ISEE-1 AND 2 MAGNETOMETER OBSERVATIONS OF THE MAGNETOPAUSE

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ABSTRACT

ISEE-1 and 2 were launched on October 22, 1977 into nearly identical highly elliptical orbits with an apogee of 23 earth radii, carrying sophisticated field, particle and plasma wave instrumentation. The unique feature of the mission is the variable separation of the two spacecraft in nearly identical orbits, permitting studies of the velocities of the boundaries relative to the satellites and allowing us to deduce the thickness of these boundaries. The ISEE measurements show that the magnetopause motion is rapid and irregular, and that thicknesses from 500 to 1600 km are observed, depending on magnetosheath field orientation.

These data suggest that reconnection often occurs in discrete increments and enough flux is transported during these events to support substorm activity.

Keywords: Magnetopause, ISEE-1, ISEE-2, Reconnection, Flux Transfer

1. INTRODUCTION

Prior to the launch of the International Sun Earth Explorer spacecraft (ISEE-1 and 2), observations of the magnetopause suffered from the spatial-temporal ambiguity inherent in single spacecraft measurements of a highly variable, moving plasma boundary. Despite this, considerable progress was made in characterizing the nature of the boundary.

The magnetopause was found to be constantly in motion (Refs. 1,2), and, under the assumption that this motion was periodic, estimates of the magnetopause thickness were made. Energetic particles were also used to measure the velocity of the magnetopause (Ref. 3). These studies gave a thickness of about 1000 km; however, the technique was unable to resolve thinner boundaries. Rapid radial motion with velocities of ~50 km/sec was sometimes observed. The minimum variance technique to determine the orientation of the magnetopause normal and the average field strength along the normal was pioneered by Sonnerup and Cahill (Ref. 4). Variability of the magnetopause motion during satellite crossings of the boundary made the determination of the normal and the normal component of the magnetic field quite difficult (Ref. 5), and it was hoped that the use of two closely spaced satellites would help resolve some of these ambiguities. As we see below two satellites are of great help in resolving the motion and structure of the magnetopause. Nevertheless the complex motion of the magnetopause continues to make such a study far from trivial.

A preliminary survey of the magnetopause has been performed using data from just after ISEE launch, when the position and separation of the two spacecraft was appropriate for such a study. Figure 1 shows the locations of the selected magnetopause encounters used in this survey in solar cylindrical coordinates. An attempt was made to confine the survey in local time, so that effects due purely to orientation of magnetosheath magnetic field would be more obvious. Crossings of the magnetopause during which the magnetosheath field was southward are denoted by 'S', and those during which the magnetosheath field was northward by 'N'.

![Figure 1. Locations of magnetopause crossings for the preliminary ISEE magnetometer survey, in solar cylindrical coordinates. The abscissa is the distance along the earth-sun line; the ordinate is the distance perpendicular to the earth-sun line.](image-url)
Since global coordinate systems such as GSE and GSM do not order data from a localized magnetopause crossing, it is important to find a coordinate system referenced to the local magnetopause surface, as shown in Figure 2. These "boundary normal coordinates" are determined from the magnetopause normal, and the orientation of the geomagnetic field. Three techniques are used to obtain the direction of \( \mathbf{\hat{n}} \): by obtaining a normal direction based on a cylindrically symmetric magnetopause model; by assuming the magnetopause is a tangential discontinuity; or by finding the direction of minimum variance. In general all these normal directions agree within a few degrees. The \( \mathbf{\hat{I}} \) direction is then the projection of \( \mathbf{\hat{n}} \) on the magnetopause surface defined by \( \mathbf{\hat{n}} \) and \( \mathbf{\hat{I}} \) completes the system. It is sometimes useful to define a "latitude", or the angle that the instantaneous field makes out of the L-M magnetopause plane, and an "azimuth", the angle made by the field with respect to the \( \mathbf{\hat{I}} \) direction in the L-M plane.

![Figure 2. The definition of boundary normal coordinates.](image)

2. CHARACTER OF THE "QUIESCENT" MAGNETOPAUSE

Results from the early ISEE magnetopause survey have shown that the magnetopause is, if anything, even more dynamic and variable than heretofore inferred. Quite apart from waves on the magnetopause and large scale expansions and contractions of the magnetosphere, the presence of flux transfer events (discussed in the next section) sometimes complicates magnetopause crossings as well. It is nevertheless possible to characterize some of the zero order attributes of the "quiescent" magnetopause, in which no evidence of reconnection appears. These attributes include current sheet thickness, velocity and variability of magnetopause microstructure.

Figure 3 shows the magnetic field from 1914 to 1954 UT on November 24, 1977 in boundary normal coordinates for a magnetopause crossing from a magnetosheath field which is nearly due north. The crossing is evidenced only by a gradual increase in field strength and a decrease in wave noise, seen nearly simultaneously by both spacecraft and spanning many minutes. Thus, as might be expected, the magnetopause is thick and diffuse on this day. The left-most vertical dashed line denotes where a drop in plasma pressure occurs, coincident with a magnetic field increase, suggesting the presence of the Zwan and Wolf effect (Refs. 6,7).

![Figure 3. Magnetic field in boundary normal coordinates for a magnetopause crossing with a northward magnetosheath field.](image)

Figure 4. Moments of the distribution function from the LASL/MPF fast plasma analyzer for the time covering Figure 3.
small scale variability and the extremely weak overall magnetic field gradient render thickness and velocity calculations impossible for this crossing.

Figure 5. Magnetic field in boundary normal coordinates for a magnetopause crossing on November 5, 1977. Spacecraft position was (10.4, -1.1, 5.2) Re GSM, and separation was 360 km along the normal, ISEE-1 leading inbound.

Figure 5 shows the magnetic field in boundary normal coordinates for a crossing on November 5, 1977 when the magnetosheath field was roughly 2° from the magnetospheric orientation. Figure 6 shows concurrent fast plasma analyzer data (Ref. 7). The gradual field enhancement beginning at 1700 on both spacecraft coincides with a plasma pressure decrease, evidence again of a depletion layer exterior to the magnetopause. The current layer proper, indicated by the transition in the B_M component near 1715, occurs after the field enhancement and, like the aforementioned crossing, is quite variable. It is nevertheless possible to estimate a current sheet thickness based on the B_M transition, as illustrated in Figure 7. There we have expanded the traces of the two spacecraft, with ISEE-1 given by the bold line and ISEE-2 by the light line. ISEE-1 is 360 km ahead of ISEE-2 along the magnetopause normal; at time "a", the field at ISEE-1 has an orientation that ISEE-2 does not observe until time "b". Thus ISEE-2 had to pass 360 km into the current sheet to get there, while ISEE-1 now sees a new orientation at "b", which ISEE-2 does not observe until time "c", another 360 km along. Meanwhile ISEE-1 observes yet another orientation which ISEE-2 does not achieve until later still. Consequently, since it required three 360 km steps to get through this part of the current sheet, the magnetopause is at least 1000 km thick here.

Figure 6. Moments of the distribution function from the LASL/MPI fast plasma analyzer for the time covering Figure 5.

Figure 7. Determination of magnetopause thickness using the B_M component for the crossing on November 5, 1977.

The results of a preliminary survey of magnetopause thickness are shown in Figure 8. Current sheet thickness is plotted here against the angle between the magnetosheath and magnetospheric magnetic fields; an angle of 0° corresponds to due northward fields, 180° to due southward fields. The results suggest that the magnetopause is thicker when the magnetosheath field is northward, and thinner (roughly 500 km on the average) when the magnetosheath field is southward, for the sun-earth-satellite angles range sampled as shown in Figure 1. In any case, the current sheet is certainly thicker than one magnetosheath thermal ion gyroradius.

The data shown in Figure 9 were taken on November 3, 1977 when the magnetosheath field was essentially horizontal. There are seven partial or complete crossings on this pass, suggesting large scale motions (possibly waves) of the boundary. Figure 10 shows how the magnetopause speed along the normal direction can be estimated on this day. The interval between the times when the two spacecraft observe the same value of B_M is approximately the time of flight (neglecting spacecraft motion) of that portion of the magnetopause over the normal spacecraft separation distance of 320 km on this day. Thus the average speed of the magnetopause
Figure 8. Magnetopause thickness as a function of the angle between the magnetosheath and magnetospheric field orientations. Error bars denote range of observed thickness for multiple crossings or uncertainty in thickness, whichever is greater.

over that interval is given by the normal separation divided by time of flight. This speed is plotted in the lower half of Figure 10. Although characteristic values are generally between 10 and 20 km/sec, speeds greater than 40 km/sec were seen on this day. Indeed, the variability of magnetopause motion is exemplified by the speeds obtained near 0751 UT, which exhibit an almost exponential drop from ~45 km/sec to less than 5 km/sec.

In addition to motional variability, the structure of the magnetopause can change markedly in a short time, as shown in Figures 11 (a)-(d). Figure 11a is a hodogram in boundary normal coordinates of the first two crossings by ISEE-1. The field rotation is well-behaved and the normal component is statistically no different from zero. Figure 11b shows the next crossing as seen by the two spacecraft; fluctuations are apparent both in the rotation and

the $B_N$ component, but the current structure is also subtly different between the spacecraft. Figure 11c shows an even more turbulent and variable crossing. Here, although the spacecraft are separated by but 320 km along the magnetopause normal, substantial differences in structure are apparent, due either to temporal variations short on the scale of the crossing time, or spatial variations on the scale of the spacecraft separation distance tangential to the magnetopause surface. Figure 11d shows the last full crossing, which is also turbulent. It is noteworthy that, for a particular crossing, one spacecraft observes a field variation broadly similar to that observed by the other spacecraft, while marked differences can occur between two sets of successive crossings. This gives some sense of the time and space variations of magnetopause currents.

Figure 9. Magnetic field in boundary normal coordinates for multiple crossings on November 3, 1977, when the magnetosheath field was roughly horizontal. Spacecraft position was (10.5, 0.5, 5.2) $R_E$ GSM, and separation was 320 km along the normal, ISEE-1 leading inbound.

Figure 10. Determination of magnetopause speed for the crossings shown in Figure 9.

Figure 11a. Hodogram in principal axis coordinates of the first two crossings in Figure 9 seen by ISEE-1.
3. FLUX TRANSFER EVENTS

While the "quiescent" magnetopause is, at the best of times, a dynamic and variable boundary, there are occasions when the magnetopause plasma environment is even more highly disturbed. Such events are observed when the magnetosheath field is southward, and are characterized by magnetic signatures consistent with passage of the spacecraft through a reconnecting flux tube. Several events appear in data taken from November 3, 1977, as shown in Figure 12, most notably at 0212 and 0236 UT. The magnetopause is crossed near 0250. The first event is revealed by an oscillatory perturbation in $B_N$, implying the existence of a tailward-going wave on the magnetopause. However, the field strength and other two components, while at first glance suggesting a partial magnetopause crossing, nevertheless exhibit odd behavior. As the field strength grows to almost magnetospheric values, the orientation becomes more nearly horizontal, turning slightly northward as the "wave" passes, then southward as the spacecraft returns to the magnetosheath. Meanwhile, the plasma bulk flow (c.f. Refs. 7 & 8) has altered in direction and magnitude consistent with magnetosheath flow deflected around the obstacle, followed by enhanced flow in the horizontal field region, returning to undisturbed magnetosheath flow by 0216. At the same time, as shown in Figure 12, hot electrons were observed with energy spectra similar to that seen later in the boundary layer, while only a minor reduction in the thermal magnetosheath plasma occurred. A similar sequence of observations occurs for the 0236 event. (See Refs. 9 and 10 for further details.) In essence, when the plasma flow data is combined with the mag-
Figure 12. Magnetic field in boundary normal coordinates on November 8, 1977, when the magnetosheath field was southward. Spacecraft position was (10.2, -1.8, 5.1) Re GSM, and separation was 299 km along the normal, with ISEE-1 leading inbound.

Magnetic field data, it is found that these events transfer 2-3 x 10^{15} Maxwells of magnetic flux tailward. A schematic view of such a flux transfer event is shown in Figure 13. Here a flux tube in the magnetosheath has been reconnected to a magnetospheric flux tube across the magnetopause. The stressed magnetic field condition represented by the "bent" flux tube gives rise to enhanced bulk flow of plasma on the flux tube as it relaxes magnetically. Such a flow would be in the sense of the large arrow in the figure. The topologically distinct magnetosheath field lines around this structure are shown draped over it, as would be the case if the flux tube were convecting relative to the surrounding magnetosheath. The magnetosheath plasma on the flux tube has access to the magnetosphere, and the magnetospheric particles gain access.

Figure 13. Schematic diagram of a flux transfer event.

Figure 14. Magnetic field in boundary normal coordinates on November 10, 1977, when the magnetosheath field was southward. Spacecraft position was (7.1, 0.3, 2.9) Re GSM, and separation was 228 km along the normal, ISEE-1 leading inbound. Flux transfer events occur near 1436, 1440, 1446, 1455, and 1458 UT.
to the magnetosheath, explaining the presence of both thermal and energetic plasmas in this region.

One difficulty arises here: the magnetospheric particles will be lost in the order of one bounce period, which for ring current electrons is a few seconds at most. Thus it is difficult to explain the presence of the energetic electrons in this region, unless (1) strong diffusion or drifts place magnetospheric particles on open field lines near the periphery of the reconnected flux tube and (2) the spacecraft pass only through this outer peripheral region.

Flux transfer events are not an uncommon feature in the data. Figures 14 and 15 show data from days when many events occurred, revealed mainly by the characteristic Bx variation and magnitude enhancements. During the November 10, 1977 pass, the occurrence of flux transfer events severely complicated the magnetopause crossings at 1440 and 1446. On November 29, 1977 the southward turning of the field associated with the event at 1421 was an unexpected variation. Further analysis of these structures in the light of plasma and particle data is central to understanding the magnetopause and reconnection.

4. CONCLUSIONS

Viewed against earlier predictions and experimental inferences, the picture of the dayside magnetopause painted by the preliminary ISEE results is no simpler but certainly more well-determined than before. When organized in terms of boundary normal coordinates, the data allow us to estimate thicknesses and speeds of the "quiescent" magnetopause current sheet, as well as characteristic time and space scales of micro-fluctuations. The magnetopause thickness when magnetosheath fields are northward is characteristically between 1000 and 2000 km; when the magnetosheath field is southward, the current sheet thickness is more typically ~500 km. Speeds exhibited by the magnetopause are typically 10-20 km/sec, but much larger and smaller values are often observed, sometimes even within a single crossing. The structure of the magnetopause currents are likewise variable, with significant fluctuations observed on the spatial scale of the spacecraft separation.

Major magnetic structures, suggestive of patchy reconnection, are sometimes observed when the magnetosheath field is southward. These "flux transfer events" appear to be consistent with reconnected flux tubes which transport dayside magnetic field to the tail. They also appear to play a role in dayside magnetopause dynamics.

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6. REFERENCES


