31	1.3
12	40	2.0	5.0	-143	-82	95	0	-20	-18	4.76	2.04	-0.7
13	10	3.2	3.2	-35	-60	-40	-8	18	-30	0.94	0.30	-2.9
14	4	1.8	4.0	-36	-43	-57	8	32	0	0.28	0.19	-2.9
15	7	2.3	4.0	-35	-50	-35	8	17	3	1.82	0.51	
16	7	2.0	6.0	-36	-77	-31	22	32	26	0.33	0.23	-0.4
17	10	2.2	5.0	-92	-65	-65	5	35	-32	0.41	0.39	-5.4



TABLE 3. Magnetopause Flow Reversal Events: Observed and Predicted Velocity Changes

Event	GSE			$\Delta V_o$	GSE			GSE			$\Delta V_p$	$\theta_{po}$
	$\Delta V_{zo}$	$\Delta V_{yo}$	$\Delta V_{xo}$		$\Delta B_x$	$\Delta B_y$	$\Delta B_z$	$\Delta V_{zp}$	$\Delta V_{yp}$	$\Delta V_{xp}$		
1	23	-54	-211	197	-8	11	47	-50	69	296	308	176
2	27	-46	-190	174	2	12	57	10	62	293	300	170
3	13	-168	44	174	-8	-54	28	-39	-264	137	300	17
4	-86	-343	182	397	-50	-80	47	-315	-504	296	664	16
5	-212	-198	217	362	-64	-36	63	-361	-203	355	545	11
6	15	285	-287	405	12	-100	205	62	-515	1055	1175	160
7	-41	-180	53	192	-4	-44	24	-31	-340	185	388	14
8	-35	-175	102	206	-7	-56	47	-34	-273	229	358	11
9	-80	-202	116	246	-40	-52	37	-195	-253	181	367	14
10	-84	-176	129	234	-35	-65	64	-163	-233	298	412	15
11	-47	-154	-89	184	9	27	20	88	264	195	340	174
12	-56	155	117	202	-25	25	54	-86	86	186	222	27
13	-34	129	-99	166	14	-50	68	97	-345	469	590	169
14	36	149	-49	161	-3	-42	35	-33	-458	382	597	157
15	89	104	-29	140	-6	-37	27	-50	-305	223	381	143
16	49	230	-98	255	-19	-70	11	-157	-578	91	606	165
17	61	242	-149	291	-5	-77	68	-35	-532	469	710	167

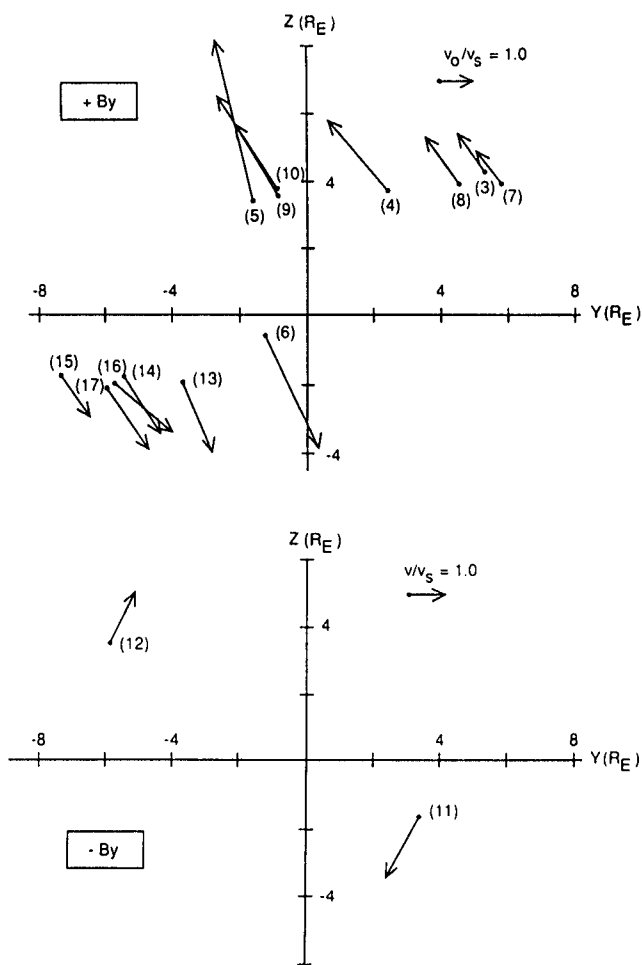


Fig. 7. GSE YZ projections of the maximum flow velocities observed in the low latitude boundary layer and magnetopause current layer plotted at the locations observed and separated according to the sign of the y component of the external magnetosheath magnetic field. The lengths of the flow vectors are normalized to the magnitude of the flow velocity in the adjacent magnetosheath, as indicated. Numbers within parentheses denote the different events.

None of the  $V_y$  reversal events also simultaneously exhibited a reversal in  $V_x$ . Thus all of the flow vectors in Figure 7 point poleward away from the XY plane. Our observations indicate therefore that the reconnection which produces  $V_y$  flow reversal events occurs primarily at low latitudes. This result is consistent with other studies of accelerated flows at the magnetopause which likewise indicate that quasi-stationary reconnection on the dayside occurs preferentially at low latitudes [e.g., Sonnerup et al., 1981; Paschmann et al., 1986].

Our events were selected on the basis of a vector flow reversal and not on the basis of an increase in flow speed; nevertheless, as is evident in Figure 7, all of the  $V_y$  reversal events had higher flow speeds within the boundary/current layer than in the adjacent magnetosheath. As shown below, however, the observed change in flow speed for these events was actually less than predicted from stress balance considerations.

Finally with respect to Figure 7, it is immediately obvious that there were far more flow reversal events for  $+B_y$  than for  $-B_y$ . The significance, if any, of this disparity in the numbers of events with + or -  $B_y$  is not known with certainty. Similar  $+B_y$  excesses for ISEE-observed magnetopause reconnection events both at the dayside and along the dusk tail flank have been reported previously [Sonnerup et al., 1981; Berchem and Russell, 1984; Gosling et al., 1986]. We note here that only two previously studied events are included in the present study. Berchem and Russell suggest that the reported dominance of  $+B_y$  events in their study was related to a dominance of  $+B_y$  in the solar wind at this time.

Figure 8, which combines the information provided in columns 5, 12, and 13 of Table 3, compares the observed vector change in velocity across the magnetopause with that predicted from stress balance. Events above the horizontal line occurred north of the reconnection site, while events below the horizontal line occurred south of the reconnection site. It is apparent that most of the observed flow deflections were within 20 deg of the directions predicted on the basis of stress balance. On the other hand, all of the observed flow speed changes were less than that predicted by stress balance, for the most part ranging between

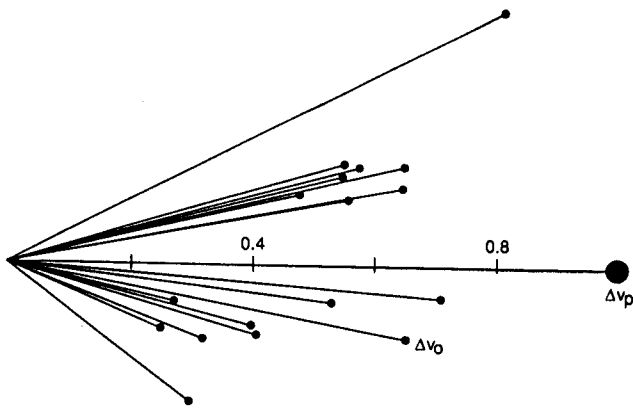


Fig. 8. Comparison between measured changes in flow velocity,  $\Delta V_o$ , with that predicted from stress balance,  $\Delta V_p$ , for 17 flow reversal events observed at the dayside magnetopause. The events have been normalized to a common scale and orientation such that the predicted velocity change is of unit length and oriented horizontally.

0.3 and 0.7 of the predicted value. Again, these results are similar to those of previous studies [e.g., Sonnerup *et al.*, 1981; Gosling *et al.*, 1986; Paschmann *et al.*, 1986]. Part of the discrepancy between observed and predicted flow speed changes may originate in our assumption that the magnetosheath plasma consists solely of protons and electrons and is isotropic.

Despite the generally good agreement of our results with previous work, there is one aspect of our observations that is not consistent with earlier studies. Paschmann *et al.* [1986] found in their study of AMPTE magnetopause reconnection events that the ratio of the observed change in flow speed (multiplied by  $\cos \theta_{po}$ ) to that predicted from stress balance considerations varied inversely with the plasma beta in the adjacent magnetosheath. They suggested that their result might be expected from theoretical considerations, which indicate that reconnection may favor low beta [e.g., Sonnerup, 1974, 1984; Quest and Coroniti, 1981]. Figure 9 shows the ratio of the observed change in flow speed to that predicted from stress balance plotted versus the magnetosheath beta immediately upstream from the magnetopause crossing for the 17 events of the present study. (We have not included the  $\cos \theta_{po}$  term in this comparison, but it is greater than 0.94 for all but two of the events.) In contrast to the Paschmann *et al.* result, no clear beta dependence of the speed ratio is discernable; if anything, the speed ratio tends to increase with beta for our events rather than decrease. Nevertheless, the fact that most of our flow reversal events occur for low magnetosheath beta is consistent with theoretical expectations.

Finally, it is worth re-emphasizing that the magnetospheric and magnetosheath magnetic fields need not be antiparallel, or nearly so, for the detection of accelerated flows at the dayside magnetopause, as has been noted in previous studies [e.g., Sonnerup *et al.*, 1981; Gosling *et al.*, 1982; Paschmann *et al.*, 1986]. Figure 10 shows a histogram of the angle through which the field rotated across the magnetopause for the 17 events of the present study. The histogram is roughly flat for field rotations greater than 100 deg, and four of the magnetopause events had field rotations of less than 100 deg. This result is consistent with the

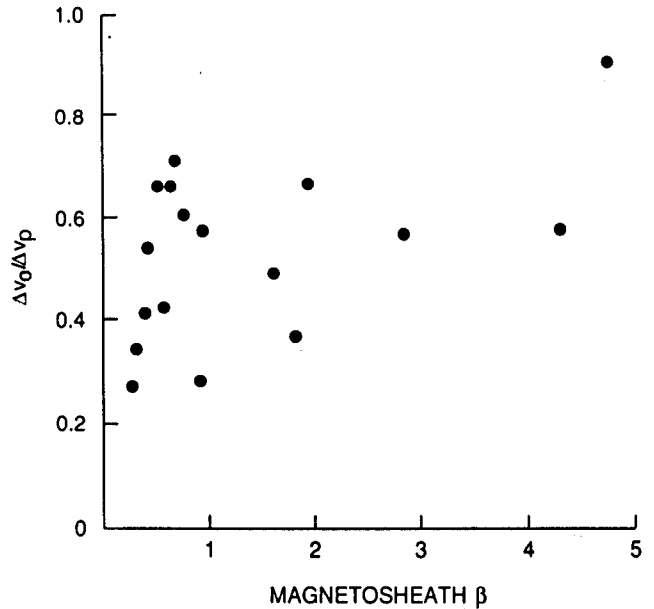


Fig. 9. Ratio of the observed speed change to the predicted speed change plotted as a function of the local magnetosheath beta for 17 flow reversal events observed at the dayside magnetopause.

earlier studies, which found magnetopause magnetic shears ranging from 60 to 180 deg at the times of accelerated flow events. On the other hand, along the near-tail flank the magnetic shear at the magnetopause is usually 130 deg or greater when accelerated flow events are detected [Gosling *et al.*, 1986].

## DISCUSSION

In the previous section we have documented a number of magnetopause crossings where the  $y$  component of the plasma flow within the dayside low latitude boundary layer and magnetopause current layer was oppositely directed to that within the adjacent magnetosheath. All of these cross-

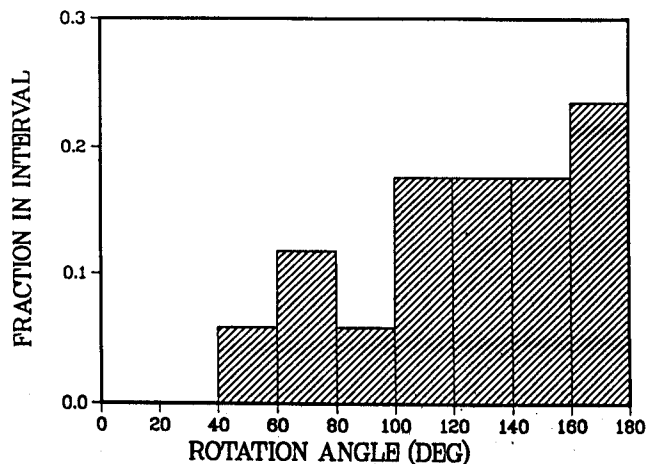


Fig. 10. Normalized histogram of the angle through which the magnetic field rotated at the magnetopause for 17 flow reversal events observed at the dayside magnetopause.

ings occurred at low latitudes and within 3 hours of the noon meridian, although our survey of magnetopause crossings encompassed local times ranging from about 0400 to 2000. The sense of the flow reversals at the magnetopause in these events depended upon the sign of  $B_y$  in the magnetosheath, and in all cases was consistent with the sketches shown in Figure 1. As the flow reversal signature is unique to reconnection models of the magnetopause, these observations leave little doubt that asymmetric polar cap convection and related effects, such as the Svalgaard-Mansurov effect and the asymmetric filling of the distant tail lobes with plasma, are consequences of  $B_y$ -dependent asymmetries associated with reconnection at the dayside magnetopause as suggested by Jorgensen et al. [1972] and Russell and Atkinson [1973].

The above result could have been anticipated on the basis of previous studies [e.g., Paschmann et al., 1979, 1986; Sonnerup et al., 1981; Gosling et al., 1986], which have demonstrated that quasi-stationary reconnection is a common aspect of the magnetopause both on the dayside and along the dusk flank. Indeed, Cowley et al. [1983] have previously documented two events similar to the events discussed here. The present work provides a firmer statistical foundation for the effect and firmly ties it to reconnection. In this regard, most aspects of the present set of observations are consistent with previous observations of accelerated flow events at the magnetopause, including: (1) the general agreement of the observed direction of velocity change at the magnetopause with stress balance considerations, (2) the preferred occurrence of reconnection at low latitudes independent of the magnitude and sign of the  $y$  component of the external (magnetosheath) field, (3) the common presence of magnetic field depressions within the magnetopause current layer, (4) the bulk heating of the magnetosheath plasma within the magnetopause current layer, (5) variable flow in the current layer and boundary layer, (6) the presence of reflected magnetosheath and leaked ring current ions on reconnected field lines upstream in the magnetosheath, (7) a mixture of magnetosheath and magnetospheric particles within the magnetopause and low latitude boundary layer, (8) occurrence when the IMF contains a southward component (GSM coordinates), and (9) a preference for low beta conditions in the magnetosheath.

On the other hand, our work has failed to confirm the result of Paschmann et al. [1986], who found that the ratio of the magnitude of the observed velocity change at the magnetopause to that predicted on the basis of stress balance varied inversely with the local value of beta in the magnetosheath. We are presently uncertain why our result, which suggests that the observed to predicted speed change ratio is roughly independent of beta, is different from theirs. The difference may arise at least partially from a selection effect inasmuch as our events were selected on the basis that the plasma acceleration at the magnetopause must be sufficiently large to cause a flow reversal. Both studies found that accelerated flow events are more common when beta is low. Analysis of further accelerated flow events with and without flow reversals may help decide whether the difference in results is fundamental, experimental, or a selection effect. Nor do we believe we have found any clear, direct evidence in our observations for the slow mode shocks predicted by some MHD models of magnetopause reconnection [e.g., Heyn et al., 1988; Biernat et al., 1989; Rijnbeek et al., 1989]. We suspect the lack of a clear signature of these predicted discontinuities is a consequence both of the con-

siderable differences in the plasmas on opposite sides of the magnetopause, as well as the intermittent nature of the reconnection process as evidenced by the highly variable flow commonly observed within the boundary and current layers in these events.

Finally, there have been several suggestions [e.g., Heelis, 1984; Newell et al., 1989; Greenwald et al., 1990] that observations of asymmetric polar cap convection and related effects are direct support for antiparallel merging models such as those of Crooker [1979] or Reiff and Burch [1985]. In such models reconnection occurs preferentially at points along the magnetopause where the magnetosheath and magnetospheric fields are oppositely directed, and thus occurs preferentially at high latitudes on the dayside as the  $y$  component of the magnetosheath field increases. However, the present observations, as well as previous observations of quasi-steady reconnection at the dayside magnetopause, indicate that such reconnection usually occurs at low rather than high latitudes, independent of the magnitude or sign of the  $y$ -component of the magnetosheath field. Further, the present study, like previous studies, indicates that dayside reconnection commonly occurs for a range of local magnetic shears between 60 and 180 deg. (Although the local measured magnetic shear need not be identical with that at the actual reconnection site, it is unlikely to be greatly different since we can infer from our observations that the reconnection site is generally nearby at low latitudes.) Only along the near-tail flanks is the antiparallel field geometry strongly favored in the observations. We thus conclude that present observations of reconnection at the dayside magnetopause do not appear to support the hypothesis that merging occurs only or preferentially in regions where the internal and external magnetic fields are nearly oppositely directed. It remains to be seen whether this conclusion can be reconciled with detailed observations of convection in the polar cap.

*Acknowledgments.* The work at Los Alamos was performed under the auspices of the U.S. Department of Energy with NASA support under S-04039-D. Work at UCLA was supported by NASA contract NAG5-1067.

The Editor thanks Nancy Crooker and Bengt Sonnerup for their assistance in evaluating this paper.

## REFERENCES

- Aggson, T. L., N. C. Maynard, K. W. Ogilvie, J. D. Scudder, and P. J. Gambardella, Observation of plasma deceleration at a rotational magnetopause discontinuity, *Geophys. Res. Lett.*, **11**, 8, 1984.
- Bame, S. J., J. R. Asbridge, H. E. Felthouser, J. P. Glore, G. Paschmann, P. Hemmerick, K. Lehmann, and H. Rosenbauer, ISEE-1 and ISEE-2 fast plasma experiment and the ISEE-1 solar wind experiment, *IEEE Trans. Geosci. Electron.*, **GE-16**, 216, 1978.
- Berchem, J. and C. T. Russell, Flux transfer events on the magnetopause: Spatial distribution and controlling factors, *J. Geophys. Res.*, **89**, 6689, 1984.
- Biernat, H. K., M. F. Heyn, R. P. Rijnbeek, V. S. Semenov, and C. J. Farrugia, The structure of reconnection layers: Application to the earth's magnetopause, *J. Geophys. Res.*, **94**, 287, 1989.
- Cowley, S. W. H., The causes of convection in the earth's magnetosphere: A review of developments during the IMS, *Rev. Geophys. and Space Phys.*, **20**, 531, 1982.
- Cowley, S. W. H., D. J. Southwood, and M. A. Saunders, Interpretation of magnetic field perturbations in the earth's magnetopause boundary layers, *Planet. Space Sci.*, **31**, 1237, 1983.

