The structure of the magnetopause

C.T. Russell*

Institute of Geophysics and Planetary Physics, Department of Earth and Space Sciences, University of California, 3845 Slichter Hall, MS 156704, Los Angeles, CA, 90095-1567, USA

Received 20 September 2002; received in revised form 23 November 2002; accepted 14 January 2003

Abstract

The solar wind is a magnetized flowing plasma that intersects the Earth’s magnetosphere at a velocity much greater than that of the compressional fast mode wave that is required to deflect that flow. A bow shock forms that alters the properties of the plasma and slows the flow, enabling continued evolution of the properties of the flow on route to its intersection with the magnetopause. Thus the plasma conditions at the magnetopause can be quite unlike those in the solar wind. The boundary between this “magnetosheath” plasma and the magnetospheric plasma is many gyroradii thick and is surrounded by several boundary layers. A very important process occurring at the magnetopause is reconnection whereby there is a topological change in magnetic flux lines so that field lines can connect the solar wind plasma to the terrestrial plasma, enabling the two to mix. This connection has important consequences for momentum transfer from the solar wind to the magnetosphere. The initiation of reconnection appears to be at locations where the magnetic fields on either side of the magnetopause are antiparallel. This condition is equivalent to there being no guide field in the reconnection region, so at the reconnection point there is truly a magnetic neutral or null point. Lastly reconnection can be spatially and temporally varying, causing the region of the magnetopause to be quite dynamic.

© 2003 Elsevier Ltd. All rights reserved.

Keywords: Flux transfer; Guide field; Magnetopause; Reconnection

Contents

1. Introduction ......................................................... 732
2. The role of the bow shock and magnetosheath in preparing the solar wind plasma for its interaction with the magnetosphere ......................................................... 732
3. The classical, thin-magnetopause, current layer ......................................................... 734
4. The subsolar magnetopause ........................................................................... 735
5. The ideal reconnecting magnetopause signature ......................................................... 736
6. How large is the reconnection region? ......................................................... 736
7. Macroscopic evidence for the lack of a guidefield ......................................................... 737
8. Reconnection for northward IMF ........................................................................... 740
9. Flux transfer events ........................................................................... 740
10. The scale size of the magnetospheric current sheet ......................................................... 741
11. Discussion and conclusions ........................................................................... 741

Acknowledgements ........................................................................... 743
References ........................................................................... 744

*Tel.: +1-310-825-3188; fax: +1-310-206-3051.
E-mail address: ctrussel@igpp.ucla.edu (C.T. Russell).
1. Introduction

The magnetopause is arguably the most critical boundary of the magnetosphere. It is here that the solar wind first interacts with the magnetosphere itself. It is here that mass, momentum and energy exchange occurs. Paradoxically the magnetopause (and the magnetosphere as a whole) acts as both a shield and an accelerator. It both protects us from the onslaught of the solar wind, deflecting most of it around the planet, and it accelerates the solar wind plasma and energetic particles, ultimately energizing the ring current and radiation belts.

The resolution of this paradox lies in the nature of reconnection and its effects on the magnetosphere. Reconnection is the process by which individual field lines lose their identity and become connected to a new region. Magnetic field lines rooted in the Earth generally remain in the magnetosphere and return somewhere else to the Earth. Field lines in the solar wind generally remain in the solar wind. But when the solar wind encounters the magnetosphere, some magnetic field lines forget their roots and it is possible to travel along a magnetic field line, pass out of the magnetosphere and into the solar wind and vice versa. The process in which this topological change occurs is reconnection (e.g. Dungey, 1961). Even though the existence of reconnection is incontrovertible (e.g. Paschmann et al., 1979) the basic physics that enables reconnection is very controversial. For example the finite resistivity of numerical simulation codes enable reconnection to occur in them but the plasmas in space are far less resistive and kinetic processes (sub gyro scale perhaps) may be needed to facilitate this partner swapping of magnetic field lines.

In reconnection a portion of the incoming solar wind flow magnetically connects with the magnetosphere. What controls how much and where the reconnection occurs is poorly known, but critical, to what happens to the magnetosphere. Once connected, the magnetic fields that connect the solar wind and the magnetosphere straighten and shorten, and accelerate the plasma on them. As the solar wind continues to flow past the magnetosphere, these connected field lines are pulled tailward and lengthen again. In the region where they move from the magnetotail into the flowing solar wind plasma, they exert a drag on the solar wind, slowing it, and extracting energy from it. This process may be thought of as a Poynting flux of energy from the flow into the magnetotail. The flux of energy is stored in the lobes of the tail for later release in substorms, or more directly into the ring current during a storm (e.g. Russell and McPherron, 1973).

While such energy exchange does not sound like the function of a shield, if the magnetopause were not at the altitude it is, then the solar wind flow would be much more effective at removing our neutral atmosphere and energetic solar cosmic rays could ground all commercial airplanes during a solar proton event, and not just the airplanes that cross the polar regions, as are now diverted during such events. There would be no escape other than to stay at very low altitudes under the protective shield of our atmosphere.

Many of the concepts of magnetospheric physics and of the magnetopause in particular were proposed early, close to four decades ago. The fact that we still debate these concepts speaks to the complexity of the magnetized solar wind flow with the Earth’s very three-dimensional dipole magnetic field. The magnetic geometry is very important in controlling the interaction. Another complexity is that the solar wind is modified by a strong bow shock and that the shocked solar wind further evolves behind the bow shock as it proceeds to the magnetosphere. Thus we need to understand how the magnetosheath works in order to understand to what conditions the magnetopause is actually exposed. Herein we present a brief synthesis of our present understanding of the magnetopause and the processes taking place there. We use examples principally from ISEE 1 and 2 and Polar because of our greater familiarity with these results. There might be equally good examples from other missions, especially in the near future from Cluster.

2. The role of the bow shock and magnetosheath in preparing the solar wind plasma for its interaction with the magnetosphere

Fluids are deflected around obstacles by pressure gradients. The pressure that must be counteracted by the magnetospheric obstacle is that of the flowing solar, and the force that does the deflecting in this case is the pressure gradient of the magnetic field and the thermal motions of the plasma constituents (e.g. Petrinec and Russell, 1997). The solar wind flows so rapidly that the thermal and magnetic pressure of the solar wind cannot provide sufficient force to deflect the flow. In other words the solar wind flows supersonically relative to the speed of the compressional wave that is required to deflect the flow. As a consequence a shock wave forms that slows, heats, and deflects the flow. Then in the region behind the standing bow shock the magnetosheath plasma has sufficient pressure that it can alter the speed and direction of the flow and divert the flow so it flows around the obstacle.

A word should be said here about where the bow shock stands in front of the magnetospheric obstacle. All the flow that passes through the shock must be able to flow around the obstacle. Thus the shock will move away from the obstacle to the point where all the compressed solar wind can move between the shock and the magnetopause. When the shock weakens, the compression ratio across the shock decreases to unity (no compression) and the shock moves to infinity (Farris and Russell, 1994).

The solar wind is a magnetized fluid, and both the magnetic field and the plasma must be carried around the obstacle, but these two quantities are quite different. Basically magnetic flux tubes move only perpendicular to their field directions while the plasma can move in any direction. So
while a normal fluid can be deflected with a simple compressional wave, a magnetized fluid requires three waves to carry any generalized perturbation (Song et al., 1999). These waves are called the fast, intermediate and slow waves and their phase and group velocities are illustrated for two different plasma conditions in the righthand panel of Fig. 1. The group velocity plots on the far right show that intermediate and slow modes are strongly guided by the magnetic field direction. The fast mode can travel both along and across the magnetic field.

The intermediate mode is responsible for rotating the direction of the field and flow. This can help bend the field to get it around the obstacle. The slow mode changes the ratio of the magnetic field strength and the plasma density. This is equivalent to stretching the flux tube, a process that does not change the field strength but does change the density. Thus the density can decrease on a field line “hung up” on the dayside magnetopause. Such a structure is called a slow mode expansion fan.

An observational phenomenon near the magnetopause is called the plasma depletion layer (Zwan and Wolf, 1976; Crooker et al., 1979). This layer consists of a region around the subsolar magnetopause where the density decreases while the magnetic field strength is increasing. Another more controversial observation is that of a standing density increase in front of the plasma depletion layer. This has been interpreted as a slow mode compression standing in front of the slow mode expansion (Song et al., 1992). The panel on the lefthand side of Fig. 1 shows such a density enhancement.

Whatever the cause of these changes in the plasma, they point out that there is evolution of the properties of the plasma as it moves away from the shock. Since reconnection is a process in which magnetic forces are important, effects that enhance the strength of the magnetic field and/or decrease the plasma density should increase the rate of reconnection. Effects that weaken the magnetic field and/or increase the density should lessen the rate of reconnection. When the Mach number of the bow shock is high, the plasma downstream becomes very hot, the plasma pressure is high and the field weak. Thus the Mach number of the solar wind flow and to a lesser extent its preshock beta should be expected to affect the rate of reconnection. Evidence for such an effect can be found in geomagnetic activity records (Scourry and Russell, 1991).

Another complication in studying the magnetopause is that it is very dynamic. First the bow shock (and foreshock region) is not very steady. Second, the reconnection process itself is not very steady even in the absence of external perturbations, and third the evolution of the properties of the plasma along streamlines leads to free energy that can lead to wave growth. One of these instabilities is the mirror made instability that converts structure in velocity space into structure in configuration space. The panel on the right-hand
side of Fig. 2 shows schematically how this occurs. Particles with excess perpendicular energy can move along field lines to concentrate their densities in weak field cavities. This produces a temporal signature in the plasma density, \( N \), and the magnetic field, \( |B| \), as shown on the bottom right in Fig. 2. Time series of such waves in the magnetic field are shown from the ISEE 1 and 2 spacecraft on the lefthand side when the spacecraft were 54 km apart along the normal to the magnetopause and 500 km apart along it. The records are very similar in behavior but differ remarkably in detail despite their proximity. As shown in the lower left, the correlation between them is close to zero (Russell, 1994). If one did not realize that they were nearly pressure-balanced structures convecting past the spacecraft, one might think that the magnetopause was moving back and forth rapidly across the spacecraft. This can happen but it is not always the explanation of the large amplitude oscillation at the magnetopause.

3. The classical, thin-magnetopause, current layer

The classical magnetopause as envisioned by Chapman and Ferraro (1940) had a plasma on one side and a magnetic field and little or no plasma on the other. The energy of the plasma particles perpendicular to the field determines the gyro radius of the particles and one might expect that the gyro radius would determine the thickness of the boundary as it would be turned around by the magnetic field and ejected by the magnetosphere in a half gyro period. This situation is shown in the upper lefthand panel of Fig. 3. In fact the turning radius can be much smaller than that of the ion gyro radius because there is an electric field set up by the change separation in the idealized situation shown here and the electron is pulled in toward the ion. If the solar wind is a cold flow, then the Chapman–Ferraro picture has particles flowing in and then flowing out antiparallel to the incoming flow. Such a beam-beam interaction is highly unstable and the solar wind would not be turned around and sent back to the Sun, as if it were an elastic fluid. In fact it is very inelastic.

To search for conditions that might approximate the Chapman–Ferraro state, we examine situations in which the solar wind Mach number is high so that the magnetic field strength is low, and the pressure balance is that between a plasma and a magnetic obstacle. Three cases are shown. The top case shows an example from Voyager 2 at the Uranian magnetopause. The Mach number of the flow in the outer heliosphere is high and the magnetic field in the magnetosheath is quite weak. Nevertheless, we see a complicated magnetic structure at the magnetopause and not the simple structure that we expect. The data in the lower two panels were obtained by ISEE-1 at the Earth under high solar wind Mach number conditions. Statistical studies using ISEE 1 and 2 show that the boundary is about 600 km thick (Le and Russell, 1994) and, as with the Uranian case, it has a complicated structure. Under these conditions the magnetopause thickness is about 2–4 gyro radii thick. The magnetopause is not the thin current sheet envisioned by Chapman and Ferraro.

Part of the difference between the idealized picture and the real magnetopause is that in the magnetosheath the flow has
been turned to flow parallel to the boundary and the pressure is not supplied by a cold beam but by the thermal pressure in the plasma. However, even in the case of a hot, stagnant plasma, the idealized solution gives a thin boundary. In contrast at the real magnetopause magnetosheath ions have become trapped within the current layer. These particles do not return to the magnetosheath but gradient drift along the boundary, providing the current needed to “terminate” the terrestrial magnetic field. It may well be that the very weak magnetic field of the magnetosheath in these instances is still sufficient to allow reconnection and the entry of magnetosheath plasma a short way into the magnetosphere.

4. The subsolar magnetopause

The subsolar region of the magnetopause should be the simplest region to understand since here the boundary motions should be the least, the flow should be slowest and the region should be least affected by dynamic events elsewhere on the magnetopause. The lefthand panel of Fig. 4 shows a pass through the subsolar magnetopause on ISEE-1 when the IMF was strongly northward. The weak current layer at 1521 UT that seems to mark the outer edge of the magnetosphere is bounded by boundary layers on either side. The outer one on the left where the density decreases and the magnetic field increases is probably the plasma depletion layer. The layers on the inside of the current layer (to the right) are probably due to magnetosheath plasma entering the magnetosphere from reconnection at high latitudes where the reconnection is occurring under these circumstances.

The panel on the right shows the conditions in this region when the IMF is southward and reconnection is occurring near the subsolar point. Again there are external and internal current layers. The overall boundary is thick but there can be layers of current internal to the magnetopause that are thin. These can be approximately an ion gyro radius in thickness.
5. The ideal reconnecting magnetopause signature

Reconnection should occur most strongly when the magnetic fields are nearly antiparallel and we expect the signature to be simplest near the subsolar point. Cassini provided an opportunity to observe such a signature as it passed through the near subsolar magnetopause on August 18, 1999 (Southwood et al., 2001). These data and the trajectory are shown in Fig. 5. The magnetic field resembles that of an ideal Alfvén wave in which the field rotates from one direction to another and there is a constant magnetic field component along the normal to the boundary assumed to be along the minimum variance direction $k$ in Fig. 5. There are two small perturbations on this Alfvén wave picture. First and most prominently there is a dip in the magnetic field magnitude right in the center of the current layer. Secondly, the rotation of the field through the boundary is not monotonic. The direction of rotation switches on both sides for a brief period. This is not due to boundary motion. Cassini is moving much faster than the magnetopause at this time.

This signature is not a rarity. Fig. 6 shows the magnetopause as seen at Polar during a storm when the solar wind dynamic pressure was high and the interplanetary magnetic field was strongly southward (Russell et al., 1998). Again the magnetopause resembles somewhat the ideal Alfvén wave with a constant field magnitude and constant normal component through the boundary as the field changes direction. As in the Cassini example there are two exceptions to this simple picture. Again there is a dip in field magnitude at the center of the current layer and the rotation of the field is not monotonic. Perhaps the signature might be quite different if we could find an example right at the reconnection point. The most important question as we discuss below is whether there is a guide field at this point. The guide field is the $B_z$ component in Figs. 5 and 6. As long as this field is large through the current layer ions stay magnetized. They move along the magnetic field. Where each of these examples was obtained, the ions were clearly magnetized, but is this condition present everywhere on the magnetopause?

6. How large is the reconnection region?

The earliest treatments of the release of energy from antiparallel magnetic fields considered what is today called magnetic annihilation, shown in the upper left diagram on
shown in the lower left panel of Fig. 7. This seems consistent with observations because bonafide observations of the true, partner-swapping reconnection site are rare.

A more modern sketch of the reconnection process is shown in the righthand side of Fig. 7. The diffusion region has shrunk to infinitesimal size and the three-dimensional nature of the region is given greater emphasis. In fact the separator along $Y_{\text{NIF}}$ (NIF = normal incidence field) may well be limited in length. Where and how long the separator or reconnection line will be depends on the orientation of the magnetosheath and the geometry of the interaction. The size of the reconnection region in the outflow ($z$) direction will be very small, much smaller than the ion cyclotron radius. Below the ion gyro radius the ions can become demagnetized but the electrons are still magnetized. Even closer to the $x$-point the electrons can become demagnetized, and then there is no memory at all of where the field lines lead. The different distances at which the ions and electrons become demagnetized naturally leads to an ambipolar electric field, the equivalent of those that the diffusion region created in the earlier model and which led to partner switching at large scales. Here there is no plasma wave or classical resistivity, only violation of invariant behavior due to scale size. This does put one important constraint on the reconnection point. If it is simply the scale size of the field gradient that causes reconnection, then there can be no guide field. While this seems like a very rigid constraint, it agrees well with the observation of reconnection on May 29, 1996 on the Polar spacecraft at high latitudes near the polar cusp (Scudder et al., 2002). The field went closely to zero at the point identified by the plasma and electric field instruments as the reconnection point.

**7. Macroscopic evidence for the lack of a guidefield**

For many years the magnetospheric physics community has been divided into two camps over the existence of a guide field at the reconnection point. One group advocates "component reconnection" in which essentially reconnection occurs along a specific line and the magnetic fields on either side of this line are not exactly oppositely directed (e.g. Sonnerup, 1974). Thus in this scenario there is a guide field. The other camp, originally much smaller but growing, believes in antiparallel reconnection (e.g. Luhmann et al., 1984). Here the line of reconnection is determined by the location of antiparallel fields. In this model the reconnection site is only at the subsolar point for directly southward (in GSM coordinates) IMF, and it moves away from the subsolar point as the IMF rotates away from due south. An early illustration of the prediction of antiparallel reconnection is shown in the upper left panel of Fig. 8 shown the isocontours of the angles between the magnetospheric and magnetosheath fields in a realistic magnetosphere and magnetosheath model. For due southward fields an extensive reconnection region occurs across the dayside with the
Fig. 6. Polar magnetic measurements near the subsolar magnetopause during a time of intense southward IMF and high solar wind dynamic pressure (Russell et al., 1998). (Top left) Projected location of ISTP spacecraft during this interval. (Top right) Time series of magnetic field for 30s around crossing. (Bottom) Hodograms of the field through crossing in principal axis coordinates calculated over times indicated. Righthand hodograms obtained for an analysis of central portion with little or no field rotation produces an ill-determined normal direction with a large apparent normal component.

Fig. 7. The geometry of reconnection. (Top left) The annihilation of magnetic fields that are precisely antiparallel. Leftmost panel shows vertical (Z) profile of magnetic field (along X) and current along (Y). (Bottom left) An x-point configuration allows reconnected magnetic flux and plasma to exit the merging region allowing new influx and increasing the rate of reconnection. Bending of the streamlines and acceleration of the flow accomplished by standing waves outside the diffusion region. The diffusion process changes field partners but does itself create the accelerated flow. (Right) Modern view of the reconnecting magnetopause with magnetosheath on the righthand side in which the partner swapping region approaches the electron gyro radius.
reconnection line cutting through the subsolar point. For southward and dawn dusk (eastward) pointed fields the reconnection line splits into two segments to the south and dawn and to the north and dusk. For horizontal eastward fields the reconnection line moves further south and north.

For due northward fields the reconnection line is found over the poles beyond the cusp. A more modern view of the antiparallel reconnection would simply draw the reconnection line itself and assume the reconnection rate varied along the line perhaps in proportion to the Alfven
speed that it is itself possible to the magnetic energy per particle.

Since magnetic flux transport from the dayside (closed) field lines to the tail’s open field lines plays an important role in the substorm process, it is important to keep track of whether the antiparallel reconnection line is on magnetospheric field lines that have two feet connected to the Earth or one foot connected. As can be surmised from Fig. 8, reconnection on open field lines occurs roughly for horizontal and northward IMF. Thus antiparallel reconnection is consistent with the large body of evidence that shows that half-wave rectification is a good approximation to the energization of the magnetosphere by the IMF. For example the lower left panel of Fig. 8 shows the energy flow into the ring current for northward IMF or dusk to dawn electric field and for southward IMF or dawn to dusk electric field (Burton et al., 1975). The rate of energization is zero for northward IMF and linear with the electric field for southward IMF. In contrast component reconnection does not have a sharp break point for northward IMF. Component reconnection does not well explain the observed dependence of geomagnetic activity on the IMF.

Another macroscopic indication that antiparallel reconnection is the correct reconnection law lies in the motion of the polar cusp as a function of the IMF clock angle. As shown in the upper right panel of Fig. 8 the cusp moves toward the afternoon when $B_x$ is eastward (positive) and toward the morning when it is westward (negative) (Zhou et al., 2000). This same dependence is seen at low altitudes as well (Newell et al., 1989). Since cusp field lines are rooted in the Earth they mark the reconnection local time rather than the transport direction. Thus the cusp motion implies motion of the reconnection site and this motion is as expected from antiparallel reconnection. We note that this motion of the cusp also occurs in MHD simulations that have different physics controlling reconnection. However that different physics also leads to antiparallel reconnection and the six color panels are included herein to illustrate the cusp displacement caused here by an eastward magnetic field in the solar wind.

8. Reconnection for northward IMF

When the IMF is southward, dayside magnetic flux is opened and transported to the tail. Magnetosheath plasma rushes into the magnetosphere and fills the newly opened field line with plasma. This is the polar cusp and it forms on the first open field lines near noon, albeit shifted to morning or afternoon as discussed above, controlled by the IMF clock angle. When the IMF is northward and the reconnection line moves to open field lines the magnetosheath plasma is added to the dayside and not nightside of the last “closed” field line (e.g. Russell, 2000a, b). In fact if reconnection occurs on the same flux tube in the north and south plasma can be inserted into the dayside magnetosphere and the field line closed, thus trapping magnetosheath plasma in the magnetosphere (Song and Russell, 1992; Le et al., 1996; Sandholt et al., 1999).

Recently a set of observations by Polar have been interpreted in terms of parallel and not antiparallel reconnection (Fuselier et al., 2000). Parallel reconnection is the antithesis of antiparallel reconnection. If component reconnection has difficulties explaining the response of the magnetosphere, then parallel reconnection must have even greater problems. The apparent reason for the misunderstanding of the Polar data is that the configuration of the reconnection point for northward IMF (shown on the top left in Fig. 9) produces a reconnection signature in the particles (shown on the right in Fig. 9) that is very similar to that for southward, low latitude reconnection (Russell et al., 2000). Furthermore, a new current sheet arises in the cusp region under these northward IMF conditions that is rightly called the magnetopause current, but it does not extend to the subsolar region, and it occurs on closed field lines, as sketched in Fig. 9, upper left. When Polar is in this region solar wind pressure changes, such as recorded in the lower left panel, can sweep the current layer over the spacecraft. Again the no-guide-field model is fully consistent with the observables.

9. Flux transfer events

Flux transfer events are temporally and spatially limited regions of reconnection that are carried from the dayside of the magnetosphere into the tail (Russell and Elphic, 1978). They occur about every eight minutes when they are present. The top panel of Fig. 10 shows a situation in which ISEE 1 and 2 were near the magnetopause when FTEs were being observed. The magnetic field pattern observed as the boundary is approached leads to the interpretation shown in the bottom two panels, a twisted tube of magnetic flux connected from the magnetosheath into the magnetosphere and moving across the surface. The diagram indicates a single tube moving northward, but they may be produced in pairs and move both north and south simultaneously. The three-dimensional nature of such structure makes probing their origin through reconnection very difficult. Thus flux transfer events are still relatively poorly understood. However, they do arise in MHD simulations (e.g. Fedder et al., 2002) and these studies should help greatly in our understanding. A high resolution MHD code should be able to accurately track their evolution. Of course care must be taken in creating the structure because reconnection occurs in an MHD code via a different physical mechanism than in nature.

The geometry shown in Fig. 10 suggests that at times one might expect to observe a magnetic field that has a very strong component directed into the magnetosphere. Indeed on one occasion an extremely large normal component was observed at the magnetopause with ISEE 1 and 2 (Zhu et al., 1988). This is illustrated in the upper right panel of Fig. 11.
Fig. 9. Evidence that reconnection occurs beyond the cusp on open field lines for northward IMF (Left upper panel) Sketch of the location of the Polar spacecraft against the magnetic configuration of the noon-midnight magnetosphere. For normal dynamic pressure the spacecraft would have moved from the position leveled 1300 to that labeled 1500 on this day but the spacecraft encountered the magnetosheath between L and M when the solar wind dynamic pressure increased. (Left lower panel) The magnetic field measured by Polar (solid line) and the Tsyganenko model (dashed line) and the solar wind dynamic pressure at this time. (Right panels) Ion velocity distributions at L and M showing reconnection just as would occur at the subsolar magnetopause under southward IMF conditions (Russell et al., 2000).

The size of FTEs may be controlled by the size of the magnetosphere, or equivalently the time for the solar wind to move across the magnetopause. This is illustrated by the lower righthand panel in Fig. 11 that shows the time series of the magnetic field through a flux transfer event at Mercury (Russell and Walker, 1985).

10. The scale size of the magnetospheric current sheet

Fortunately the scale size of the magnetopause current is not as small as the subgyro radius scale predicted by the Chapman and Ferraro model or we would have great difficulty probing them with our spacecraft. The separation of spacecraft needed for the so-called curlometer measurement of magnetic fields has to be a small fraction of the thickness of the boundary. The lefthand panel of Fig. 11 shows measurements of the magnetopause current sheet by ISEE 1 and the difference field between ISEE 1 and 2 at this time when they were about 10 km apart (Russell, 2000b). The maximum differences are about 10% of the background magnetic field. These are in the thinner sheets. In the thicker sheets the differences can be less than 1% of the background field. We conclude that one needs separation distances of the order of 10 km or even less to measure the thinnest current sheets (say 100 km thick) since all spacecraft should be well within the boundary when applying this technique. Presently Cluster does not reach separations this small. The proposed NASA Magnetosphere Multiscale mission will.

11. Discussion and conclusions

To predict the rate of reconnection at the magnetopause we must both understand how reconnection works and what the conditions are in the reconnection region. It is important to remember that the solar wind plasma is altered in transit to the magnetopause, first by the bow shock and then by the motion through the magnetosheath. The condition at the magnetopause may be quite different than in the solar wind.

To first order the magnetopause is in pressure balance with a plasma pressure gradient force pushing inward and a
magnetic pressure gradient pushing outward. The boundary is several gyro radii thick even when there is only a weak magnetic field in the magnetosheath. The subsolar magnetopause also usually includes much structure both in the adjacent magnetosheath and in the magnetosphere for northward and southward conditions. However, this structure is quite different for the two situations.

At times, when the magnetic field is nearly antiparallel, the magnetopause is quite simple. It resembles an Alfvén wave with a reduced field strength in the middle. In these cases there is a guide field but there might not be a guide field at the location where reconnection began. Nevertheless, even in this simple situation, there is structure and that structure makes determining the magnetopause orientation with a single spacecraft difficult.

While most measurements of the magnetopause current have been at low latitude, polar measurements at high latitude have been most instrumental in giving us new insight into the reconnection process. They in fact suggest that a guide field is not present at the reconnection point. This is equivalent to saying that the correct picture of reconnection is antiparallel reconnection and not component
reconnection. This also predicts that the reconnection line moves around in response to shifts in the IMF clock angle. This behavior is very much consistent with the observed control of the geomagnetic activity, the ring current and the location of the polar cusp. This observation further indicates that it is simply the small scale size at the x-point that leads to the demagnetization of ions and electrons, to ambipolar electric fields and the swapping of magnetic partners, the key element of reconnection.

We are learning much with our present spacecraft combined with numerical simulations. However, there is much left to be done. Because the magnetopause contains three-dimensional structure and is time varying, we need to employ multiple spacecraft clusters to study this problem. For the magnetopause separations of about 10 km are needed. This is possible with the proposed Magnetosphere Multiscale mission but does not seem achievable with the planned separation strategy of Cluster.

Acknowledgements

This research was supported by the National Aeronautics and Space Administration under research grant NAG5-11329 and by the National Science Foundation under research grant ATM 01-01145.
References


