Observations of magnetic reconnection at the lobe magnetopause

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Abstract. Measurements made by the Fast Plasma Experiment on ISEE 2 provide direct evidence for the reconnection of the open field lines of the tail lobes with the interplanetary magnetic field at the lobe magnetopause. The evidence, obtained on seven different dates at locations well removed from the noon-midnight plane, consists primarily of observations of accelerated magnetosheath plasma within the lobe magnetopause current layer. These accelerations were either sunward or tailward, depending on the position of the satellite relative to the reconnection site. Such accelerations have been observed in both the northern and the southern hemispheres, on both the dawn and the dusk sides of the magnetosphere, and both sunward and tailward of the dawn-dusk terminator. Except for one event, all of the lobe magnetopause reconnection events examined here occurred at times of large local field shears at the magnetopause; these large field shears were associated primarily with large $x$ and $y$ magnetic field components rather than with the $z$ component. In each case the magnetosheath plasma crossing into the magnetopause current layer was heated as well as accelerated. Often, this newly heated and accelerated plasma, which was confined to the current layer where the field rotated from its magnetosheath orientation to its magnetospheric orientation, coexisted as a double-ion beam with unaccelerated mantle plasma that had entered the magnetosphere earlier upstream from the reconnection site. The change in velocity experienced by the newly entered plasma within the current layer was usually in reasonable accord with stress balance at the magnetopause. Apparent accelerations and decelerations observed upstream from the magnetopause in two of these events were associated with secondary, field-aligned ion populations that appeared to result from reflection of magnetosheath ions at the magnetopause.

I. Introduction

Dungey [1961] was the first to suggest that the Earth's magnetic field commonly interconnects or reconnects with the magnetic field carried by the solar wind at the Earth's magnetopause. Models of magnetic reconnection predict that solar wind plasma entering the magnetosphere from the magnetosheath on reconnected field lines should experience a change in velocity, which for an isotropic temperature is given by $\pm \Delta B/(4\pi \rho)^{1/2}$, where $\Delta B$ is the vector change in the magnetic field (Gauss) across the magnetopause, $\rho$ is the plasma mass density (grams per cubic centimeter), the sign depends upon the observer's location relative to the reconnection site, and the velocity change is in centimeters per second. (See Sonnerup et al. [1981] for the correct equation for the velocity change when the temperature is anisotropic. For the examples discussed in this paper the anisotropy typically is small.) Plasma accelerations observed at the magnetopause have provided direct and convincing evidence that reconnection occurs commonly at the magnetopause both on the dayside and along the near-tail flanks at low latitudes [e.g., Paschmann et al., 1979, 1986; Sonnerup et al., 1981, 1990; Gosling et al., 1982, 1986, 1990; Scoury et al., 1994; Phan et al., 1996]. At these magnetopause locations, magnetospheric field lines are initially closed, i.e., tied to the ionosphere at both ends, and reconnection produces "open" field lines that are tied at one end to the ionosphere and at the other end to the interplanetary magnetic field (IMF). Field lines newly opened by the reconnection process are subsequently dragged across the polar caps and into the tail lobes by the flow of the solar wind past the magnetosphere.

Magnetic reconnection at the dayside magnetopause occurs for a wide range of local field shears, although it favors antiparallel terrestrial and interplanetary field components [e.g., Gosling et al., 1990; Scoury et al., 1994; Sonnerup et al., 1995]. Since field lines in the outer dayside magnetosphere are primarily directed northward, dayside reconnection favors IMF orientations with southward components. In contrast, reconnection at low latitudes along the flanks of the magnetosphere strongly favors local field shears near 180°. Since geomagnetic field lines there generally have strong $x$ and $y$ (GSM) components, reconnection along the flanks favors draped IMF field lines with strong $x$ and $y$ components [Gosling et al., 1986].

Most satellite studies of reconnection at the magnetopause have concentrated on crossings to or from the magnetosphere.
at low latitudes where field lines are initially closed and populated by the hot plasma of the plasma sheet and its dayside extension. This emphasis at least partially reflects the fact that the ISEE 1 and 2 and AMPTE satellites, which have provided much of the direct observational evidence for the reconnection process at the magnetopause, had orbits that were only moderately inclined to the Earth's equator. Nevertheless, at times when the Earth's dipole was tilted strongly toward or away from the Sun the ISEE satellites often crossed the magnetopause adjacent to the tail lobes where geomagnetic field lines are open. Most of these lobe magnetopause crossings occurred tailward of the dawn-dusk terminator, although occasional crossings occurred sunward of the terminator.

It has long been suggested that a northward turning of the IMF might lead to reconnection between the IMF and the open field lines of the tail lobes at the lobe magnetopause [Dungey, 1963], a process we have previously called "reconnection." This suggestion reflects the fact that just tailward of the cusp the lobe magnetic field is expected to have a strong negative $z$ component in both hemispheres near the noon-midnight meridional plane. However, well away from that plane the $x$ and $y$ components are the strongest field components in the tail lobes at the magnetopause. We have previously discussed a set of crossings of the lobe magnetopause by ISEE 2 on June 11, 1978, near the dawn-dusk terminator where large sunward and tailward plasma accelerations were observed within the magnetopause current layer [Gosling et al., 1991]. These accelerations were in substantial agreement with models of the reconnection process and provided the first direct confirmation for the hypothesized reconnection between the IMF and the open field lines of the tail lobes. The large field shear at the magnetopause during these crossings was associated with a draped IMF in the magnetosheath having large $x$ and $y$ components rather than a strong $z$ component. Indeed, the draped IMF at the spacecraft position (GSM latitude 38.6°N, local time 18.2 hours) was oriented slightly southward. More recently, Hawkeye observations during a crossing of the lobe magnetopause at considerably higher magnetic latitudes just tailward of the dawn-dusk terminator and near the noon-midnight meridional plane have provided direct evidence for reconnection for northward IMF [Kessell et al., 1996]. Reconnection at the lobe magnetopause for northward IMF has also been inferred from ISEE 2 observations of accelerated plasma flows observed at the low-latitude dayside magnetopause [e.g., G. Le et al., ISEE observations of low latitude boundary layer for northward interplanetary magnetic field: Implications for cusp reconnection, submitted to Journal of Geophysical Research, 1996; S. A. Fuselier et al., Electron and ion signatures of field line topology at the low shear magnetopause, submitted to Journal of Geophysical Research, 1996].

To date, direct observations of rereconnection at the lobe magnetopause have been limited to the two examples noted above. However, plasma accelerations consistent with the rereconnection of lobe and IMF field lines at the lobe magnetopause were observed by ISEE 2 on at least seven occasions during the 2.5-year lifetime of the fast plasma experiment on board the satellite. All of these crossings occurred well removed from the noon-midnight plane, and most of these events involved large field shears at the magnetopause. However, as for the ISEE 2 lobe magnetopause event previously discussed, these large field shears were associated primarily with draped IMF having strong $x$ and $y$ components rather than strong $z$ components. This helps reemphasize that northward directed IMF is essential for reconnection at the lobe magnetopause only near the noon-midnight meridional plane. Our purpose here is to present the results of a survey of the ISEE 2 lobe magnetopause reconnection events that are distinguished by plasma accelerations observed with the magnetopause current layer. These results are consistent with and strengthen our earlier conclusions based on the study of a single event.

2. Observations

ISEE 2 was launched into an elliptical orbit with apogee near 22.5 $R_E$ and with an inclination of $-23°$ to the geographic equator. Among other instruments the spacecraft carried a joint Los Alamos/Garching Fast Plasma Experiment (FPE) [Bame et al., 1978] and a University of California, Los Angeles magnetometer [Russell, 1978]. In high (low) data rate the FPE returned 3-s snapshots of two-dimensional ion and electron velocity distributions every 3 (12) s. The open field lines of the polar caps and tail lobes can be recognized in the FPE data by the absence of the hot ions and electrons that characterize the plasma sheet and its dayside extension on closed field lines. Often, the lobe field lines immediately earthward of the magnetopause are populated by a moderately dense, slow, tailward flowing plasma known as the mantle [e.g., Rosenbauer et al., 1975]. The mantle is believed to consist primarily of solar wind plasma that enters directly into the magnetosphere on reconnected field lines sunward of the spacecraft and that is decelerated and heated in the process. This paper concentrates on crossings of the lobe magnetopause where the plasma accelerations characteristic of

![Figure 1](image1.png)

**Figure 1.** GSM coordinates (top, $z$ and $y$; bottom, $x$ and $y$) of ISEE 2 for seven lobe magnetopause reconnection events.
rereconnection between the IMF and the open fields of the polar caps and tail lobes were clearly evident. Such events constitute a small subset of all of the available ISEE 2 magnetopause crossings. Reconnection events in which the plasma acceleration is small, such as would occur when the field shear across the magnetopause is low, might possibly have been missed in our survey. However, we believe that there are few such unidentified reconnection events in the data.

Event Locations

Figure 1 shows the GSM coordinates of ISEE2 for all seven lobe magnetopause reconnection events identified in our survey. Five of the events occurred at northern latitudes on the duskside of the tail, and two occurred at southern latitudes on the dawnside of the tail. Five of these events occurred well tailward of the dawn-dusk terminator, one (the June 11, 1978, event previously discussed) occurred near the terminator, and one occurred sunward of the terminator. (As previously noted, there were significantly fewer crossings of the lobe magnetopause sunward of the terminator.) Primarily sunward plasma accelerations were observed for the event sunward of the terminator, both sunward and tailward accelerations were observed for the event near the terminator, and only tailward accelerations were observed for the events well tailward of the terminator. This suggests that at these latitudes reconnection

(as distinguished by accelerated plasma flows) between the IMF and the open field lines of the lobes occurs preferentially in the vicinity of and sunward of the terminator.

February 7, 1980, Event

Figure 2 displays selected plasma and magnetic field data surrounding a relatively simple outbound crossing of the lobe magnetopause on February 7, 1980. This was a southern latitude crossing on the dawnside of the tail and occurred 9.47 $R_E$ tailward of the terminator. As is common at these intermediate latitudes and downtail distances, $B_x$ and $B_y$ were the strongest field components within the lobes; the large field shear of $\sim 164^\circ$ across the magnetopause was associated mostly with changes in these components. Note that $B_z$ in the magnetosheath adjacent to the magnetopause was negative. Accelerated plasma having a density comparable to but slightly lower than that in the magnetosheath, a temperature somewhat higher than the variable temperature in the magnetosheath, and a tailward flow $\sim 75$ km s$^{-1}$ faster than in the magnetosheath was observed within the magnetopause current layer where the field rotated from its magnetospheric orientation to its magnetosheath orientation. If we assume that the plasma observed within the current layer was newly entered magnetosheath plasma that was accelerated by the field stresses associated with reconnection of IMF and lobe field lines sunward of the spacecraft position, then for an isotropic temperature the predicted speed change, based on the change in the magnetic field across the magnetopause and the observed magnetosheath density, was $326$ km s$^{-1}$. The observed and predicted speed changes are in reasonable, although not perfect, agreement with one another.

Figure 3 shows representative 3-s snapshots of two-dimensional ion velocity distributions ($f(v)$) at the times indicated by the small triangles beneath the flow angle plot in Figure 2. From left to right these snapshots were obtained within the lobe adjacent to the magnetopause, within the magnetopause current layer, and within the magnetosheath. The distributions are shown in the satellite spin plane, which is nearly parallel to the ecliptic plane, and have been derived from measurements spanning $\pm 55^\circ$ about that plane. The distribution observed within the magnetopause current layer (Figure 3, middle) was distinctly different from those observed in either the magnetosheath (Figure 3, right) or the lobe (Figure 3, left). In particular, the current layer distribution appeared to consist primarily of magnetosheath plasma that had penetrated into the current layer and that had been heated and accelerated tailward in the process. The penetrating plasma had a higher temperature ($\sim 3 \times 10^6$ K) at the magnetopause edge of the current layer than at the magnetosheath edge where the temperature ($\sim 2.5 \times 10^6$ K) was comparable to that in the adjacent magnetosheath. Moreover, the temperature was roughly isotropic both in the magnetosheath and in the current layer, the perpendicular to parallel temperature ratio being $\sim 1.2$ in the magnetosheath and $\sim 1.4$ in the current layer.

June 10, 1979, Event

Figure 4 shows similar plasma and magnetic field data for a somewhat more complex set of encounters with the lobe magnetopause on June 10, 1979. These encounters occurred in the northern hemisphere on the duskside of the tail, 8.9 $R_E$ tailward of the terminator. ISEE 2 was in the lobe both in the beginning and at the end of the interval shown. Two brief
encounters with the earthward edge of the current layer occurred between 2320:10 and 2321:00 UT and between 2321:20 and 2322:15 UT. During each of these brief encounters a relatively dense, hot, and fast tailward flowing plasma was observed. A complete crossing of the current layer from the lobe to the magnetosheath occurred in the interval from 2323:50 to 2326:10 UT, during which time a relatively hot, dense, and accelerated plasma was once again observed. This plasma was flowing tailward with a maximum speed ~240 km s\(^{-1}\) faster than that of the plasma in the adjacent magnetosheath and had a temperature somewhat higher than that in the immediately adjacent magnetosheath. The magnetic field shear across the magnetopause during this crossing was ~163° and was associated largely with changes in the x component of the field, although \(B_y\) and \(B_z\) also changed sign at the magnetopause. It is noteworthy that \(B_z\) in the magnetosheath was small and slightly negative. The predicted speed change for this crossing assuming reconnection sunward of the spacecraft and an isotropic temperature was 363 km s\(^{-1}\), somewhat greater than that observed. Finally, no accelerated plasma was observed during the transition back into the tail lobe near 2329:30 UT. The field shear for this latter crossing was difficult to ascertain owing to the fluctuating nature of the field within the magnetosheath.

Figure 5 displays 3-s snapshots of representative two-dimensional ion distributions at the times indicated by the small triangles beneath the flow azimuth plot in Figure 4. These snapshots were obtained in the lobe (Figure 5, top left), during the first current layer encounter (Figure 5, top right), during the complete current layer crossing (Figure 5, bottom left), and in the magnetosheath (Figure 5, bottom right). The distribution shown for the complete current layer crossing (Figure 5, bottom left) was quite simple and appeared to consist entirely of magnetosheath plasma that had entered into the current layer, been heated to ~5 \(\times\) 10\(^6\) K (from a magnetosheath value of ~3 \(\times\) 10\(^6\) K), and accelerated tailward and duskward. This distribution is representative of all distributions observed during this complete magnetopause crossing. On the other hand, the distribution shown for the first current layer encounter was more complex in that two different ion populations were clearly visible. The lower-speed component was mantle-like in all respects (density, temperature, flow speed), while the higher-speed component was similar in nature to the tailward accelerated beam observed during the complete magnetopause crossing. Indeed, it seems certain that the low-speed component was mantle plasma already present on the lobe field lines prior to their reconnection with the IMF, while the high-speed component was newly entered magnetosheath plasma accelerated tailward by the reconnection process. Similar double-ion beams were observed throughout both brief partial
encounters with the current layer. These well-resolved beams were comparable to those observed during portions of the June 11, 1978, event previously discussed [Gosling et al., 1991]. There was at least a hint of such double-ion beams during portions of each of the seven sets of lobe magnetopause crossings examined in this study (for example, in the February 7, 1980, current layer distribution shown in Figure 3). The presence of unaccelerated mantle plasma on the recently reconnected field lines affects the moment calculations shown in Figure 4, which were integrated over the entire velocity distributions. When we restrict the moment calculation to speeds above 500 km s\(^{-1}\), we find that during the first two encounters with the current layer the newly entered magnetosheath population had a speed between 600 and 800 km s\(^{-1}\), a temperature ranging from 3 to 8 \(\times\) 10\(^6\) K, and a temperature anisotropy of \(\sim 2.0\) (as compared to an anisotropy of \(\sim 1.2\) in both the later current layer crossing and in the magnetosheath).

July 3, 1979, Event

Only one of the lobe magnetopause crossings where clear evidence for reconnection was observed occurred sunward of the dawn-dusk terminator (see Figure 1). Figure 6 shows plasma and magnetic field data for this slow outbound magnetopause crossing, which occurred in the northern hemisphere on the duskside of the magnetosphere, 4.8 \(R_E\) sunward of the terminator on July 3, 1979. The large field shear of \(\sim 160^\circ\) across the magnetopause was associated primarily with the \(x\) and \(y\) components of the field rather than with the \(z\) component. Indeed, \(B_z\) was negative in the magnetosheath adjacent to the magnetopause.

From the moment calculations, which we integrated over the entire velocity distribution, we find that the plasma observed within the current layer had a density comparable to but smaller than that in the adjacent magnetosheath and a temperature that was considerably higher. The flow there was highly variable, being predominantly sunward on the earthward side of the current layer, and tailward on the magnetosheath side of the layer. The overall sunward flow within the current layer was of variable speed and was generally slower than what was observed in the adjacent magnetosheath (\(\sim 225\) km s\(^{-1}\)). In general, these sunward flow speeds were also considerably lower than was predicted on the basis of stress balance across the magnetopause assuming reconnection tailward of the spacecraft and an isotropic temperature. For example, the predicted sunward flow speed at 2210:40 UT is approximately 400 km s\(^{-1}\), whereas the observed sunward flow speed then was \(\sim 180\) km s\(^{-1}\). External to the magnetopause in the magnetosheath near 2216 UT, small (\(\sim 100\) km s\(^{-1}\)) negative and positive speed changes were observed. These flow speed changes were associated with a relatively large temperature increase.

Some representative ion distribution functions from the July 3 magnetopause crossing, obtained at the times indicated by the solid triangles beneath the azimuthal flow angle plot in Figure 6, are shown in Figure 7. These distributions were obtained in the lobe (Figure 7, top left), the earthward edge of the current layer (Figure 7, top right), just adjacent to the magnetopause in the magnetosheath (Figure 7, bottom left and middle) and in the magnetosheath proper (Figure 7, bottom right). It is clear that multiple-ion populations were present both within the current layer and in the region external to the magnetopause where plasma accelerations and decelerations were observed. For example, two ion components were present within the current layer (Figure 7, top right): a newly entered and heated (temperature \(\sim 10^7\) K)
magnetosheath population that was flowing sunward at ~400 km s$^{-1}$ and a preexisting mantle population flowing tailward at approximately the same speed (100 km s$^{-1}$) as observed in the adjacent lobe. The moment calculations shown in Figure 6 reflect the presence of these multiple ion components but provide correct values for the individual beams only when one beam is present. Thus, although the moment calculation of overall flow speed within the current layer did not agree with the stress balance calculation at this time, the newly entered plasma at 2210 UT was, in fact, flowing sunward at approximately the speed predicted by stress balance. The temperature of the newly entering plasma was $-2 \times 10^7$ K, and the anisotropy was $-1.5$.

Similarly, it is clear from Figure 7 (bottom left and middle) that secondary ion populations were responsible for the overall flow speed changes observed in the magnetosheath just adjacent to the magnetopause. The lower-speed interval was associated with a secondary population streaming sunward along the magnetic field relative to the magnetosheath population, whereas the higher-speed interval was associated with a secondary population streaming tailward along the magnetic field. In both cases the prime magnetosheath population appeared to be relatively unchanged throughout. The Alfvén speed $V_A$ in the magnetosheath at this time was ~285 km s$^{-1}$. Since both the sunward flowing and the tailward flowing beams were streaming at about $2V_A$ relative to the prime magnetosheath population, we believe these secondary beams were the result of reflection of magnetosheath particles at the magnetopause tailward and sunward of the spacecraft, respectively. This suggests that the reconnection site was alternately tailward and sunward of the spacecraft during the observing interval. We have previously demonstrated the $2V_A$ separation of incident and reflected magnetosheath ions in the reconnection geometry at the lobe magnetopause during the June 11, 1978, event [Gosling et al., 1991], and this separation has also been shown for the low-latitude magnetopause in the subsolar region by Fuselier et al. [1991].

Finally, we have previously noted that the sense of convection of newly reconnected field lines depends on whether the magnetosheath flow is sub-Alfvénic or super-Alfvénic [Gosling et al., 1991]. When the flow is super-Alfvénic, reconnected field lines sunward of the reconnection site should convect tailward, and transmitted and reflected magnetosheath ions there should have sunward directed speeds (when the external flow speed is less than $2V_A$) that are less than the flow speed in the adjacent magnetosheath. However, when the magnetosheath flow is sub-Alfvénic, field lines sunward of the reconnection site should convect sunward and the entering magnetosheath ions should have sunward directed speeds that are higher than the flow speed in the adjacent magnetosheath. This was the situation for the July 3, 1979, event since the magnetosheath flow speed ($\sim 225$ km s$^{-1}$) was less than the Alfvén speed ($\sim 285$ km s$^{-1}$) and the entering magnetosheath ions had a sunward speed ($\sim 400$ km s$^{-1}$) that exceeded the tailward flow speed in the adjacent magnetosheath. For this example, reconnection at the lobe magnetopause should have induced sunward convection of field lines within the polar cap at lower altitudes.

Field Shear and Plasma Beta

Previous work has shown that reconnection at the magnetopause occurs preferentially when the magnetosheath plasma beta is low (field dominated) [Paschmann et al., 1986; Scully et al., 1994; Sonnerup et al., 1995]. Moreover, it has been shown that on the dayside at low latitudes reconnection occurs for a wide range of local field shears, although it favors antiparallel terrestrial and interplanetary magnetic field components. Along the flanks of the magnetosphere at low latitudes, however, reconnection (as distinguished by accelerated plasma flows) strongly favors large local field shears. Figure 8 summarizes the total plasma beta and field shear statistics for the seven lobe magnetopause reconnection events under consideration here. Contrary to expectations based on dayside observations, the events occurred for a wide range of plasma beta. On the other hand, all but one of the events did have large local field shears, as is also the case when reconnection occurs along the magnetospheric flanks.
adjacent to the plasma sheet. It is interesting to note that the one exception to this rule (a crossing on June 15, 1979) also had a high value of beta.

**Interplanetary Conditions During the Lobe Magnetopause Reconnection Events**

All of the ISEE 2 lobe magnetopause reconnection events considered in this paper occurred well away from the noon-midnight plane in regions where \( B_z \) and \( B_y \) were the strongest magnetoospheric field components. Thus the large local field shears at the magnetopause in these events did not involve draped northward interplanetary \( B_z \) components. Figure 9 helps demonstrate that northward interplanetary \( B_z \) upstream from Earth was also not an essential element of these events. The figure shows plots of the interplanetary magnetic field \( z \) component in GSM coordinates as measured by ISEE 3 \(-200 R_E\) upstream from Earth for six of the events (the interplanetary data are unavailable for the June 11, 1978, event). In each panel the dashed vertical line indicates the time of the ISEE 2 magnetopause crossing, whereas the two solid vertical lines bracket the appropriate corresponding upstream time interval. The first solid vertical line corresponds to radial convection from ISEE 3 to the magnetopause, whereas the second solid vertical line corresponds to the corotation lag between ISEE 3 and the magnetopause using the measured upstream solar wind velocity and the \( x \) and \( y \) components of the field. Cross-hatching denotes all of the times between these two extremes. For four of the events the upstream field in the bracketed interval was clearly directed southward, while for the other two events the \( B_z \) polarity was mixed. Regardless, it is clear that northward interplanetary \( B_z \) and, in particular, strong northward \( B_z \), is not essential for reconnection to occur at the lobe magnetopause well away from the noon-midnight meridional plane.

**3. Discussion**

Ground [e.g., Maezawa, 1976] and low-altitude satellite [e.g., Mozer and Gonzalez, 1973; McDiarmid et al., 1978; Burke et al., 1979; Reiff, 1982] measurements of sunward convection of magnetic field lines within the polar cap at times when the IMF is northward have long provided indirect evidence for the reconnection of the open field lines of the tail lobes with the IMF at the lobe magnetopause. In this paper as well as in our previous paper [Gosling et al., 1991] we have presented direct evidence for reconnection at the lobe magnetopause in the form of accelerated magnetoasheath plasma within the magnetopause current layer. (See also recent work by Kesel et al. [1996].) The observed plasma accelerations in the events studied are in reasonable accord with expectations based upon stress balance.

We have concentrated on events where the plasma accelerations associated with reconnection were obvious in the data. Our study shows that such events occur at the lobe magnetopause only when the local field shear is large (near 180°). The plasma accelerations expected for reconnection when the field shear is significantly different from 180° would be smaller and more difficult to detect; nevertheless, we are confident that there are few such events in the ISEE 2 data. Our result at the lobe magnetopause is thus in contrast to results obtained at the dayside magnetopause, where reconnection often occurs in the presence of relatively modest magnetic field shears [e.g., Gosling et al., 1990]. These differences suggest that reconnection is more strongly driven by the external flow at the dayside than along the flanks and that a

![Figure 9](image-url)
combination of component and antiparallel merging models is appropriate for the Earth’s magnetopause.

Well away from the noon-midnight plane and near and tailward of the dawn-dusk terminator the large local field shears associated with the reconnection process commonly involve draped magnetosheath fields with strong $x$ and $y$ components and relatively weak $z$ components. A northward IMF is not necessary for reconnection at the lobe magnetopause well away from the noon-midnight plane; indeed, a majority of the events studied here occurred during southward IMF, as might be expected from considerations of magnetospheric field orientations at such locations [e.g., Crooker, 1979]. As in our previous studies [Gosling et al., 1986, 1990, 1991], we find that the magnetosheath plasma entering the magnetopause current layer is heated, sometimes by a substantial amount, indicating operation of a dissipative process at the magnetopause during these events. It is not yet clear if this dissipation is associated with slow or intermediate shocks; such shocks are difficult to identify at the magnetopause. The one notable example of a slow shock at the magnetopause in the ISEE data, observed during reconnection at the dayside magnetopause, has been studied extensively by Walshour et al. [1994].

During reconnection along the tail flanks the accelerated plasma is confined to a relatively broad current layer where the field rotates from its magnetosheath orientation to its magnetospheric orientation. This is true both adjacent to the plasma sheet [Gosling et al., 1986] and adjacent to the lobe (as shown here and by Gosling et al. [1991]) and is in contrast to the situation at the dayside magnetopause where accelerated plasma from the magnetosheath commonly occupies a broad region earthward of the magnetopause. Indeed, such plasma often fills the low-latitude boundary layer on the dayside and is perhaps the best evidence that the low-latitude boundary layer is often, but certainly not always, found entirely on open field lines. This contrast between the structure of the flank and dayside magnetopauses during reconnection has been explained by Lin and Lee [1994] and by Labeille-Hamer et al. [1995] to be a consequence of essentially two facts: (1) the Alfvén speed is generally considerably higher inside the magnetosphere than in the adjacent magnetosheath and (2) a large shear flow commonly exists in the magnetosheath at the flank magnetopause but not at the dayside magnetopause. As a result, the major field rotation occurs on the magnetosheath side of the reconnection layer (the layer of connected field lines at the magnetopause) at the dayside magnetopause, but it occurs throughout the reconnection layer or on its magnetospheric side along the flanks of the magnetosphere.

Another consequence of the large flow shear at the flank magnetopause is that field lines on either side of the reconnection site are convected tailward if the flow speed in the magnetosheath exceeds the Alfvén speed there. Thus reconnection at the lobe magnetopause does not necessarily lead to sunward convection of field lines in the polar cap [Gosling et al., 1991]. On the other hand, sunward convection was inferred for one of the events presented here (July 3, 1979) since in that case the plasma flow in the magnetosheath was sub-Alfvénic and magnetosheath ions entering the current layer were directed sunward with a speed that exceeded the magnitude of the tailward flow in the adjacent magnetosheath.

Double-ion beams are a common but not universal aspect of ion distribution functions observed within the current layer during the reconnection process at the lobe magnetopause. One component of these double-ion beams is the newly entered magnetosheath plasma that is heated and accelerated as it traverses the kink in the field associated with the current layer. The other component is mantle plasma that entered the open magnetosphere from the magnetosheath sunward of the reconnection site and was decelerated in the process. This mantle plasma preexists as a nearly field-aligned flow on the open lobe field lines adjacent to and within the magnetopause prior to the reconnection process. It does not experience an acceleration during reconnection unless it traverses the magnetopause out into the magnetosheath. Moment calculations integrated over all velocity space are affected when secondary ion components are present. We have seen, for example, that the actual speed of the newly entered plasma component can be quite different from that inferred from such moments. In one example we found relatively good agreement between the actual entering beam speed and the value predicted by stress balance even though the speed resulting from the total moment calculation appeared to be in substantial disagreement with the prediction. This suggests that a kinetic approach to the reconnection problem at the magnetopause, such as outlined by Cowley [1982], may be more useful than a fluid approach when multiple ion beams are present, particularly when a spacecraft does not sample the same reconnected field lines on either side of the magnetopause. Finally, double-ion beams observed within the current layer during reconnection are nominally similar in appearance to double-ion beams commonly observed in the solar wind well upstream from the Earth’s bow shock [e.g., Feldman et al., 1973]. The origin of the latter beams has long been a mystery [e.g., Marsch, 1990]. It has recently been suggested that reconnection in the solar corona may produce the nearly ubiquitous solar wind double-ion beams [e.g., Feldman et al., 1993; Hammond et al., 1995]. Although our lobe magnetopause observations clearly indicate that double-ion beams can be produced by reconnection in certain situations, it remains to be seen if this is the correct explanation for solar wind double-ion beams.

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References


GOSLING ET AL.: MAGNETIC RECONNECTION AT THE LOBE MAGNETOPAUSE


Maehara, K., Magnetospheric convection induced by the positive and negative z components of the interplanetary magnetic field: Quantitative analysis using polar cap magnetic records, *J. Geophys. Res.*, 81, 2289, 1976.


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