Magnetopause structure and the role of reconnection at the outer planets

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Abstract. In situ measurements have been obtained at the magnetopause boundary of all the giant outer planets. The Jovian magnetopause was probed by Pioneers 10 and 11, Voyagers 1 and 2, Ulysses, and most recently by Galileo. Saturn was visited by Pioneer 11 and Voyagers 1 and 2, and Uranus and Neptune were visited by Voyager 2. The observations at Jupiter show evidence for flux transfer events (FTEs) and rotational discontinuities associated with magnetic reconnection with the interplanetary magnetic field (IMF), but in accord with previous studies we find no FTE signatures beyond Jupiter in the data sets we studied. At Saturn, one magnetopause encounter shows evidence for reconnection in the form of a rotational discontinuity with a finite magnetic field component through the boundary and significant plasma acceleration. At Uranus and Neptune the flank magnetopause boundary observed by Voyager 2 exhibits a complex structure (similar to that seen at Earth during high-B conditions) for which unsteady reconnection appears to occur. Closer spaced multiple magnetopause crossings at Jupiter and Saturn are consistent with a boundary surface disturbance or wave, occurring with unsteady reconnection, and coincident with a jump in upstream solar wind dynamic pressure in the Jupiter case. Because of the transient, bursty nature of the reconnection signatures and their low (<0.1 to 0.4 m/s) convective electric fields compared to those of corotation at Jupiter and Saturn, the role of reconnection in driving the dynamics of these magnetospheres is thought to be minimal in the general case. Nevertheless, the unsteady reconnection observed is important to the properties of the boundary layers. At Uranus and Neptune, observations are limited (Voyager 2 only) but suggest that bursty reconnection at the flank magnetopause can only remove plasma (in the antisunward direction), and infrrequent reconnection on the dayside would provide little opportunity for solar wind entry to energize the ionospheric plasma and supply the magnetosphere; these factors may contribute to producing the relatively empty magnetospheres that were seen.

1. Introduction

The nature of the magnetopause boundary and the role of reconnection constitute an important issue in the field of planetary magnetospheres. The classical idea of a thin boundary separating the solar wind plasma from the planetary magnetic field was introduced by Chapman and Ferraro [1931], who discussed "switch-off" of the internal planetary field by a current at the boundary surface, and the associated jet-like force bringing the upstream plasma to rest. With the development of magnetopause boundary models the question of boundary stability arose. Parker [1958] believed in an unstable solar wind-magnetosphere interaction with boundary surface waves and penetrating solar wind plasma tongues, while Dessler [1963] argued for stability based on the lack of large magnetospheric disturbances during the geomagnetic storm initial phase. The cause(s) of magnetopause surface waves continues to be the subject of much debate [e.g., Kivelson and Chen, 1995; Fitzenreiter and O’Gleive, 1995, and references therein].

Following Dungey’s [1961] suggestion of the open magnetosphere, the first models were developed for the reconnection process [Praszek 1964] and for the effect of this process on the magnetosphere [Dungey, 1963]. Where the perfect conductivity approximation breaks down locally, nonparallel magnetic field lines "diffusing" from both sides of the boundary may break and change partners in the process of magnetic merging or reconnection. When the two field regimes have an antiparallel component, some fraction of the field lines in the magnetosphere become open in these processes, providing a pathway for mixing and exchange of plasma from the sheath and magnetosphere along the field which has a normal component through the boundary. Solar wind momentum can effectively be transferred into the magnetosphere and is usually responsible for driving large-scale magnetospheric convection (at Earth). The magnetic curvature force causes the open flux tubes to contract along the current sheet at the Alfvén speed, releasing magnetic energy which heats and accelerates the plasma. The magnetic merging causes the...
tangential discontinuity boundary to decay into standing wave modes [Leyv et al., 1964]; these waves provide more rapid dissipation than diffusion. Reconnection can take place as a quasi-stationary process [Sommer et al., 1981] or in a patchy or transient process such as a magnetic flux transfer event (PTE) [Russell and Elphic, 1978]. Away from the subauroral region on the boundary, plasma flow effects can become more important than field effects where the deflected sheath flow increases toward the Alfven speed, and in some circumstances, steady reconnection may not be possible [e.g., Cowley and Owen, 1989].

The planetary magnetosphere in reality rarely resembles the simple Chapman-Ferraro ideal; it is highly structured, and the plasma and field transitions occur over different spatial extents [e.g., Song et al., 1993; Paschmann et al., 1993; Pfleger et al., 1994]. The ratio of the thermal pressure to the magnetic pressure, \( \beta \), in the magnetosheath characterizes the relative importance of the field and plasma in governing the processes taking place at the magnetopause. Obviously, the weaker the magnetosheath magnetic field, then the weaker any reconnection processes would be, and this is a particularly significant point for the outer planets situated within a low interplanetary magnetic field (IMF) where reconnection is not expected to provide much of a convective electric field (\(-\mathbf{v} \times \mathbf{B} \)). In comparison with the typical case near 1 AU, at the larger heliocentric distances of the outer planets the IMF is weaker, the Mach number of the solar wind relative to the planet is higher, the sheath plasma is therefore more greatly heated, and the \( \beta \) of the sheath is thus generally higher than that at Earth. FTE occurrence statistics for Earth have shown slightly lower rates for increased solar wind Mach numbers [Kuo et al., 1995]. Under high-\( \beta \) conditions the structure of the magnetopause might be expected to approach the classical boundary discussed above. However, this is not clear-cut, and in practice, in some Earth high-\( \beta \) cases the structure can be particularly [Russell and Russell, 1994].

The importance of corotation of the magnetospheres of Jupiter and Saturn with the planet's rotation has brought into question the role of reconnection at the outer planets. However, recent Ulysses observations at high jovian magnetic latitudes and Hubble space telescope auroral images have brought renewed interest in solar wind control [ Rufon et al., 1996; Dens and Simnett, 1996]. The jovian magnetopause is a particularly unusual case. It is not as blue as the Saturn or typical Earth case and is influenced by the shape of the internal corotating plasma-halo magnetodisk. The magnetopause surface is contracted (flattened) in the north/south direction and wobbles with the rotation period as a result of the 9.7° offset between spin axis and dipole axis [Smith et al., 1976; Huddleston et al., 1997]. The hot internal plasma in the jovian magnetosphere originates primarily from Io, and its importance in the pressure balance results in an unusually large range of magnetopause subauroral standoff distances and responsiveness to solar wind flow [e.g., Lepping, 1995]. Total external pressure applied to the magnetopause is best approximated by

\[
\mathbf{P}_{\text{total}} = \mathbf{\kappa} \cdot n_i m_i v_i^2 \cos \mathbf{\theta} + n_i (T_e + T_i) v_i^2 \sin \mathbf{\theta} + \mathbf{\kappa} \cdot \mathbf{B}^2 / (2 \mu_0)
\]

for dynamic (ram) pressure plus plasma thermal pressure plus magnetic pressure, where \( B \) is the solar wind magnetic field, \( v_i \) is the upstream solar wind plasma density, \( T_e \) and \( T_i \) are the proton and electron temperature, respectively, \( m_i \) is the proton mass, \( V \) is the upstream solar wind flow speed, and \( \mathbf{\theta} \) is the angle of the flow to the boundary normal [Paschone and Russell, 1997]. The constant \( \mathbf{\kappa} \) is adjusted downward from unity to account for divergence of streamlines around the obstacle, and \( \mathbf{\kappa} \) accounts for

the difference in mass flux along the outer magnetopause (MP) surface from that in the undisturbed upstream flow. Total internal pressure balances total external pressure at the equilibrium magnetopause. Typically, at the magnetisols the dynamic pressure dominates. For solar wind, the magnetic and thermal pressure dominate just outside the MP boundary in the sheath, and the magnetic pressure dominates within the MP. Just inside the Jupiter and Saturn magnetospheres the energy density of the hot plasma approximately equals that of the magnetic field [Krimigis et al., 1979a, 1979b; Krimigis and Rosaf, 1983; Cogdal, 1986; Mauck et al., 1996]. For Jupiter, all internal plasma and magnetic pressure terms are important, particularly the hot particle pressure and the centrifugal force of the cold corotating plasma. While most of the mass of the jovian middle magnetosphere is contained in the cold corotating plasma sheet (which determines the stretched magnetodisk configuration), the energetic particles nevertheless dominate the plasma pressure everywhere [Cogdal, 1986; Mauck and Krimigis, 1987], and at times of low solar wind dynamic pressure the location of the jovian magnetopause is determined by the pressure of the hot gases in the outer magnetosphere. Only at Saturn do centrifugal forces dominate over all other radial particle forces in a limited region of the equatorial middle magnetosphere [Mauck and Krimigis, 1987], but this region does not exhibit magnetodisk characteristics. In this paper we look at the following questions: does reconnection occur at the magnetopause boundaries of the outer planets, and if so, how important is it in determining the structure of the magnetopause and in driving the dynamics of these magnetospheres? Rotational discontinuity type magnetopause structure [e.g., Somer et al., 1981] and also FTEs [Wieler and Russell, 1985] have previously been identified at Jupiter, but the electric field generated by reconnection is thought to be smaller than that associated with the corotation of the jovian magnetospheres. The existence and size of the magnetopause have not been established in previous literature; we will present some evidence and our interpretations.

In contrast to Jupiter and Saturn the magnetospheres of Uranus and Neptune were found relatively "empty" during the Voyager 2 flyby [e.g., Cheng et al., 1987; Mauck et al., 1987; Belcher et al., 1989]. Following this discovery, reconnection has been suggested as a likely mechanism to allow tailward escape of the plasma, but it could take place as outlined by Ouyed et al. [1983] in the tail without necessarily being driven externally by the solar wind. Dayside entry of solar wind plasma into the magnetosphere by reconnection could very well be weak and intermittent because of the high-\( \beta \) conditions in the magnetosheath [Russell et al., 1989], thus providing very little energy to raise the cold ionospheric plasma to magnetospheric levels. Field line merging is expected to be periodic at both Uranus and Neptune because the large dipole axis tilt (see Table 2) results in oppositely directed sheath and internal fields on the dayside during part of the planes' rotations [e.g., Lepping, 1994]. There might also be geomagnetic substorms [both Table 2].

In this paper we survey the available magnetospheric data on the magnetopause boundary. The magnetopause boundary appeared most likely to be a rotational discontinuity suggesting an "open" magnetosphere [Sasano et al., 1991; Zhang et al., 1990; Lepping et al., 1992]. To date, evidence for reconnection has not been observed at low magnetic latitudes at Uranus and Neptune.
information, and Table 2 lists the number of magnetopause observations during these encounters, the encounter dates, and the spacecraft closest approach (C/A) distances in units of planetary radii. The next section describes our method of analysis of the boundary normal direction, and thereafter the paper is organized by planet: Jupiter, Saturn, and finally Uranus and Neptune considered together. For each planet we discuss, where applicable, multiple crossings and waves surface, magnetic structure, and plasma signatures observed. The example magnetopause observations that are presented and discussed in detail in this paper are listed in Table 3.

2. Analysis of the Boundary Normal Direction

A minimum variance technique [Sommerer and Cahill, 1987] is used to obtain estimates of the normal direction to the magnetopause boundary at each of the multiple crossings. To determine the expected error in our estimate of the normal field component, Bz, we use an adaptation of the Sommerer [1971] formulation:

\[
\delta B_\theta = \sqrt{(\delta B_x/\lambda_x)^2 + (\delta B_y/\lambda_y)^2 + (\delta B_z/\lambda_z)^2}
\]

where \(\lambda_x\), \(\lambda_y\), and \(\lambda_z\) are the minimum, intermediate, and maximum variance eigenvalues. \(B_x, B_y,\) and \(B_z\) are the magnetic field components in the maximum and intermediate variance directions (averaged over the analysis period). We estimate the uncertainty in the normal direction to be

\[
\delta B_\theta = \tan^{-1}(\lambda_z/\lambda_x)
\]

in the N-M plane such that when \(\delta B_\theta = \lambda_y\), then \(\delta B_\theta = 90^\circ\) and the axes N and M are interchangeable. When \(\lambda_x \ll \lambda_y\), then \(\delta B_\theta = 0^\circ\), and the axes are well defined. An analogous formula gives the (smaller) angular error in the N-M plane.

Sets of multiple MP encounters have been observed on the dayside, near the “nose,” at Jupiter, Saturn, and (questionably) Uranus. These have previously been interpreted in terms of a warping of the magnetopause boundary by surface waves [Layton et al., 1981, 1987] for the Saturn and Uranus cases, and recently, a semiglobal "breathing" mode [Collins and Lepping, 1996] was suggested in the case of Jupiter. Here we will extend the analysis of Lepping and coworkers to investigate the regularity of the "wave," we will incorporate the Jupiter, Saturn, and Uranus cases, and we will attempt to distinguish between possible causes. These causes are internally driven, such as by the coronal magnetospheric plasma via the Kelvin-Helmholtz instability, a boundary wave launched by a "burst" reconnection event (FTE) and/or externally driven by a solar wind dynamic pressure change, or the "relaxation" (oscillatory settling) of the boundary location to equilibrium position following such a pressure change. Figure 1 illustrates a perturbed magnetopause boundary surface and the idealized variation in the direction of the boundary normal due to the presence of sinusoidal surface waves. The magnetopause (initially a horizontal plane in the Figure) is perturbed by the wave passage. When the spacecraft approaches this interface on its inbound path, the wave passes over the spacecraft, taking it in and out of the magnetosphere with each passing wave front. The observed normals to the MP thus oscillate about the nominal upstream position \(N_{up}\), with angular deviations dependent on the amplitude of the wave and its wavelength and phase at the crossing. For a simple plane wavefront, the plane in which the normals oscillate (vertical plane in the figure) then defines a direction of wave motion along the intersection of this plane with the MP surface, which is estimated by taking cross products as illustrated. A wave path is calculated in this way for each successive pair of observed boundary normals (e.g., \(N_1\) and \(N_2\)) from the multiple crossings. Thus during passage of a plane surface wave on the magnetopause, observed normals would be
expected to lie in the same plane, and hence each pair would give approximately the same projected wave direction. If the boundary normal oscillations are irregular, these projected vector directions will vary. On the other hand, for a "relaxation" mode such as that proposed by Collier and Lepping [1996], one might expect the boundary standoff location to move in and out globally (or semiglobally) but with very little variation in the direction of the normal to the boundary.

3. Jupiter

At Jupiter, strong evidence for reconnection has previously been found, including FTE signatures [e.g., Walker and Russell, 185; Somogyi et al., 1981]. In Figure 2 a classic example of an FTE is presented. This event was observed by Pioneer 10 inbound, on November 27, 1973 (and was previously discussed by Walker and Russell [1985]). Solid vertical lines indicate the interval over which the minimum variance procedure was applied to rotate the field data into the boundary normal coordinates, and the dashed vertical lines identify the FTE event, which was observed on the MP ramp itself in this particular case. This FTE exhibits the classic bipolar signature in Bn, on a timescale of less than 1 min. Reconnection is believed to occur when the magnetic fields on either side of the boundary at the initial reconnection site have an antisymmetric component. The field rotation across this boundary is over 100°, quite favorable for the reconnection process.

Figure 3 shows the magnetic field data in RTN coordinates for the Voyager 1 passage into the Jovian magnetosphere on March 2, 1979, for the period 0700 UT to the end of that day. In the RTN coordinate system the R axis is directed from the Sun.
Figure 3. Magnetic field data from the Voyager 1 spacecraft at Jupiter on March 2, 1979, in the RTN coordinate system (see text). Upper Plot of 16 hours of data, during which the bow shock was observed twice and the magnetopause was observed 7 times, indicating considerable boundary motions at Jupiter at this time. (bottom) Expanded view of the five closely spaced multiple magnetopause crossings.

through the spacecraft. T lies in the solar equatorial plane, positive in the direction of solar rotation, and N completes the right-handed set. On March 1, both the bow shock and the magnetopause moved out over the spacecraft, then moved back in and out again on March 2. Clearly, there was significant large-scale motion of the boundaries during this encounter. Jupiter’s huge, plasma-laden magnetosphere produces a gradual pressure gradient in the outer magnetosphere; even for modest external pressure changes the MP can move a considerable distance to find equilibrium. In addition to external solar wind pressure control, the MP location will depend on the internal hot plasma content of the magnetodisk, of which Io is the primary source. The timescales for Io volcanic materials to be accumulated in the Io torus and to ultimately affect the plasma content of the jovian magnetosphere are not well known [e.g., Hill et al., 1983, and references therein; J. Spencer, private communication, 1996]. Probable ionization lifetimes in the near-Io torus are of the order of hours to days [e.g., Brown et al., 1983], and outward radial transport of torus plasma via the interchange instability occurs on timescales of days to months [e.g., Siscoe and Summers, 1981; Hill et al., 1983]. We do not expect very sudden internal pressure changes as a result of the variability of this source.

Normals and error estimates are listed in Table 4a, and the calculated extrapolated vectors of “wave front motion” are presented in Figure 4, for the series of Voyager 1 Jupiter multiple MP crossings observed between 2000 and 2230 UT on March 2. This plot is in units of planet radii (dr) in this case, where the radius values are given in Table 1 and represents the collapsed plane of the MP surface near the sun on the Sun-planet line, for an observer viewing the system from the Sun. Voyager’s position is shown, defined in planetocentric solar orbital (PSO) coordinates x, y, z, where x is directed from the plane toward the Sun and y is antiparallel to the plane’s orbital direction (approximately antiparallel to T of the RTN system, being the negative orbital direction of the Sun’s spin axis as viewed from the planet, which varies during the planet’s orbit). The z axis is up out of the orbital plane. Projected “wave motion” vectors A, B, C, and D in Figure 4 are calculated from normal vector pairs 1 and 2, 2 and 3, 3 and 4, and 4 and 5, respectively, corresponding to the crossings labeled in Figure 3, and are rotated from RTN into PSO coordinates. Waveforms for three of these multiple crossings (labeled 2, 3, and 5 in Figure 3) are included in Figure 5 (see also

![Figure 4. Projection of the calculated lines of surface wave motion onto the magnetopause “plane” in the vicinity of the suborbital point for the Voyager 1 Jupiter multiple MP observations of March 2, 1979. The plot is in planetocentric solar orbital (PSO) coordinates, and the observer is looking toward the planet.](image)
Collier and Lepping (1986). These sets of histograms show the magnetic field components in boundary normal coordinates in the planes of \( B_1 \), \( B_2 \), \( B_3 \), and \( B_4 \), for each of the crossings (time intervals are given in the figure). Crossings 3 and 5 have a finite \( B_4 \) component of the order of 2 nT, suggesting an open, reconnecting magnetosphere. (There is additional structure on the ramp itself during crossings 2 and 5.) Figure 3 shows that the magnetic shear is large and the field magnitude is reasonably steady, both as expected in the presence of reconnection. The plasma flow becomes tangential to boundaries 3 and 5 are \(-100\) and \(-210\) km/s, respectively, implying reconnection \( E \) fields of \(-0.2\) to 0.4 mV/m.

To investigate whether an internal or external change initiated the boundary disturbance evidenced by the multiple Voyager 1 encounters, we wish to investigate the upstream solar wind conditions. Voyager 2 encountered Jupiter only months after Voyager 1 (see Table 2) and was around 0.5 AU radial distance short of Jupiter during the Voyager 1 encounter. Figure 6a compares the solar wind plasma data sets from these two spacecraft at this time, where the Voyager 2 data have been shifted to a time of arrival at Jupiter (see caption), and a 10^6 density fall off with heliocentric distance has been applied. The data are 1-hour averages, covering a period of approximately three solar rotations. The Voyager 1 inbound pass apparently occurred in the vicinity of streamer belt solar wind flow, a period of rather variable solar wind density and pressure. There is remarkable agreement between the two data sets, and thus we use the Voyager 2 data as an approximate proxy for the upstream solar wind conditions at Jupiter during the Voyager 1 encounter. Figure 6b is a subset of those Voyager 2 data, showing the upstream solar wind dynamic pressure for the time period relevant to the Voyager 1 inbound pass, and the time of the multiple MP encounters is indicated (dashed vertical line). The coincidence of a large increase in dynamic pressure at this time is indicative of an external cause for the boundary motions.

We therefore favor a boundary "wave" explanation, rather than a "breathing" mode (Collier and Lepping, 1996) for which one would expect a relatively constant normal to the boundary. The jump in solar wind dynamic pressure causes a magnetopause surface disturbance occurring with (or even launched by) the observed unsteady reconnection discussed above.

Close examination of the field and plasma data for the first inbound Jovian magnetopause crossing of Voyager 1 on March 1,
1979, shows that this is a particularly interesting event. In the top seven panels of Figure 7 are the bollity velocity moments, density, and thermal velocity of the plasma from the plasma science (PLS) instrument [Ridgway et al., 1977], and in the bottom four panels are the magnetic data. Vector components are in boundary normal coordinates as determined from the field data (1952 in 2000 UT), for which the normal is (0°,0°,0°) in RTN. No PLS moment data are shown on the magnetosphere side of the MP, where the plasma temperatures were higher than the PLS instrument was designed for. Here the low-energy charged particle (LECP) instrument [Krimigis et al., 1977] observed energetic particles of high temperature and pressure; the absence of plasma in the PLS energy range should not be taken to indicate that internal plasma is not important on the magnetospheric side of the boundary. Indeed, the hot plasma pressure is comparable to the magnetic pressure just within the jovian magnetopause in the typical case [Krimigis et al., 1979a, 1979b; Cuddy, 1983; Mauck and Krimigis, 1987].

An interesting point of note from Figure 7 is that the normal component of plasma velocity ($V_N$) does not simply tend toward zero (as expected at the classical MP) but passes through zero at ~1820 UT and then becomes considerably positive, reaching around 260 km/s just outside the boundary. This behavior indicates that the MP moves outward from the planet as the plasma upstream of it, which should have nearly zero $V_N$ in the MP frame, therefore has a strong velocity component toward the Sun (away from the planet) in the spacecraft frame. Staney et al. [1980] and Suess et al. [1980] have performed theoretical calculations of statistically likely spacecraft-MP boundary encounter speeds (for spacecraft with negligible velocity in relation to the planet) based on Voyager 2 solar wind plasma dynamic pressure data and a subsolar standoff dependence on pressure to the ~1/3 power. They estimated 50% of encounters at ~40 km/s and 15% at speeds ~100 km/s. On the basis of the above results we therefore conclude that the ~260 km/s speed of the Figure 7 MP crossing is a relatively unusual case. The motion is consistent with an upstream dynamic pressure decrease at this time, marked by an arrow in Figure 6b. The MP boundary probably moves outward over the spacecraft in response to the pressure reduction. During the 3.5 hours prior to this crossing, the plasma $V_N$ data of Figure 7 indicate that the MP moves of the order of ~14 R_J, about half of the expected thickness of the magnetosheath. The total motion of the MP in response to the estimated ~0.1 MPa pressure change (Figure 6b) unfortunately cannot be accurately determined because of possible continued outward motion of the boundary beyond the observation point; thus 14 R_J is the lower limit estimate. Additionally, we note the observation of heated plasma (a huge jump in the thermal velocity in Figure 7) adjacent to the MP boundary on the sheath side and a large positive $V_N$ ~100 km/s (where $V_N$ is approximately along $\mathbf{y}$ in Figure 4) indicating deflected plasma flow from the subsolar region around the MP. For reference, note that the convection velocity at the MP location (~66 R_J for this observation) is 840 km/s, i.e., much greater than $V_N$ ~100 km/s, and for the observed magnetospheric $B$ field north-south component of ~5 of the corresponding convection $E$ field is ~4 mV/m. For the FTEs observed at Jupiter [Walker and Russell, 1985], reconnection generates $E$ fields only ~0.1 mV/m.

![Figure 6b](image)

**Figure 6b.** Subset of Voyager 2 solar wind pressure data for times corresponding to the Voyager 1 Jupiter inbound pass. The dashed vertical line indicates when the multiprobe readings (Figure 3) took place. The arrow indicates the time of the first Voyager 1 inbound MP crossing at ~167 UT on March 1.

![Figure 7](image)

**Figure 7.** Plasma data from the PLS instrument and the magnetic field observed at Jupiter for the first inbound magnetopause crossing by Voyager 1. The vector components are in boundary normal coordinates (see text). (top to bottom) Three components of the plasma bulk velocity, the velocity magnitude, proton density, thermal speed, three components of the magnetic field, and the total field strength. (Note that PLS moments are not shown within the magnetosphere because of high plasma temperatures beyond the capability of the instrument; see text.)
4. Saturn

Voyager 1 inbound at Saturn encountered the magnetopause multiple times on November 12, 1980. These data are displayed in Figure 8. The data show five crossings within a period of about an hour before the spacecraft finally entered and traversed the magnetosphere on its inbound pass. The spacecraft velocity is relatively slow (~17 km/s in inertial space) compared to the expected velocity of the magnetopause, as evidenced by the multiple crossings of the boundary. The detailed magnetic structure of the multiple magnetopause encounters is presented in Figure 9 in hodogram format. Local shear in B at each of these crossings is large, nearly 190° in some cases (i.e., crossings 1 and 4). Note that the time interval displayed for the third crossing includes a rotation due to the magnetosheath waves present, prior to the main magnetopause ramp. The fourth crossing at around 0242 UT is particularly interesting. The field rotates ~180° in the L-M plane during this interval, while Bl and the field magnitude remain approximately constant. This is a good example of a rotational discontinuity with a finite normal (Br) component through the boundary, suggestive of an open or reconnecting magnetopause at Saturn at this time. One then expects that sheath plasma enters the magnetosphere along the field lines.

In Figure 10 we present the PLS instrument magnetosheath plasma data for the multiple crossings of Voyager 1 at Saturn. We note that the LECP instrument recorded a hot internal plasma within the Saturn magnetosphere. The plasma bulk velocity components from the PLS are shown in boundary normal coordinates for the average normal direction (N=0.90,0.38,0.21)
merging process. From Figure 9, \( R_p \) = -1 nT through the boundary, and the corresponding electric field \( \mathbf{E} \times \mathbf{B} \) is of magnitude -0.2 mV/m. This is comparable to the electric fields of a few tens of millivolts per meter inferred at Earth's magnetosphere and similar to the values obtained for PTEs observed at Jupiter (Walker and Russel, 1983). However, these values are small in comparison with the convection \( F \) field, which is -1.4 mV/m at \( R_p \) (where the convection velocity is 240 km/s and the observed north-south \( m \)-magnetospheric B field component is -6.6 T in Figure 8).

Table 4b (list the oscillating boundary normal estimates for the Saturn multiple crossings, which we analyse by using the field in the same way as for the Jupiter case. Figure 11 shows the equatorial axis for the Saturn field direction plotted in the same basic frame as in Figure 4. These show a boundary surface oscillation with little scatter in alignment of "wave fronts." The oscillations are therefore consistent with a boundary wave that originated from the direction of the subsonic point. Regarding the possibility of a solar wind cause, the radial separation of the two Voyager spacecraft was -1.7 AU during the Voyager 1 Saturn encounter, and the correspondence between the data sets on the required timescales is unreliable. Thus we cannot positively distinguish either an internal (e.g., Kelvin-Helmholtz) or external cause. However, on the basis of the evidence for "open" magnetospheric field lines at this time the MP surface disturbance wave is occurring at the same time as unsteady reconnection and may even be caused by it. Therefore the MP boundary surface wave at Saturn is in some ways similar to the Jupiter case. The more regular nature of the oscillations at Saturn could in part be due to

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**Table 4b. Voyager 1 Multiple MP Crossings at Saturn**

<table>
<thead>
<tr>
<th>Crossing</th>
<th>Normal in RTN Coordinates</th>
<th>Error Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>T</td>
</tr>
<tr>
<td>1</td>
<td>0.908</td>
<td>0.357</td>
</tr>
<tr>
<td>2</td>
<td>0.976</td>
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<td>4</td>
<td>0.762</td>
<td>-0.622</td>
</tr>
<tr>
<td>5</td>
<td>0.634</td>
<td>0.700</td>
</tr>
</tbody>
</table>
the closer proximity of the spacecraft to the subsolar point, 8 R\(_J\) (~5 \times 10^6 km) compared to ~15 R\(_J\) (~1 \times 10^7 km) at Jupiter, if it is assumed the waves were launched there.

5. Uranus and Neptune

First, for completeness and for comparison, we review the magnetic field measurements obtained by Voyager 2 inbound at Uranus, displayed in Figure 12. The data are rotated into boundary normal coordinates by applying the minimum variance technique on the magnetopause traversal between ~1004 and 1013 UT as indicated by the pair of vertical lines, for which the normal vector is (0.71, 0.51, 0.48) in ITR coordinates. R\(_J\) (top trace) is in the direction of maximum field variance, B\(_N\) (third trace) is the boundary normal component of the field (i.e., in the minimum variance direction), which is typically zero for a tangential discontinuity type MP, and B\(_\parallel\) is the field along the axis of intermediate variance (second trace). The main full MP crossing shown exhibits a large (~270°) B field rotation and in some aspects resembles a slow shock [Russell et al., 1989], as is occasionally seen under high-B conditions at Earth. The structures observed from around 0947 UT upstream of the main MP crossing have been discussed previously in the literature. Initially, Lapping et al. [1987] suggested that these are partial crossings due to an MP surface wave. However, our analysis of successive normal vectors again does not indicate a simple plane wave. The structures are not complete crossings, since B\(_\parallel\) does not reach full magnetospheric strength. It was later suggested by Russell et al. [1989] that these sheath structures are mirror mode waves such as those also seen in Earth’s magnetosheath [Tsunoda et al., 1982; Hubert et al., 1989].

For the outbound pass at Uranus, Voyager 2 observed a broad, highly structured magnetopause on the flank, with the complete spacecraft traversal lasting a couple of hours. These magnetic field data are presented in Figure 13. The local shear in B on either side of the boundary is ~100°. The sheath field is relatively small. A particular feature of this crossing is a very large spike in the normal component of the magnetic field at ~0645 UT. This does not have the signature of an OPE but does resemble the unidirectional R\(_J\) pulse seen at the Earth’s magnetopause by the ISEE spacecraft [Zhu et al., 1988]. Since one would not expect the boundary normal direction to change so considerably and on such a short timescale, we believe there was indeed a large localized B\(_N\) component through the boundary itself at this time. This implies perhaps a high (but transient) reconnection rate (R\(_{\parallel}\)/R\(_J\)). Unfortunately, the plasma densities in the outer magnetosphere (for both Uranus and Neptune) are at the limits of the plasma instrument capability.

In the Uranus sheath region following the MP in Figure 13, the flow is predominantly antiparallel at ~400 km/s, the plasma density is ~0.04 cm\(^{-3}\), and the Alfven speed is ~30 km/s. Richardson et al. [1988] found velocity decreases in the sheath (the first occurring at ~1800 UT, beyond the period shown in Figure 13), which they interpreted as possible evidence for drag on reconnected flux tubes. The deceleration occurred with a periodicity approximately that of planet rotation. However, favorable conditions for reconnection coincide approximately with the optimum times for plasma mantle encounters [Zhang et al., 1996], so there are two variations in interpretation. The mantle, which extends from the cusp region, exhibits an open magnetospheric structure: a magnetotail-aligned field with a magnetosheath-type plasma. At Neptune, Voyager 2 passed through the cusp on its inbound pass. This event has been discussed in some detail by Szabo et al. [1991, 1995] and Lapping et al. [1992] and will not be addressed here. Outbound, Voyager 2 traversed the magnetopause on the flank; the data for this event are shown in Figure 14. The complete crossing again apparently took place over a couple of hours, indicative perhaps of the slow relative velocity of the spacecraft, as well as a thick boundary. In the approximate plane
of the boundary the local $B$ shear is $-125^\circ$ across the main ramp between $-0800$ and $0900$ UT, suggesting that reconnection is possible, although the ambient sheath field at later times (after $-1000$ UT) has a smaller angle to the local magnetospheric field. Figure 14 shows that the observed boundary is complex, and there is significant structure on the ramp itself, including variations in $B_z$, which is reminiscent again of some high-$\beta$ cases seen at Earth [Le and Russell, 1994]. On the sheath side of this crossing, the antisunward flow velocity is $\sim 300$ km/s. The average sheath density is $\sim 0.004$cm$^3$, the Alfvén speed is $\sim 50$ km/s which is
much less than the flow velocity, and the plasma distributions appear unusually hot. There is a strong southward flow of the order of ~100 km/s through the boundary layer, which persists until ~1500 UT before settling to an average of zero. Two possible plasma mantle encounters during the outbound stealth traversal were identified by Zhang et al. [1990] at ~1430-2100 on August 26th and at ~0730-1200 on August 27th, which would suggest that the mantle reaches considerably into the downstream magnetosphere at high magnetic latitudes.

In summary, the normal B0 component and complex structure of the Uranus and Neptune flank magnetopause as observed by Voyager 2 suggest a nonuniform current layer there. For both these cases the sign of B0 is the same on the magnetosphere and magnetosheath sides, and B0 locally changes sign across the MP indicating that there is some relative antiparallel B component, confirming that reconnection toward the cusp is possible at this time. Observations of high-latitude reconnection at Earth with antiparallel local fields have been reported by Gosling et al. [1991], Fuhrer et al. [1993], and recently by Kesel et al. [1996], who presented evidence for approximately field-aligned, Alfvénic, subauroral plasma flow. At Uranus and Neptune no subauroral flows were seen, but instead there were decelerated antisunward flows, which have been interpreted as either periodic reconnection or plasma mantle encounters (Zhang et al., 1990; Richardson et al., 1988). On the flank magnetopause we found that the magnetosheath flow greatly exceeds the Alfvén speed, so that the contraction of reconnected flux tubes to the sunward side is opposed by the flow, and transient bursty reconnection only is possible. This finding is consistent with the observations of possible transient reconnection, e.g., the large B0 spike in Figure 13. Under such a regime, sunward plasma transport into the magnetosphere is difficult, while expulsion of plasma tailward is more significant. We note, however, that since only the one spacecraft visited Uranus and Neptune, we cannot confirm whether the encounters occurred during usual or exceptional magnetospheric conditions of these planets.

6. Conclusions

FTEs are the most convincing signatures of "bursty" reconnection events. In our present study, besides Jupiter, no clear examples of FTEs as such have been found at the more distant outer planets in any of the available data sets. However, only limited regions of the magnetospheres are explored on a spacecraft flyby, and because there are few data sets available at Saturn, Uranus, and Neptune, we cannot make statistical assessments of the occurrence. Note that statistical studies at Earth (Kao et al., 1995) found FTEs on ~30% of dayside magnetopause passes [and found a small dependence of occurrence rate on solar wind magnetic Mach number to the -0.4 power]. Thus one would not necessarily expect to encounter an FTE on a single flyby trajectory such as the ones of Voyager 2 at Uranus and Neptune.

Despite the low IMF B field and high Mach number of the solar wind at the outer planets, bursty reconnection can occur there. We have identified evidence for reconnection in one case at Saturn that has not, to our knowledge, been previously pointed out. On the dayside, in one case we closely spaced multiple magnetopause crossings, a very clear rotational discontinuity type boundary was observed, with a finite B0 component (and significant plasma acceleration) indicating an open magnetosphere at this time. At the outer planets the Impinging IMF is weak, the solar wind Mach number is high, sheath plasma temperatures are high, and B is high; thus conditions are less favorable for steady reconnection than they are perhaps at Earth. Bursty, unsteady reconnection is observed. This process can lead to complex magnetopause boundary structures, such as those seen by Voyager 2 on the flank MPs of Uranus and Neptune (which are reminiscent of semiregular high-B cases). On the fluxes during transient reconnection, tailward expulsion of the plasma may occur, but contraction of reconnected flux tubes toward the dayside is impossible [e.g., Cowley and Owen, 1989] for the cases observed, since we find that the antisunward plasma flow speed greatly exceeds the Alfvén speed there. This may be a contributing cause of the relatively "empty" magnetospheres of Uranus and Neptune during the Voyager 2 encounters. We expect the Alfvén speed to exceed the flow speed only in the vicinity of the subsolar region where the incoming plasma stagnates. Weak, infrequent reconnection on the dayside would provide little opportunity for solar wind plasma to enter and energize the ionospheric plasma to supply the magnetosphere. Again, we reiterate that from a single spacecraft encounter we cannot know whether or not the encountered magnetospheric configuration is common at Uranus and Neptune.

Multiple crossings of the magnetopause are encountered at the outer planets just as they are at Earth. For the outer planets, internal plasma sources (in particular, Jovian volcanism at Jupiter) are important in determining the boundary standstill locations, perhaps changing over timescales of the order of days, but we believe that the variability of this source is highly unlikely to cause boundary surface waves. Solar wind control is also important. From the observations at the giant outer planets we may postulate that for gradual trends in solar wind dynamic pressure the magnetosphere may react fast enough to maintain approximate equilibrium; however, under more variable solar wind conditions the magnetosphere may frequently be encountered in motion and out of pressure balance. For some pressure changes it is plausible that a relaxation or "breathing mode" (as suggested by Coller and Lepping [1996]) may result as the boundary settles to an equilibrium location. However, in response to very sudden dynamic pressure jumps we suggest that if the IMP B direction is at a favorable angle to the magnetospheric field, a bursty reconnection event may allow solar wind momentum to be transmitted into the magnetosphere, and/or energy may be dispersed around the magnetosphere by a wave on the MP boundary surface. This scenario is consistent with the Jovian case during the Voyager 1 inbound pass, when multiple boundary crossings indicate a surface oscillation along with evidence for reconnection, coincident with a large jump in solar wind pressure as seen by Voyager 2 upstream (Figure 6). Similar observations at Saturn are identified as an MP wave surface originating in the vicinity of the MP nose, occurring with unsteady reconnection, although in this case we have insufficient information to positively identify the cause.

On the basis of the available data sets the relatively weak and unsteady reconnection apparent at the outer planets suggests that internal energy sources must in general dominate the dynamics within these magnetospheres; in particular, plasma corotation at Jupiter and Saturn provides E fields about an order of magnitude greater than those associated with the observed cases of reconnection. As Jupiter, Neptune encounters generally possess IMF fields of ~0.1 to 0.6 nT, while the E fields associated with corotation are of the order of 4 nT. At Saturn we find a combination of E field ~0.2 nT in one case, where the corotation E field ~1.4 nT. Thus, while dayside reconnection is important in determining local irregularities and structure of the