



WHAT DO WE REALLY KNOW ABOUT THE MAGNETOSHEATH?

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ABSTRACT

A comprehensive review is given of our current knowledge about the physical processes in the magnetosheath. Major breakthroughs on both theoretical and observational fronts occurred in the last few years in understanding the steady-state magnetosheath. These new results are changing our view of the magnetosheath. Significant progress was made in understanding the waves in the magnetosheath. There are new techniques that can predict the consequence of the solar wind variations in the magnetosheath. The nature of the solar wind-magnetopause interaction is becoming clear with these techniques. We are moving toward being able to forecast conditions extending from the solar wind monitor ahead of the bow shock to the magnetopause. Compared with other regions in space, the magnetosheath remains to be one of the most poorly understood regions and more work needs to be done.

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INTRODUCTION

A sharp-nosed object such as a supersonic aircraft creates a shock wave attached to its nose, but the nose of the magnetosphere is blunt and the shock is detached from the object so that the magnetosheath completely surrounds the nose region of the magnetopause. The interaction of the magnetosheath with the magnetopause can be described in terms of waves. These waves carry the information to warn the incoming solar wind of the existence of the magnetopause, an obstacle to the flow. The waves in general can take various forms, such as oscillations, discontinuities or standing waves, and infinitesimal increments. (A gradual change can be considered as a series of small incremental changes.) The function of these waves is to reconfigure the solar wind flow and its frozen-in magnetic field from the solar wind state to the state specified by the magnetopause boundary condition. It is obvious that either changes in the upstream solar wind or in the downstream boundary condition at the magnetopause will produce additional temporal variations in the magnetosheath. Furthermore, waves can also be generated by the processes of the solar wind-bow shock interaction as reviewed in the previous chapter of this volume. Because the variations associated with these two additional sources are so strong, they have for a long time prevented the processes in the magnetosheath from being uncovered. In this paper, we review our current observational knowledge and physical understanding of the processes in the magnetosheath and discuss the issues needing further investigation.

HISTORICAL NOTES

Figures of the magnetopause with a detached bow shock can be found in publications as early as in 1962 (e.g. Axford [1962], Kellogg [1962]). The term "the magnetosheath" is found to first appear in Dessler and Fejer [1963]. The characteristics of the magnetosheath and the locations of the bow shock and the magnetopause described by Dessler and Fejer appear similar to what we know nowadays.

The earliest observations of the magnetosheath were made by Pioneer 1 [Sonett and Abrams, 1963]. Sonett and Abrams described this region as "shocklike disturbances, sharp and rapid changes in the field direction ..." They referred to this region as "the magnetopause", the first time that the term "the magnetopause" appeared in literature. According to their definition, this region is "the transition region between the magnetosphere proper and the interplanetary medium." Today, the magnetopause appears to refer to only the inner edge of this transition region because the modern technology provides us with very high resolution observations so that more and more distinct regions can be resolved. As we will see later in this paper, even the transition

from the "magnetosheath" to the "magnetopause" becomes difficult to define.

STEADY-STATE MAGNETOSHEATH

Understanding the steady-state magnetosheath is essential to understanding the fundamental physical processes in the magnetosheath. The understanding is not only important to magnetospheric physics but also to general fluid dynamics, because this setting is a classical problem of supersonic flow around a blunt body. The difference from what is discussed in common textbooks is that this flow is not an ordinary flow but a "magnetized highly electrically conducting flow". The understanding of the processes in this system can be applicable to many problems in astrophysics, solar physics, space physics and plasma physics.

In this system, the existence of the magnetic field changes the processes from those of ordinary fluid or gasdynamics because the fluid equations become coupled to Maxwell equations. No longer is the fluid isotropic, and additional wave modes can transmit information through the fluid. In magnetohydrodynamic (MHD) theory, three different wave propagation modes exist called the fast, intermediate and slow modes [e.g., Kantrowitz and Petschek, 1966]. Each mode has a particular function and a generalized fluid perturbation will require contributions of all three modes to describe it. In analogy to the standing sonic shock in a supersonic flow of unmagnetized fluid or a gas, the three modes may form standing fronts in a supersonic magnetized plasma flow past an obstacle. Since the modes each travel at a different velocity, these standing waves will be spatially separated with the slow mode standing closest to the obstacle. When the fluid is collision-free, such as some plasmas in space physics, solar physics, and astrophysics, whether the above description is correct remains controversial because the kinetic effects become important. To study this process in a terrestrial laboratory to date has proven to be very difficult and our present knowledge is based principally on theoretical models, simulations, and observations in space.

From a theoretical viewpoint, two major issues have been identified concerning the magnetosheath processes. One is whether the magnetosheath processes are monotonic or not. In a monotonic process, the waves in the magnetosheath take the form of increments. A standing wave in the sheath will form shock-like profile in contrast. The other issue concerns the symmetry/asymmetry of the sheath flow pattern. Both issues are not only scientifically challenging but also important to modeling the magnetosheath-magnetopause coupling, for example, in space weather programs.

Monotonic Versus Shock-Like Profile

Theoretical Models. The effects of the magnetic field on the sheath flow were recognized soon after the magnetosheath was introduced [Midgley and Davis; 1963, Lees, 1964]. Zwan and Wolf [1976] (Z-W) provided the first formulation and numerical solution of the magnetosheath. Their model, see Fig 1, is essentially one-dimensional with three-dimensional characteristics. It follows a magnetic flux tube moving from the bow shock to the magnetopause while satisfying the conservation laws along the flux tube. The temporal evolution of this flux tube provides the description of the second dimension that is along the trajectory of the flux tube. The third dimension that is normal to the plane containing the magnetic field and the flow is incorporated according to the electric potential difference across such a flux tube based on the frozen-in condition. Z-W identified two mechanisms that lead to draining and depletion of the plasma inside of the flux tube. Hence

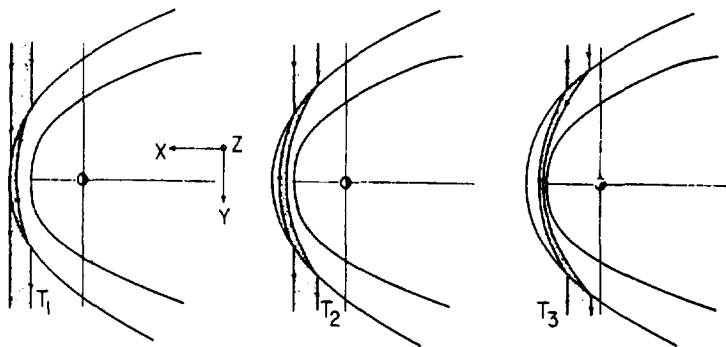


Fig. 1. Zwan and Wolf [1976] plasma depletion model. It calculates the density within a flux tube as it moves toward the magnetopause. The flux tube gets compressed across the bow shock and the plasma starts diverting away from $y=0$ along the flux tube, the first depletion effect. Near the magnetopause, the flux tubes start piling up and squeezing the plasma out, the second depletion effect.

the model is widely known as the plasma depletion model. The first depletion mechanism is the diversion of the flow at the bow shock along the magnetic field direction and away from the stagnation streamline. It is

important to point out that the diversion may not necessarily lead to a decrease in the density because while the flux tube moves toward the magnetopause, it also gets compressed which tends to increase the density. The rate of the compression is proportional to the rate of the deceleration of the flow. A net density decrease could be achieved in the region where the deceleration of the flow is not efficient and the diversion is dominant. The second depletion mechanism is the so-called squeezing effect. This effect occurs near the magnetopause where the magnetic flux tubes pile up. As the magnetic pressure increases, to maintain the total pressure balance, the plasma pressure has to decrease and hence the plasma is squeezed out. Many people describe this mechanism as squeezing toothpaste out of the tube. Although this analogy is useful to convey the concept, an important issue is what processes play the role of the "hand" in squeezing the plasma. Note here that every flux tube is completely enveloped in other flux tubes. In Z-W's paper, a mathematical solution is derived describing a smooth transition between these two mechanisms. It is important to point out that it is not impossible for a discontinuity to exist in the region where the two mechanisms are in transition. In other words, the solutions of the two mechanisms, if each is solved starting from one of the boundaries, would not necessarily match and a jump condition between the two solutions may be required. The solution of the Z-W model predicts a monotonic density decrease from the bow shock to the magnetopause with a layer near the magnetopause where the density drops rapidly while the field strength increases. This layer is referred to as the plasma depletion layer. Z-W correctly pointed out that the plasma depletion layer is physically a slow mode rarefaction wave.

Wu [1992] reported the results of the magnetosheath profile from a 3-D MHD calculation. An important difference from Z-W is that the density along the sun-earth line increases rather than decreases in the outer magnetosheath. This indicates that in the outer magnetosheath in Wu's calculation, the diversion of the flow is not sufficient to compensate the compression of the flux tube. Figure 2 shows a comparison of the MHD

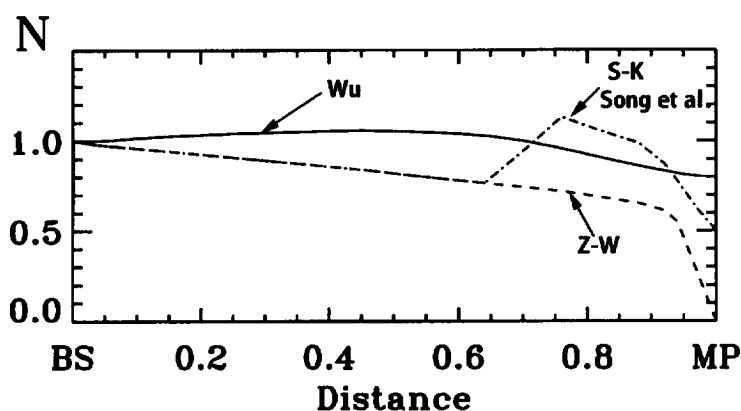


Fig. 2. Comparison of the density profiles along the sun-earth line predicted by models: Wu's MHD calculation [1992] (solid line), the Z-W depletion model [1976] (dashed line), and Southwood and Kivelson's new model [1995] and Song et al.'s observations [1992a] (dot-dashed line).

magnetosheath result with the depletion model. A depletion layer near the magnetopause is confirmed in Wu's results. Most other MHD simulations show similar profiles (e.g. Lee et al., 1991; Lyon, 1994; Yan and Lee, 1994; Berchem et al., 1995).

Southwood and Kivelson [1992,1995] revisited the Z-W formulation and made significant contribution to the physical understanding. They provided a comprehensive discussion on the assumptions made in the Z-W model and the physical consequence of these assumptions. The assumption that allows Z-W to follow and calculate an isolated flux tube in the magnetosheath is the so-called thin flux tube approximation. With this approximation, the forces acting on the isolated flux tube are provided by its surrounding medium in the form of external forces. These external forces vary according to the location of the flux tube in the sheath and are different from the external forces given by the boundary conditions if the flux tube is away from the boundary. In the Z-W model the force is specified using the condition at the magnetopause boundary that introduces a kinematic element into the model.

Most importantly, Southwood and Kivelson [1995] identified the following paradox in the Z-W formulation. We first recall that in isotropic plasmas the only force that can make the plasma move along the field is the plasma pressure gradient force because the Lorentz force is zero along the flux tube, (in anisotropic plasmas, the mirror force can provide an additional depletion mechanism.) When flux tubes pile up near the stagnation region, the magnetic pressure increases. The resulting lower thermal pressure will act against further squeezing. If the first depletion mechanism, the diversion, results in a lower density along the stagnation streamline, according to the Z-W model, there will be little plasma available to produce the higher thermal pressure needed for the second depletion. One possible solution, as proposed by Southwood and Kivelson [1995], is to add a

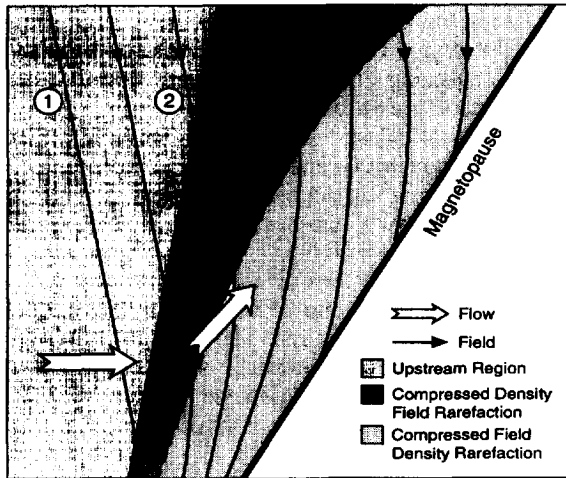


Fig. 3. Southwood and Kivelson model [1995]. The sheath plasma gets compressed at the slow front while the field is rarefacted, and then the opposite process in a rarefaction wave. The model requires 3-D geometry: the field lines ending at the magnetopause are bent either out of or into the page.

al, 1981] or transient reconnection (e.g Russell and Elphic [1978]).

The overall density profile of the magnetosheath was not known until the work by Song et al. [1990]. Song et al. surveyed the satellite passes near the sun-earth line and reported some then unexpected profiles: the density remains fairly constant and similar to expectations in the outer part of the magnetosheath and undergoes some relatively abrupt enhancements in front of the magnetopause, see Figure 4 for an example. These density enhancements can be simplified as a compressional front followed by a depletion as the magnetopause is approached, plus oscillations. They interpreted this compressional front as a slow mode (shock) front. Similar density enhancements in front of the magnetopause are later found in observations from AMPTE/IRM and WIND, and the Jovian magnetosheath [Hammond et al., 1995], see Figure 5.

Because some numerical calculations [Wu, 1992; Lyon, 1994; Yan and Lee, 1994; Berchem et al., 1995] and observations from the Venus magnetosheath [Luhmann, 1995] failed to confirm the slow compressional front, some skepticism about the existence of the slow shock front has arisen. It further arose because of various theoretical concerns, e.g., the Landau damping of the slow mode (see

slow mode compressional front at the end of the diversion-dominant region, see Figure 3. This compressional front provides the required higher thermal pressure for the second depletion process.

From the Z-W model to the Southwood-Kivelson model, the understanding of the magnetosheath processes and profile evolves from monotonic to shock-like.

Previous Observations. Signatures of the plasma depletion layer have been observed on occasions [Paschmann et al, 1978, Crooker et al. 1979, Song et al. 1993]. Phan et al. [1994] reported based on a statistical study that the depletion layer is more likely to occur during northward interplanetary magnetic field (IMF) but not during southward IMF. This dependence is understandable because the degree of depletion is proportional to the duration of depletion. The longer a flux tube stays near the subsolar region before it convects away tangentially from this region, the more plasma is depleted. For southward IMF, flux tubes near the subsolar region are quickly removed by either steady-state reconnection [Paschmann et al. 1979, Sonnerup et

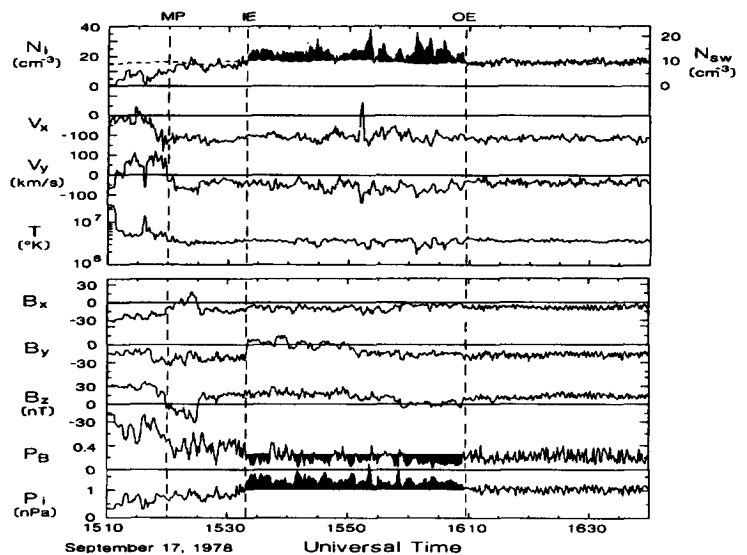


Fig. 4. An example of ISEE 2 outboard magnetosheath passes [Song et al., 1992a]. The dashed line on the top panel are the simultaneous solar wind density shifted by the time delay from the solar wind monitor to ISEE 2. The sheath satellite encountered a density enhancement in front of the magnetopause (MP) as indicated by the shaded area. The magnetic field (P_B is the magnetic pressure) is weaker during the density enhancement, a characteristics of slow modes. Also note that the fluctuations (in the density and field) change their characteristics across the outer edge (OE) of the density enhancement with a smaller amplitude and higher frequency upstream.

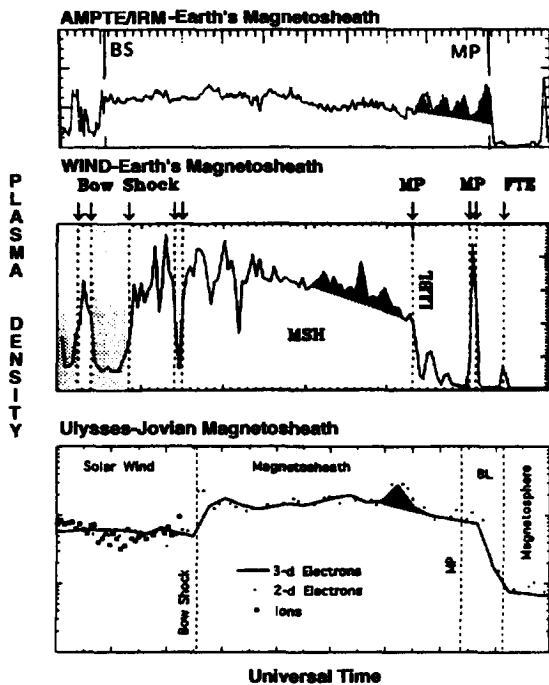


Fig. 5. Density enhancements in front of the magnetopause recorded by AMPTE/IRM [Hill et al., 1995] (upper panel) and WIND [Phan et al., 1996] (middle panel) in the terrestrial magnetosheath, and Ulysses from Jovian magnetosheath [Phillips et al., 1993] (bottom panel). The baselines of the shaded regions follow the trend appearing before the shaded enhancements keeping in mind the plasma depletion model.

with the predictions from the Gasdynamic Convective Field Model (GDCFM).

The GDCFM [Spreiter and Stahara, 1980, 1985] uses the solar wind and IMF measurements from upstream monitors as the input to determine the location and shape of the bow shock and magnetopause, calculate the flow and density fields according to steady-state gasdynamics, and derive the magnetic field in the magnetosheath assuming it is frozen to the flow. The GDCFM provides three very important references: the time delay from the solar wind monitor to the magnetosheath, the locations of the magnetopause and bow shock, and a reference value for each physical quantity at each point in the magnetosheath. Most importantly, as the upstream conditions change, these references change in a systematic physically understandable manner.

Comparing the GDCFM with standard ideal MHD models, two effects are neglected in the GDCFM. First, the time derivatives are

more discussion in the next section), and the possibility that the density enhancements observed in the magnetosheath could come from solar wind irregularities. This latter issue is particularly difficult to solve: a successful test of the shock jump conditions across a front in the magnetosheath [Song et al., 1992a] does not exclude the possibility because a jump condition test does not provide information about the source of a discontinuity. Moreover, the solar wind plasma and magnetic field, which provide the input boundary conditions, vary in time, sometimes suddenly, and the size of the obstacle varies in response to the changing dynamic pressure of the solar wind flow. The position of a satellite relative to the two boundaries changes in response to these solar wind changes. To isolate the steady-state magnetosheath processes from these dynamic upstream variations is extremely challenging but becomes a crucial issue if one is to conclusively identify a new shock front in the magnetosheath. If such a shock front does exist, our understanding of how a magnetized collision-free flow changes its fluid properties as it flows around an obstacle will be altered significantly.

A New Technique. An new approach has been taken that provides a rigorous means in data analysis to separating the magnetosheath processes from those upstream variations [Zhang et al., 1996]. This technique, as illustrated in Figure 6, compares the simultaneous magnetosheath observations

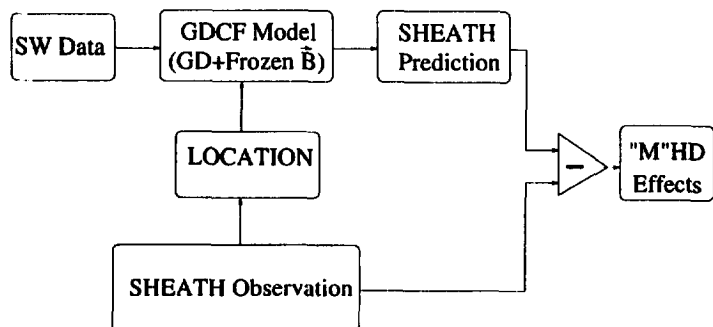


Fig. 6. A scheme using the GDCFM to study the steady-state magnetosheath processes. Solar wind data and the location of the magnetosheath satellite are input to the GDCFM. Its output prediction is compared against the magnetosheath observations. The differences between the two provide a measure of the effects of the magnetic force.

not included. Second the magnetic forces are omitted from the momentum equation. In return, the calculation can be done at the same speed as the solar wind measurement input. What physical processes are neglected due to these two assumptions? Let us examine the MHD momentum equation,

$$\rho[\partial\mathbf{v}/\partial t + (\mathbf{v} \cdot \nabla)\mathbf{v}] = -\nabla p - \nabla B^2 / 2\mu_0 + (\mathbf{B} \cdot \nabla)\mathbf{B} / \mu_0$$

where ρ , \mathbf{v} , p , \mathbf{B} , and μ_0 are the density, velocity, thermal pressure, magnetic field, and permeability in vacuum. The first term on the left is the time varying term. Setting it zero neglects non-standing waves. Loosely speaking, the balance between the second term on the left and the first term on the right can be referred to as the sonic mode. The second term on the left and the third term on the right gives the Alfvén (or intermediate) mode. The first and second terms on the right have two possible relationships. One is that they vary in phase and the other is that they vary out of phase. The in-phase case, combined with the second term on the left, is the magnetosonic (or perpendicular propagating fast) mode; and the out-of-phase case, combined with the last term on the right is the slow mode. Since the physics of the magnetosonic mode is similar (by using a different definition of the pressure) to that of the sonic mode, the omission of the magnetic force effectively neglects the Alfvén and slow modes. Therefore, we expect that any significant systematic differences between the GDCFM prediction and magnetosheath *in situ* observations should be associated with the Alfvénic and slow mode processes neglected by the GDCFM. In the terrestrial magnetosheath, the plasma beta, the ratio of the thermal to magnetic pressures, is significantly higher than one. Under this condition, the speeds of the Alfvénic and slow modes are similar. If both exist, the Alfvénic and slow standing fronts may not be spatially distinguishable.

Figures 7 and 8 show two sample calculations of this comparison. Here we will discuss in moderate detail what differences we have seen in these two cases. The solar wind/IMF data are shown on the top panel. Panels 2 to 4 show the comparison of the magnetosheath observations (solid lines) with the GDCFM prediction (dashed lines). For the first case, shown in Figure 7, the solar wind was steady and there were small rotations in the IMF during this interval. An outbound bow shock crossing is indicated by decreases in both plasma density and magnetic field strength, a characteristic of a fast mode shock. A crossing of the magnetopause is indicated on the magnetospheric side by a drop in the plasma density and an increase in the magnetic field strength while the field turns to the direction of the Earth's dipole field, a smaller absolute value of the clock angle. The model predicts the thickness of the magnetosheath accurately. The overall prediction in the density and magnetic field strength is good in the middle and outer magnetosheath (after 1600UT). But the prediction is poor near the magnetopause. In particular, the model does not predict

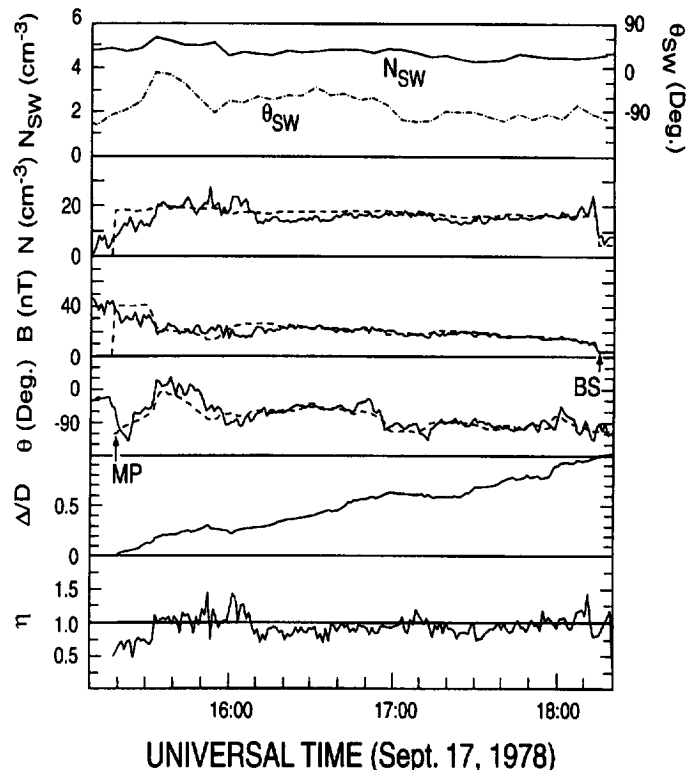


Fig. 7. An ISEE 2 outbound magnetosheath pass. The observed ISEE 2 magnetopause (MP) and bow shock (BS) traversals are indicated by arrows in panel 4. The top panel shows the solar wind density (solid line), and clock angle (dotted-dashed line), that is the angle between north and the magnetic field on the plane perpendicular to the Sun-Earth line, measured by ISEE 3 (shifted by 57 min to account for approximately the solar wind travelling time from ISEE 3 to ISEE 2). Panels 2 to 4 are the densities, field strengths and clock angles of ISEE 2 observation (solid lines) and GDCFM prediction (dashed lines). Panels 5 and 6 show the location of ISEE 2 from the magnetopause normalized by the thickness of the magnetosheath, i.e. normalized radial distance, and the ISEE 2 observed density normalized by GDCFM prediction that is similar to the value downstream of the bow shock for this pass, respectively.

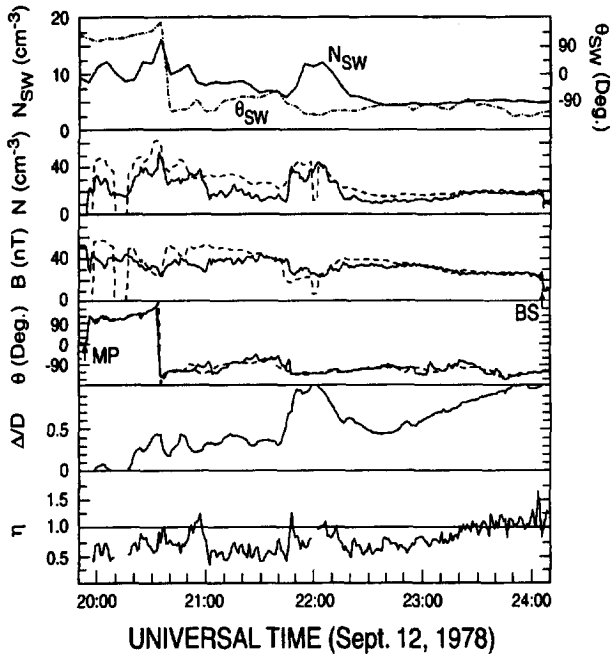


Fig. 8. Another ISEE 2 magnetosheath pass in the same format as Fig. 2. The ISEE 3 data is shifted by 50 min.

slow modes. From this case, one may suspect that the slow mode structures come from the solar wind and are not generated in the magnetosheath, even though one then encounters the difficulty in explaining the first case. This will be addressed next.

Because the GDCFM provides a reference to the simultaneous upstream conditions, we can remove the effects of the upstream variations by normalization. For example, as the solar wind density changes, so does the density downstream of the bow shock predicted by the model. Likewise, as the magnetopause and bow shock move, so does the prediction of the satellite location relative to the two boundaries. Two normalized quantities can be defined as the predicted satellite location from the magnetopause normalized by the predicted thickness of the magnetosheath at that particular solar zenith angle, and the observed density normalized by the predicted one. In the former normalization, the magnetopause is at zero and the bow shock is at one. In the latter normalization, the deviation of the normalized density from unity provides the error of the model. The time series of these two normalized quantities are shown in the bottom two panels in Figures 7 and 8. One can see that the satellite traversed relatively smoothly outward from the magnetopause to the bow shock in the first case; but in the second case, the changes in the solar wind

the density enhancement near 1610UT. During the density enhancement, the magnetic field is weaker than the predicted field. This has been interpreted as a slow mode compressional front [Song et al., 1992a].

During the interval shown in Figure 8, there are brief changes in the IMF and solar wind density. The model again very well predicts the first magnetopause and the last bow shock crossings. There are a pair of magnetopause crossings near 2015UT and a pair of bow shock crossings near 2200UT, predicted by the model but not actually recorded in the observations. Below we will show that the satellite at the time was indeed very close to the magnetopause and bow shock respectively within the spatial resolution of GDCFM. This indicates that the model predicts a slightly (although within the accuracy of the model) thinner magnetosheath than it is for this particular case. The magnetic field prediction is better near the bow shock than near the magnetopause. The density prediction indicates that several density enhancements observed in the sheath are correlated with the solar wind density enhancements. Looking at the sheath observations alone, these density enhancements are associated with field depressions and hence are

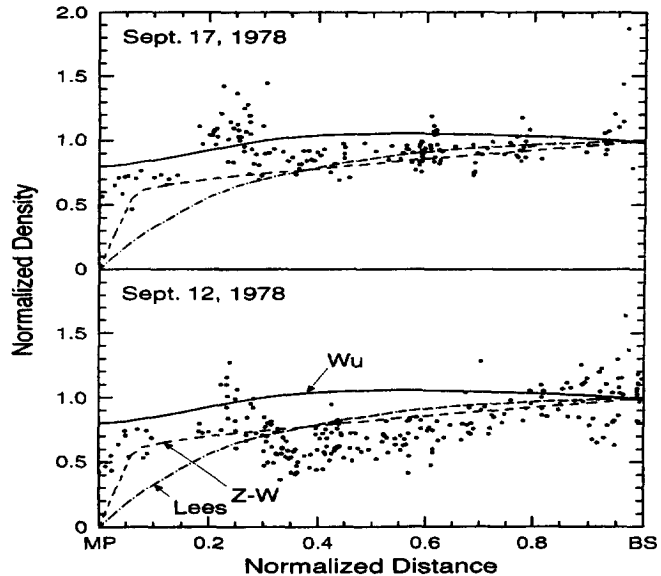


Fig. 9. The normalized density as functions of normalized radial distance. The slow shock front occurs from 0.2 to 0.4 in both cases. The two lines are from theoretical calculations, Lees [1964], Zwan-Wolf [1976], and Wu [1992]. The prediction from the GDCFM is 1 in this presentation. The density predicted by the GDCFM in the sheath is similar to that just downstream of the bow shock for these two particular orbits.

caused the magnetopause and bow shock to move and in turn the satellite to swing a few times in the sheath before it moved out of the sheath. Combining these two normalized quantities, or performing the double normalization, we can remove variations due to temporal changes. We do this by plotting the normalized density versus the normalized radial distance as in Figure 9. Similar to its time series, the normalized density of the first case shows a clear declining trend from the bow shock and a compressional shock front standing in the magnetosheath. While the normalized density of the second case does not show any particular pattern in its time series, in its normalized distance plot, remarkably, the normalized density shows a similar pattern to the first case: only one significant density bump remains. The compressional fronts for both cases are located near 0.3 with amplitudes greater than 40% above the declining trend from the bow shock. Now we have shown that a compressional front is inherent in the magnetosheath. We refer to this front as a shock although the dissipation appears to be weak.

In Figure 9, we also show the density profiles given by two model calculations (but remember that GDCFM predicts a constant of unity in this plot). Comparing these profiles with the two sets of observations, the density decrease in the outer and middle magnetosheath is relatively well modeled by the depletion model [Zwan and Wolf, 1976]. However, the slow shock front where the density jumps well in front of the obstacle is predicted by neither model. Southwood and Kivelson's proposal [1995] describes very well the observations.

Asymmetry Of The Sheath Flow

Stagnation Point Versus Stagnation Line. In a gasdynamics model, the solar wind flows along the sun-earth line and strikes the subsolar point and then is diverted radially from this point. In this model, the subsolar point is a stagnation point and the flow is axially symmetric. When the magnetic field is present in the flow, there is a serious problem with this picture. From steady-state mass conservation and the frozen-in condition, one can derive the so-called MHD Helmholtz equation,

$$(\mathbf{v} \cdot \nabla)\mathbf{B}/\rho = (\mathbf{B}/\rho \cdot \nabla)\mathbf{v}$$

At a stagnation point, the left-hand side is zero while the right-hand side is not because the velocity changes its direction. Unless the change in B/ρ goes to infinity the equation presents a dilemma. There are two ways to have $B/\rho = \infty$, ie either $B = \infty$ or $\rho = 0$. Obviously, $B = \infty$ is unphysical, a problem identified from the gasdynamic approach [Spreiter and Alksne, 1967]. A zero density that leads to a zero current is also unphysical because it contradicts the assumption that the magnetopause is a current layer. Pudovkin and Semenov [1977] and Sonnerup [1980] suggested a solution to avoiding such a dilemma: replacing the stagnation point with a stagnation line of a finite length, see Figure 10. Pudovkin et al. [1982] and Pudovkin and Semenov [1985] described a mathematical approach to model the stagnation line with reconnection flow. Kinematic components appear to be introduced with their assumptions because the density profile is similar to that of gasdynamics [Spreiter and Stahara, 1980] when the IMF is northward and to that of Wu's simulation [1992] when the IMF is southward. Sonnerup and Lyon [1995] presented a formulation that describes exact local 3-D incompressible MHD solutions valid near the transition from a stagnation line to a magnetic null line.

This dilemma also occurs in ideal MHD because the Helmholtz equation applies to ideal MHD. This dilemma may not occur when reconnection takes place at the subsolar point because there is no stagnation region as the sheath plasma flows into the magnetosphere. The essence of the stagnation line proposal is the introduction of an anisotropy to the flow with respect to the magnetic field. Consequently, near the subsolar point the flow is more likely to be perpendicular to the field than parallel to the field. Such a tendency has been recently reported by Phan et al. [1994].

Stagnation Point Versus Subsolar Point. In the gasdynamic model, the subsolar point is the stagnation point and the flow is axisymmetric. The stagnation line model breaks the axisymmetry and replaces it with two

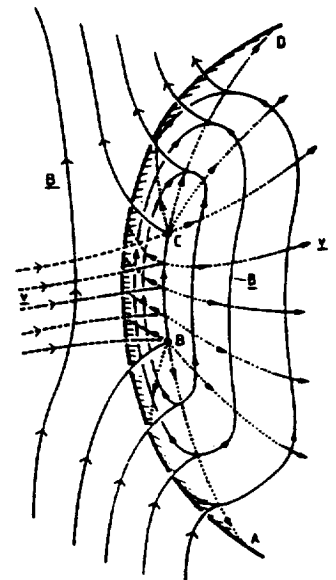


Fig. 10. The stagnation line model [Sonnerup 1980]. The stagnant magnetic field line, BC, splits. AB and CD are magnetic null lines. Note the flow is not axially symmetric.

line symmetries. One is with respect to the stagnant magnetic field line, and the other is with respect to the line that crosses the subsolar point and is perpendicular to the stagnant field line. The analysis is based on the assumption that the sheath field is parallel to the magnetopause boundary. This would be a good assumption when the IMF is perpendicular to the solar wind flow. When the IMF is neither along nor perpendicular to the flow, i.e. when the IMF has a non-zero incident angle to the boundary, the line symmetry across the field may break.

The possible effects of the IMF direction on the location of the stagnation point were first investigated by Walters [1964]. His analysis was based on the additional deflection of the flow at the bow shock associated with the magnetic field. It predicts a very large, 10° to 25° , overall tilt of the flow to the west if the IMF is along the Parker's spiral. This effect further predicts that the magnetotail also tilts with the same amount from the sun-earth line. However, the large tilt has not been observed. It appears that Walters' conclusion was based on a too large estimate of the IMF strength, about 3-5 times stronger than average observed IMF strength. In fact, at the bow shock, because the field is very weak, its effects on the flow are not important. Near the magnetopause, on the other hand, the magnetic force becomes important and can modify the flow pattern. The stagnation point will be shifted from the subsolar point due to the magnetic curvature force [Zhuang and Russell, 1981; Russell et al., 1981]. The consequence of this shift of the stagnation point could be substantial to the global modeling. For example, reconnection sites may be more related to the stagnation point than the subsolar point. No observational report has been made on this possible effect.

WAVES IN THE MAGNETOSHEATH

Observationally, the magnetosheath is filled with a variety of waves (e.g. Kaufmann et al., 1970; Tsurutani et al., 1982; Fairfield et al., 1990; Takahashi et al., 1991; Schwartz et al., 1996). Most of the wave power is concentrated in the 0.01~0.1 Hz range although some waves appear to be broad-banded. Very often the waves are nonlinear with amplitudes greater than 10 percent. In principle, there are three sources for these waves. One possible source is the solar wind itself. Because the solar wind seldom carries oscillations in this frequency range at the earth's orbit, it is not an important source for the sheath waves. The solar wind-bow shock interaction appears to be the most important source for the waves in the magnetosheath. The waves can be generated in two ways. A fraction of the incoming solar wind particles are reflected at the bow shock back into the solar wind and form the foreshock region [Greenstadt, 1972; Fairfield, 1976; Russell et al., 1983; Luhmann et al., 1986]. Waves start growing in the foreshock and convect into the magnetosheath. This is the most powerful wave generation mechanism. The other mechanism is associated with the significant modification of the properties of the bulk solar wind at the bow shock. The plasma becomes unstable to certain instabilities and waves start growing in the outer magnetosheath. The third source is the magnetopause because the magnetosheath is the region where the magnetopause communicates with the solar wind. Although this communication usually does not necessarily take the form of oscillatory waves, oscillations from the upstream region will be partially reflected at the magnetopause into the magnetosheath. Therefore the magnetopause may appear to be a source of oscillatory waves. In general, unless these reflected waves are fast modes, they can propagate into the magnetosheath only to a limited distance. This outermost distance in principle should coincide with the slow mode front, which was discussed in the last section, if the waves are slow modes. Therefore, it is expected the wave activity to be enhanced in the region between the slow mode front and the magnetopause as shown, for example, in Figure 4. The shock geometry appears to be the most important factor that controls the wave properties in the magnetosheath.

Downstream Of The Quasi-Perpendicular Shock

It is well-known that foreshock is associated with quasiparallel shocks [Luhmann et al, 1986; Le and Russell, 1992]. Therefore most waves downstream of a quasiperpendicular shock are generated at or downstream of the bow shock. At a quasiperpendicular shock, more plasma flow energy is converted into thermal energy perpendicular to the magnetic field than parallel to it. The anisotropy may continue to build up in the sheath [Crooker and Siscoe, 1977]. This temperature anisotropy, $T_{\perp} > T_{\parallel}$, is unstable to the ion cyclotron anisotropy instability and the mirror instability.

Mirror Waves. Regular compressional waves with periods about 20 sec are perhaps the most recognizable feature of the terrestrial magnetosheath downstream of quasiperpendicular shocks [Tsurutani et al., 1982; Hubert et al., 1989; Lacombe et al., 1992; Song et al., 1992b; Fazakerley and Southwood, 1994; Anderson et al., 1994], see for example, fluctuations after 1610UT in Figure 4. Note that the mode of the fluctuations

before 1610UT, which have a lower frequency and greater amplitude, is still under debate, see later this section. Similar waves are also observed in the cometary magnetosheath [Russell et al., 1987] and Jovian magnetosheath [Tsurutani et al., 1993]. These waves have been identified as mirror waves. Mirror waves are not propagating waves in homogeneous plasmas. In the plasma frame, they are static structures. When these structures pass by a satellite with the flow, they appear to be oscillations due to the Doppler effect. Using measurements from two satellites, one can show that these structures have a minimum velocity relative to the flow, the real proof that the waves are static in the flow. The mirror mode structures are created by the mirror mode instability that becomes unstable associated with temperature anisotropy usually in high beta plasmas. Progress has recently been made in understanding the microphysics of the mirror instability [Gary, 1992; Southwood and Kivelson, 1993; McKean et al., 1993; Kivelson and Southwood, 1996].

Because the mirror mode structures are often observed with large amplitudes, it has been for long an outstanding question as to how the mirror mode is saturated and at what level. For example, one can easily show that from the mirror mode instability condition and double adiabatic [Chow et al., 1956] assumption, the growth of the mirror mode will never stop. Therefore, one of the ways for the mode to saturate is to invoke wave-particle interaction that heats the plasma and takes the energy away from the wave. Southwood and Kivelson [1993] and Kivelson and Southwood [1996] provided the following interesting analysis. As the mirror mode grows, mirror points are formed associated with the regions of field maxima. Particles start being trapped between two mirror points. When the amplitude increases, more particles become trapped. The further growth of the instability leads to the following important process. As illustrated in Figure 11, some trapped particles, those with larger pitch angles, see the two mirror points between which the particles are trapped moving apart. These particles experience a Fermi deceleration process and lose energy. This process helps the wave to grow. Other trapped particles, those with smaller pitch angles, see the two mirror points moving toward each other, and they undergo Fermi-acceleration. This latter wave-particle interaction takes energy from the waves and stabilizes the instability. The increase in the latter population, as the wave grows helps to saturate the wave. The change in the field strength can also heat/cool particles. The rate of the particle energy change is $\mu \cdot dB/dt$, where μ is the magnetic moment of a particle. Particles gain (lose) energy in the regions undergoing field compression (rarefaction). To stop the growth or to saturate the wave, it requires an increasing number of particles that gain energy and a decreasing number of particles that lose energy. Phrasing the above two statements in a different way, one may expect that at the saturation stage, the wave profile contains more regions of increased field than regions of decreased field. This is consistent with the fact that large amplitude mirror structures are often observed with a longer duration in the field maxima than minima.

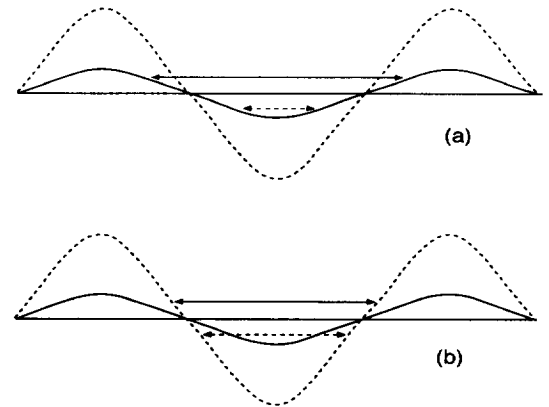


Fig. 11. Illustration of the motion of mirror points as the mirror mode grows [Kivelson and Southwood, 1996]. The arrowheads of solid (dashed) lines indicate the mirror points of particles with small (large) pitch angles. (a) In the early stage of the mode growth, the wave amplitude is small, as indicated by the solid sinusoidal curve. (b) When the wave amplitude becomes large, dashed sinusoidal curve, the mirror points for large pitch angle particles move apart while the mirror points for small pitch angle particles move close. The former experience a Fermi-deceleration and the latter Fermi-acceleration.

Anisotropy-Beta Relation. It is obvious that the temperature anisotropy is a source of free energy for waves to grow. The physical meaning of the plasma beta in the context of waves is interesting. Kennel and Petschek [1966] introduced the concept of critical energy $B^2/2\mu_0N$, where N is number density. The physical meaning of this quantity is the magnetic field energy available to each particle. Although this quantity is derived specifically for cyclotron resonances, we may generalize to use it as a measure of required energy for a particle to significantly contribute to a wave. Fewer particles with energies greater than the critical energy will result in a weaker wave, and vice versa. The plasma beta happens to be the ratio of the average thermal energy per particle of the plasma to the critical energy. A higher beta indicates that more particles are qualified for being important to the wave. In this case, a little free energy will trigger large amplitude waves. Therefore, one may not be surprised to see an inverse relation between the anisotropy and the beta.

Anderson et al. [1994] reported the evidence for such an inverse relation from AMPTE/CCE observations. Phan et al. [1994] observed a similar relation from AMPTE/IRM but they found that the quantitative relationship differs from cases to case, see Figure 12. Denton et al. [1994] and Gary et al. [1995] pointed out that most observed values of anisotropy and β_{\parallel} from CCE are marginally unstable to the proton cyclotron anisotropy instability where β_{\parallel} is the beta evaluated using the pressure parallel to the field. This phenomenon can be understood as the effectiveness of the wave-particle interaction that self-limits the anisotropy: as the anisotropy increases, the waves grow; the waves scatter the particles to smaller pitch angles, through the so-called pitch angle diffusion, leading to a reduction of the anisotropy; and therefore the plasma conditions remain to marginally stable/unstable to the instability.

The observed anisotropy-beta relation has been used to close the anisotropic MHD equations [Denton et al., 1994]. Here we recall that the anisotropic MHD is not closed unless an additional constraint is given on the relationship between the two temperatures. The double adiabatic model [Chew et al. 1956] does not well describe the processes in the magnetosheath because of the presence of high heat flux [Song et al., 1992a; Phan et al., 1994].

The above anisotropy-beta relation has not been shown to have a simple conversion to spatial location. Wave activity is complicated. The waves near the bow shock seem to depend strongly on the local plasma conditions. The ion cyclotron modes appear to be very effective [Skopke et al., 1990] unless there is a large concentration of He^{++} particles [Russell and Farris, 1995]. A high concentration of the He^{++} suppresses the growth of the ion cyclotron modes and results in a faster growth of the mirror modes [Price et al., 1986; Russell and Farris, 1995]. Not very close to the bow shock downstream of quasiperpendicular shocks, most waves are mirror modes. Near the magnetopause on the other hand, as the result of flux tube piling up and plasma depletion, the plasma beta is low. The ion cyclotron anisotropy instability has a greater growth rate than the mirror instability near the magnetopause [Gary et al., 1995]. Ion cyclotron modes are often observed near the magnetopause [Anderson et al., 1994].

Slow Mode Versus Mirror Mode. This issue has drawn heated debates in the last a few years. People agree that the waves upstream of the slow mode front are mirror modes but disagree on what are those between the magnetopause and the slow mode front, for example, the waves from the magnetopause to 1610UT in Figure 4. Some think they are slow modes [Song et al., 1992b, 1994] and others think they are mirror modes [Anderson et al., 1994; Denton et al., 1995]. The center of the debate is not the terminology but the source and the function of the waves. In particular, whether the magnetopause is also a source of the waves in the magnetosheath. The slow mode referred to is not necessarily to be a wave that obeys strictly the MHD slow mode dispersion relation, but a wave with a finite propagation speed and the same characteristic perturbation relations as the MHD slow mode.

The proponents of the mirror modes suggest that the low frequency compressional waves near the magnetopause arise from the simple progressive evolution of the mirror modes upstream. They do not recognize the existence or significance of the slow front. The observations that can be used to support their argument include the observed anisotropy-beta relation to be continuous and unstable to the mirror mode instability. Their key theoretical argument against the slow modes is that the slow mode is heavily Landau damped and essentially does not exist in the kinetic theory. Here we recall that the Landau resonance occurs when the velocity of a particle parallel to the wave propagation direction equals the wave phase velocity, or $\omega = \mathbf{k} \cdot \mathbf{v}$. A wave is Landau damped if more particles gain energy than lose energy through the Landau resonance. The Landau damping does not occur in a standing front because no Landau resonance can take place.

The proponents of the slow modes showed that the compressional wave near the magnetopause are

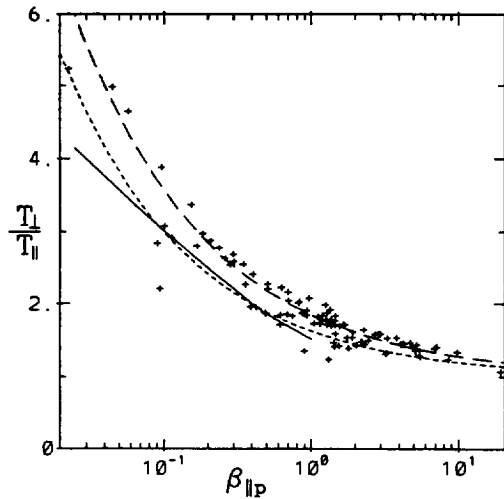


Fig. 12. The temperature anisotropy-beta relations [Denton et al., 1994]. The solid line shows the marginally stable condition for the proton temperature anisotropy instability. The crosses and long-dashed line are AMPTE/CCE observations and the fit. The short-dashed line is the fit of IRM observations.

propagating upstream from the magnetopause rather than convecting with the flow toward the magnetopause and that there is a significant change in the wave properties at the slow front [Song et al., 1992b, 1994]. This change is also visible in the case shown in Figure 4. They argue that the observational results used by the opponents are not exclusive to the slow modes and that the spatial dependences of the anisotropy and beta are not monotonic [Hill et al., 1995; Zhang et al., 1996]. The physical picture they push forward is that the magnetopause is not a simple passive recipient of the waves upstream but an active source of part of the waves. The mirror waves are either significantly modified at the slow front and become propagating or are reflected at the magnetopause. The reflected waves cannot be mirror modes. They propagate upstream and cannot go farther than the slow front because of their finite phase velocity against the incoming flow. With regard to the expected Landau damping of the slow modes, they suggest that it can be overcome either by nonlinear effects or nonuniformity of the plasma near the magnetopause.

One of the key points in the debate is whether the compressional waves near the magnetopause are propagating or purely convective. If the two sides agree that the waves are upstream propagating, there is no real physical difference between the two sides. The reason why the mirror modes can survive the Landau damping is that they have no real frequency and hence have zero phase velocity. If the mirror modes can be of non-zero phase velocity, they are open to the Landau damping, the same problem with which the slow modes are attacked. On the same token, if the mirror modes with a finite phase velocity can survive the Landau damping, so do the slow modes.

Omidi and Winske [1995] performed a 1-D hybrid simulation of solar wind-magnetopause interaction. Their results remarkably resemble many observed features: mirror mode fluctuations in the outer magnetosheath, a compressional front in the inner sheath, enhanced compressional oscillations downstream of the front, and a depletion region as part of the magnetopause barrier. They found that the oscillations between the front and the magnetopause are propagating upstream with a dispersion relation between the mirror and slow modes and therefore they termed the waves "MIAOW" (mirror and slow) waves. They attributed the change of the wave properties from the mirror mode to the nonuniformity of the plasma near the magnetopause.

Johnson and Cheng [1996] recently took a different approach and performed eigen mode analysis of the magnetosheath. In this analysis, each existing mode is a global mode in the sheath. As the plasma conditions change from the bow shock to the magnetopause, the properties of a mode, such as the frequency and amplitude, change accordingly. A major advantage of this treatment over a local analysis is that the changes in the Doppler shift due to the change in the flow speed can be modeled. In a local theory, the phase velocity is described in the plasma frame, but the theory tells nothing about the changes in the plasma frame. If a flow slows down, can a part of the flow energy feed into the wave energy and hence amplify the wave? The global analysis may be able to address this question. Nevertheless, this method needs to be significantly developed before it becomes realistic.

Mode Identification. A major advance driven by the debate of slow versus mirror mode is the active development and test of techniques of wave analysis. One area of the development is to use two spacecraft measurements and conventional wave analysis methods to directly determine the phase velocity [Gleaves and Southwood, 1991; Song et al., 1992b]. Another area involves the usage of the so-called transport ratios.

A transport ratio is the ratio between two perturbed quantities. While the perturbation of a quantity is small and varies from case to case, a transport ratio can be more definitive for each particular wave mode. For example, for an incompressible Alfvén wave, the perturbations occur only in the direction of the field but not in the strength. Therefore, the ratio of transverse perturbation to the compressional perturbation goes to infinity. From theory, one can obtain a set of transport ratios for a particular wave mode. Then one can compare the theoretical prediction of these ratios with the observed ones to determine the mode of a wave. In principle, one can derive many different transport ratios. In reality, some of them are not diagnostic and hence not useful, but others may not be well measured. Therefore, a researcher has to determine a minimum set of the ratios that are reasonably well measured and contain independent information about different aspects of the wave. For example, one may need the information about both the background and perturbed values of the field strength and its direction, flow velocity, and density or pressure (if he/she assumes the plasma to be polytropic). Therefore four or five transport ratios of which each involved quantity is self-normalized are the minimum set. This self-normalization is important to reduce the possible calibration errors in the measurements of a quantity.

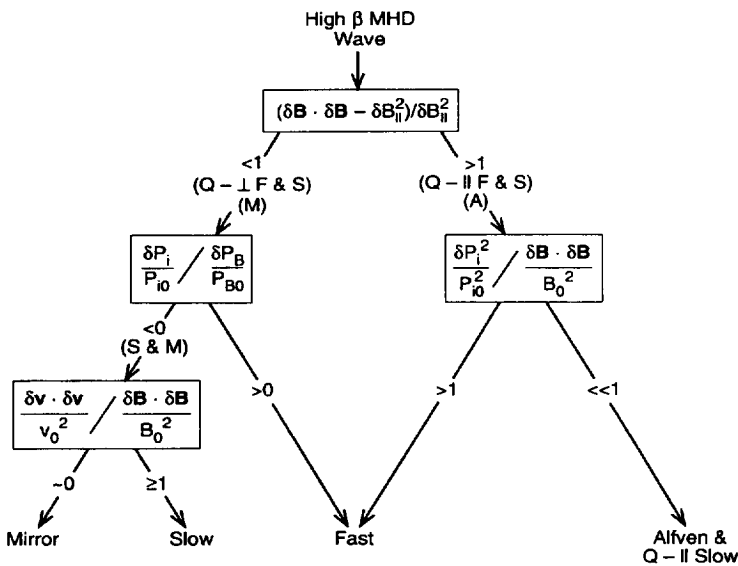


Fig. 13. A hierarchical scheme of wave mode identification [Song et al., 1994]. A given fluctuation can be distinguished among four different modes. At each step, the user makes a yes-no decision. The level of a box is determined according to the accuracy of the measurements.

When comparing the observed transport ratios with those calculated from theory, one could find that none of the modes in theory completely match the observations. In order to characterize a fluctuation with a mode, one has to choose a mode that is "most likely" to represent the wave. Different schemes will evaluate the "likelihood" from different angles. Song et al. [1994] first introduced a hierarchical scheme. This scheme, as illustrated in Figure 13, is a qualitative deterministic scheme. Four transport ratios are employed to distinguish four modes. One follows the chart and makes a yes-no decision at each point. The level of the boxes have been determined according to the accuracies of the measurements. The most accurately measured quantity is on the top.

Denton et al. [1995] proposed a parallel scheme. In this scheme, all transport ratios are treated to be equally accurately measured. Each observed ratio is then compared with the theoretical values for all modes with different possible propagation angles. A mode is identified as the one with the smallest sum of the differences between theoretical and observational values of a selected set of ratios.

Downstream Of The Quasi-Parallel Shock

Upstream of quasiparallel shocks in the foreshock region, because of the reflected particles from the bow shock which create free energy in the plasma, there exist significant wave activities. These fluctuations are carried by the solar wind flowing into the magnetosheath and most likely are amplified at the bow shock. On the other hand, the background field in the sheath is usually weak because only the tangential component of the field, which is small for quasiparallel shocks, is amplified. Combining these two, downstream of quasiparallel shock are often found field fluctuations to be of the same order as the background field (e.g. Engebretson et al., [1991]). We know little about the properties of these fluctuations, but we do know that there is a significant amount of energy associated with these fluctuations transferred into the magnetosphere [Engebretson et al., 1991; Fairfield et al., 1990].

SOLAR WIND DISCONTINUITIES SEEN IN THE MAGNETOSHEATH

The bow shock will significantly modify a solar wind discontinuity when it enters the magnetosheath [Zhuang et al., 1981]. In theory the collision of a solar wind discontinuity with the bow shock creates seven discontinuities: a pair of shocks for each of fast, intermediate and slow modes plus a contact discontinuity. This is the so-called Riemann problem [see a comprehensive review by Lin and Lee, 1994]. Each pair consists of a forward moving and a backward moving shock relative to the contact discontinuity. The backward moving fast shock forms the new bow shock front as required by the downstream condition of the solar wind discontinuity. In the Earth's frame, all other six discontinuities move in the anti-sunward direction. Because of the differences in the phase velocities among the discontinuities, they should spatially spread as they propagate. The search for such differentiation has not yet reported any positive results.

If the discontinuities that are created by interaction of a solar wind discontinuity with the bow shock cannot be spatially separated, what is seen in the magnetosheath would be a discontinuity consisting of many modes and different from the one in the solar wind. This appears to be a mode conversion. For example, an upstream incompressible rotational discontinuity may become a compressible discontinuity in the sheath [Wu et al.,

1992; Yan and Lee, 1995, Lin et al., 1996].

MODELING SOLAR WIND-MAGNETOPAUSE INTERACTION

One of the reasons why the magnetosheath is important in magnetospheric physics is that the magnetosheath plays a crucial role in the solar wind-magnetopause interaction. After all, it is the magnetosheath field and plasma that actually interact with the magnetopause. Early models describing the solar wind-magnetopause interaction without the bow shock and magnetosheath have been useful. Examples of such models include calculation of the magnetopause location and shape using the solar wind pressure [e.g., Mead and Beard, 1964] and the model of antiparallel merging at the magnetopause using the IMF direction directly [Crooker, 1979]. As we now know, the location and the shape of the magnetopause also depend on reconnection [e.g. Fairfield, 1971; Petrinec et al., 1992; Shue et al, 1996], and the draping of the magnetic field due to the bow shock and the magnetosheath processes will modify the locations where the fields on the two sides of the magnetopause are antiparallel [Luhmann et al., 1984]. Furthermore, the reconnection processes are sensitive to the plasma conditions, such as field shear [Paschmann et al., 1979, Sonnerup et al., 1981], the flow pattern and plasma beta [Paschmann et al., 1986]. Therefore, the magnetosheath becomes an essential element for any realistic solar wind-magnetopause interaction model, in particular for a space weather forecast model. Interestingly enough, some models of the solar wind-magnetopause interaction need the bow shock-magnetosheath processes to be unpredictable when they fail in comparison with observations. Some heated debate in the last a few years originated because of this. The predictability of the sheath properties near the magnetopause to the changes in the solar wind becomes important in constraining models of the dynamic interaction between the solar wind and the magnetopause.

As we showed in Figures 7 and 8, the GDCFM provides remarkable prediction of the solar wind convection. In these two cases, the convection time, field draping and the location of the sheath satellite relative to the bow shock and magnetopause are accurately handled. In the cases that we have tested, many show similar predictability but others are not so good. Figure 14 shows one of the latter cases. The magnetopause and bow shock positions are reasonably well predicted. The prediction indicates that ISEE 2 was close to the bow shock near 0150UT and the density enhancements that appear in Figures 7 and 8 occur in the inner magnetosheath. The field direction and magnitude are well predicted after 0120UT, but not before 0120UT. Some of the differences seem to be caused by a different timing, as large as 20 min. This timing difference indicates that the structures associated with these fluctuations propagate relative to the flow. Because the real arrival time is later than the predicted one, the propagation is upstream in the plasma frame, consistent with the idea of the magnetopause as a source of the sheath perturbations. Some other differences are not clearly understood. A systematic study of where, when and by how much these differences occur is necessary to understand the predictability of the solar wind dynamic processes and to improve models.

To test the limit of predictability using the GDCFM, we use 15 sec resolution upstream data as the input.

Note here we have stretched the application beyond the limit of the model. Since the GDCFM is not a dynamic model, the forecast capability is limited by the Alfvén transient time in the magnetosheath which is 1-2 min. However, as shown in Figure 15, the prediction catches many of the small scale fluctuations in the sheath. Interestingly enough, the perturbations near 0604 and 0623UT are not predicted. These two perturbations last about 1-2 min each and are FTEs [Russell and Elphic, 1978]. Because the prediction is good

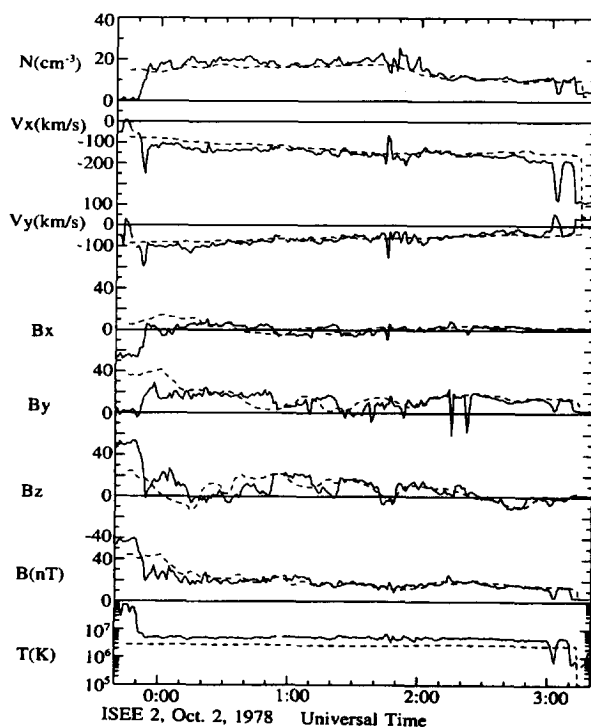


Fig. 14. An example when the comparison of the GDCFM and ISEE 2 observation is not very good. Significant differences in the field direction occur in the inner sheath.

everywhere else and has many points within each FTE interval, the source of the FTEs must not be either in the solar wind or foreshock. This case provides convincing negative evidence for reinterpretation of FTEs as to be created by upstream sources. Again the density enhancements occur in front of the magnetopause, same as the other three cases shown.

TOPICS FOR FUTURE RESEARCH

Steady-State Magnetosheath

The theoretical understanding of the steady-state magnetosheath processes is just the beginning. Substantial work is needed in particular in the area of quantitative modeling. These models have to address such basic issues as the shape, distance, dependence of upstream conditions of the slow front. Is there any anisotropy in the shape and distance? In observations, the slow front does not seem to be present in several cases. Why?

The biggest mystery in Figure 9 may be why the complicated magnetosheath structure is not found in existing global simulation models. Because the Zwan-Wolf model is not fully 3-D and is not completely self-consistent, one may expect and accept some differences from observations. However, Wu's [1992] calculation is 3-D ideal MHD which should

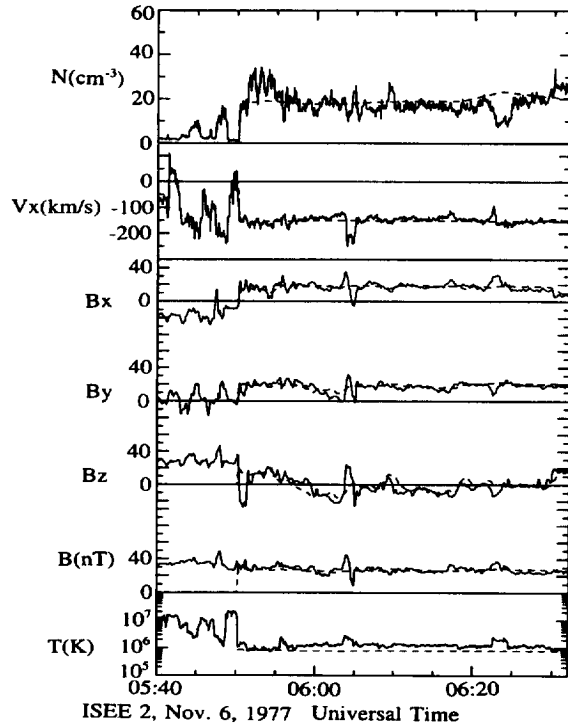


Fig. 15. Comparison of the GDCFM and ISEE 2 observations using 15 sec resolution input. The prediction is accurate most places but not near 0604 and 0623UT when two FTEs occur; indicating the FTEs are not generated by upstream sources.

subsection. Other models may be used for a similar normalization. With GDCFM, we can develop a third normalization procedure. In this normalization, we take the direction of the IMF on the y-z plane as the polar direction of a new planar polar coordinate system. Then we determine the satellite's location in this coordinate system. For example, if the satellite is located in the northern hemisphere at local noon, an IMF rotation from northward to eastward will move the satellite from zero degree to 90 degree in this planar polar coordinate presentation. Using this normalization, we will be able to discern the effects of the IMF direction. The asymmetry of the field and flow, from axisymmetry for example, will provide important information about the effects of the magnetic curvature force. Interesting topics to address include the existence of a stagnation point versus a stagnation line [Sonnerup, 1980] and the dependence of the location of the stagnation point/line on the IMF orientation.

Waves In The Magnetosheath

Among the observational evidence under debate, the slow front is critical. If it does exist and is as strong as we showed in Figure 9, we expect that more people will agree that the wave properties change at the front similar to the way the wave properties change at the bow shock. As the evidence for the slow front is becoming more and more convincing as discussed in section 3, we expect the debate of mirror versus slow soon to come to an end.

The techniques developed during the debate will prove to be very useful to analyze the wave properties in the sheath. A survey of the wave properties as functions of spatial location and of the shock geometry, becomes crucial for further studies of the sheath waves. Techniques to analyze the large amplitude fluctuations downstream of the quasiparallel shocks remain to be developed.

How the waves evolve through the magnetosheath from theoretical viewpoint is not clear yet despite the significant progress made in the last few years, in particular how the mirror modes convert to the slow modes at the slow shock or reflect at the magnetopause.

Solar Wind Discontinuity Interacting With The Bow Shock

This is a subject that has been widely recognized only recently. The observational component lags significantly behind the theory. Close collaboration of the theorists with observationalists may be important to fully realize the potential importance of the new physics added by this process.

Modeling The Solar Wind-Magnetopause Interaction And Space Weather Forecast

As an example, we have shown that the solar wind variations can be modeled and predicted even using a simple gasdynamic model. More realistic models that include the physics causing the differences between the GDCFM and observations need to be developed. Currently, a database of the solar wind measurements and magnetosheath observations are available for test of any realistic new numerical models. These tests are important for further development of these models.

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REFERENCES

- Anderson, B. J., S. A. Fuselier, S. P. Gary, R. E. Denton, Magnetic spectral signatures in the Earth's magnetosheath and plasma depletion layer, *J. Geophys. Res.*, **99**, 5877, 1994.
- Axford, W. I., The interaction between the solar wind and the earth's magnetosphere, *J. Geophys. Res.*, **67**, 3791, 1962.
- Berchem, J., J. Raeder, M. Ashour-Abdalla, Reconnection at the magnetospheric boundary: Results from global magnetohydrodynamic simulations, in *Physics and Magnetopause*, edited by P. Song, B. U. O. Sonnerup, M. F. Thomsen, AGU Monograph, Vol. 90, 205, 1995
- Chew, G. F., M. L. Goldberger, and F. E. Low, The Boltzmann equation and the one-fluid hydromagnetic equations in the absence of particle collisions, *Proc. R. Soc. London Ser. A.*, **236**, 112, 1956.

- Crooker, N. U., and G. L. Siscoe, A mechanism for pressure anisotropy and mirror instability in the dayside magnetosheath, *J. Geophys. Res.*, **82**, 185, 1977.
- Crooker, N. U., Dayside merging and cusp geometry, *J. Geophys. Res.*, **84**, 951, 1979.
- Crooker, N. U., T. E. Eastman, and G. S. Stiles, Observations of plasma depletion in the magnetosheath at the magnetopause, *J. Geophys. Res.*, **84**, 869, 1979.
- Denton, R. E., B. J. Anderson, S. P. Gary, and S. A. Fuselier, Bounded anisotropy fluid model for ion temperatures, *J. Geophys. Res.*, **99**, 11225, 1994.
- Denton, R. E., S. P. Gary, X. Li, B. J. Anderson, J. W. LaBelle, and M. Lessard, Low-frequency fluctuations in the magnetosheath near the magnetopause, *J. Geophys. Res.*, **100**, 5665, 1995.
- Dessler, A. J., and J. A. Fejer, Interpretation of Kp index and M-region geomagnetic storms, *Planet. Space Sci.*, **11**, 505, 1963.
- Engebretson, M. J., N. Lin, W. Baumjohann, H. Luehr, B. J. Anderson, L. J. Zanetti, T. A. Potemra, R. L. McPherron, and M. G. Kivelson, A comparison of ULF fluctuations in the solar wind, magnetosheath, and dayside magnetosphere, 1, Magnetosheath morphology, *J. Geophys. Res.*, **96**, 3441, 1991.
- Fairfield, D. H., Average and unusual locations of the Earth's magnetopause and bow shock, *J. Geophys. Res.*, **76**, 6700, 1971.
- Fairfield, D. H., Magnetic fields of the magnetosheath, *Rev. Geophys. Space Phys.*, **14**, 117, 1976.
- Fairfield, D. H., W. Baumjohann, G. Paschmann, H. Luhr, and D. G. Sibeck, Upstream pressure variations associated with the bow shock and their effects on the magnetosphere, *J. Geophys. Res.*, **95**, 3773, 1990.
- Fazakerley, N. A., and D. J. Southwood, Mirror instability on the magnetosheath, *Adv. Space Res.*, **14**(7), 65, 1994.
- Gary, S. P., The mirror and ion cyclotron anisotropy instabilities, *J. Geophys. Res.*, **97**, 8519, 1992
- Gary, S. P., D. Winske, M. E. McKean, S. A. Fuselier, R. E. Denton, and B. J. Anderson, Proton anisotropies upstream of the magnetopause, in *Physics of the Magnetopause*, edited by P. Song, B. U. O. Sonnerup, M. F. Thomsen, AGU Monograph, Vol. 90, 123, 1995
- Gleaves, D. G., and D. J. Southwood, Magnetohydrodynamic fluctuations in the earth's magnetosheath at 1500LT: ISEE 1 and ISEE 2, *J. Geophys. Res.*, **86**, 129, 1991.
- Gombosi, T. I., D. L. De Zeeuw, R. Haberli, and K. G. Powell, Three-dimensional multiscale MHD model of cometary plasma environments, *J. Geophys. Res.*, **101**, 15233, 1996.
- Greenstadt, E. W., Field-determined oscillations in the magnetosheath as a possible source of medium period daytime micropulsations, paper presented at the Solar Terrestrial Relations Conference, Univ. of Calgary, Calgary, Alberta, Canada, Aug. 28 to Sept. 1, 1972.
- Hammond, C. M., Phillips, J. L., Balogh, A., Ulysses observations of slow mode transition in the Jovian magnetosheath, *EOS Trans. AGU* **76**, (17), 5251, 1995.
- Hill, P., G. Paschmann, R. A. Treumann, W. Baumjohann, N. Sckopke, and H. Luhr, Plasma and magnetic field behavior across the magnetosheath near local noon, *J. Geophys. Res.*, **100**, 9575, 1995.
- Hubert, D., C. Perche, C. C. Harvey, C. Lacombe, and C. T. Russell, Observation of mirror waves downstream of a quasiperpendicular shock, *Geophys. Res. Letts.*, **16**, 159, 1989.
- Johnson, J. R., and C. Z. Cheng, Global structure of mirror modes in the magnetosheath, *J. Geophys. Res.*, submitted, 1996.
- Kantrowitz, A., and H. E. Petschek, MHD characteristics and shock waves, in *Plasma Physics in Theory and Application*, edited by W. B. Kunkel, p. 148, McGraw-Hill, New York, 1966.
- Kaufmann, R. L., J. T. Horng and A. Wolfe, Large amplitude hydromagnetic waves in the inner magnetosheath, *J. Geophys. Res.*, **75**, 4666, 1970.
- Kellogg, P. J., Flow of plasma around the earth, *J. Geophys. Res.*, **67**, 3805, 1962.
- Kennel, C. F., and H. E. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res.*, **71**, 1, 1966.
- Kivelson, M. G., and D. J. Southwood, Mirror instability II: The mechanism of nonlinear saturation, *J. Geophys. Res.*, **101**, 17365, 1996.
- Le, G., and C. T. Russell, A study of ULF wave foreshock morphology-I. ULF foreshock boundary, *Planet. Space Sci.*, **40**, 1203, 1992
- Lee, L. C., Yan, M. and Hawkins, J. G., A study of slow mode structure in front of the dayside magnetopause, *Geophys. Res. Lett.*, **19**, 381-384, 1991.
- Lees, L., Interaction between the solar plasma wind and the geomagnetic cavity, *AIAAJ*, **2**, 1576-1582, 1964.
- Lin, Y., and L. C. Lee, Structure of reconnection layers in the magnetosphere, *Space. Sci. Rev.*, **65**, 59, 1994.
- Lin, Y., D. W. Swift, and L. C. Lee, Simulation of pressure pulses in the bow shock and magnetosheath driven by variations in the interplanetary magnetic field direction, *J. Geophys. Res.*, in press, 1996.
- Lacombe, C., F. G. E. Pantellini, D. Hubert, C. C. Harvey, A. Mangeney, G. Belmont, and C. T. Russell, Mirror and Alfvénic waves observed by ISEE 1-2 during crossings of the Earth's bow shock, *Ann. Geophys.*, **10**,

- 772, 1992.
- Luhmann, J. G., R. J. Walker, C. T. Russell, N. U. Crooker, J. R. Spreiter, and S. S. Stahara, Patterns of magnetic field merging sites on the magnetopause, *J. Geophys. Res.*, **89**, 1739, 1984.
- Luhmann, J. G., C. T. Russell, R. C. Elphic, Spatial distributions of magnetic field fluctuations in the dayside magnetosheath, *J. Geophys. Res.*, **91**, 1711, 1986.
- Luhmann, J. G., The inner magnetosheath of Venus: An analogue for Earth? *J. Geophys. Res.*, **100**, 12,035-12,045, 1995.
- Lyon, J. G., MHD simulations of the magnetosheath, *Adv. Space. Sci.*, **14**, (7), 21-28, 1994.
- McKean, M. E., S. P. Gary, and D. Winske, Kinetic physics of the mirror instability, *J. Geophys. Res.*, **98**, 21313, 1993.
- Mead, G. D., and D. B. Beard, Shape of the geomagnetic field solar wind boundary, *J. Geophys. Res.*, **69**, 1169, 1964.
- Midgley, J. E., and Davis, L., Jr. Calculation by a moment technique of the perturbation of the geomagnetic field by the solar wind, *J. Geophys. Res.*, **68**, 5111-5123, 1963.
- Omidi, N. & Winske, D., Structure of the magnetopause inferred from the Kinetic Riemann problem, *J. Geophys. Res.*, **100**, 11,935-11,955, 1995.
- Paschmann, G. et al., ISEE plasma observations of near the subsolar magnetopause, *Space Sci. Rev.*, **22**, 711, 1978.
- Paschmann, G., B. U. O. Sonnerup, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russell, R. C. Elphic, Plasma acceleration at the earth's magnetopause: Evidence for reconnection, *Nature*, **282**, 243, 1979.
- Paschmann, G., I. Papamastorakis, W. Baumjohann, N. Sckopke, C. W. Carlson, B. U. O. Sonnerup, and H. Luhr, The magnetopause for large magnetic shear: AMPTE/IRM observations, *J. Geophys. Res.*, **91**, 11099, 1986.
- Petrinec, S. M., P. Song, and C. T. Russell, Solar cycle variations in the size and shape of the magnetopause, *J. Geophys. Res.*, **96**, 7893, 1991.
- Petrinec, S. M., T. Makai, A. Nishida, T. Yamamoto, T. K. Nakamura, and S. Kokubun, GEOTAIL observations of magnetosheath flow near the magnetopause, using WIND as a solar wind monitor, *J. Geophys. Res.*, **101**, submitted, 1996.
- Phan, T., G. Paschmann, W. Baumjohann, N. Sckopke, H. Luhr, The magnetosheath region adjacent to the dayside magnetopause: AMPTE/IRM observations, *J. Geophys. Res.*, **99**, 121, 1994.
- Phan et al., The subsolar magnetosheath and magnetopause for high solar wind ram pressure: WIND observations, *Geophys. Res. Lett.*, **23**, 1279, 1996.
- Phillips, J. L., S. J. Bame, M. F. Thomsen, B. E. Goldstein, and E. J. Smith, Ulysses plasma observations in the Jovian magnetosheath, *J. Geophys. Res.*, **98**, 21189, 1993.
- Pudovkin, M. I., and V. S. Semenov, Stationary frozen-in coordinate system, *Ann. Geophys.*, **33**, 429, 1977.
- Pudovkin, M. I., and V. S. Semenov, Magnetic field reconnection theory and the solar wind-magnetosphere interaction: A review, *Space. Sci. Rev.*, **41**, 1-89, 1985.
- Pudovkin, M. I., M. F. Heyn, and V. V. Lebedeva, Magnetosheath's parameters and their dependence on intensity and direction of the solar wind magnetic field, *J. Geophys. Res.*, **87**, 8131, 1982.
- Roelof, E. C., and D. G. Sibeck, Magnetopause shape as a bivariate function of interplanetary magnetic field Bz and solar wind dynamic pressure, *J. Geophys. Res.*, **98**, 21421, 1993.
- Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev.*, **22**, 681, 1978.
- Russell, C. T., J. G. Luhmann, T. J. Odera, and W. F. Stuart, The rate of occurrence of dayside Pc 3,4 pulsations: The L-value dependence of the IMF cone angle effect, *Geophys. Res. Lett.*, **10**, 663, 1983.
- Russell, C. T., and M. H. Farris, Ultra low frequency waves at the earth's bow shock, *Adv. Space Res.*, **15**, (8/9)285, 1995.
- Russell, C. T., H-C. Zhuang, R. J. Walker, and N. U. Crooker, A note on the location of the stagnation point in the magnetosheath flow, *Geophys. Res. Letts.*, **8**, 984, 1981.
- Russell, C. T., W. Riedler, K. Schwingensuh, and Y. Yeroshenko, Mirror instability in the magnetosphere of Comet Halley, *Geophys. Res. Letts.*, **14**, 644, 1987.
- Schwartz, S. J., et al., *Ann. Geophys.*, **14**, 1134, 1996.
- Sckopke, N., G. Paschmann, A. L. Brinca, C. W. Carlson, and H. Luhr, Ion thermalization in quasi-perpendicular shocks involving reflected ions, *J. Geophys. Res.*, **95**, 6337, 1990.
- Shue, J.-H., J. K. Chao, H. C. Fu, C. T. Russell, P. Song, K. K. Khuruna, and H. Singer, A new functional form to study the solar wind control of magnetopause size and location, *J. Geophys. Res.*, in press, 1996.
- Song, P., Russell, C. T., Gosling, J. T., Thomsen, M. F., and Elphic, R. C., Observations of the density profile

- in the magnetosheath near the stagnation streamline, *Geophys. Res. Lett.*, *17*, 2035-2038, 1990.
- Song, P., Russell, C. T. and Thomsen, M. F., Slow mode transition in the frontside magnetosheath, *J. Geophys. Res.*, *97*, 8295-8305, 1992a.
- Song, P., C. T. Russell, and M. F. Thomsen, Waves in the inner magnetosheath: A case study, *Geophys. Res. Letts.*, *19*, 2191, 1992b.
- Song, P., et al., Structure and properties of the subsolar magnetopause for northward IMF: Multiple-instrument particle observation, *J. Geophys. Res.*, *98*, 187, 1993.
- Song, P., C. T. Russell, and S. P. Gary, Identification of low-frequency fluctuations in the terrestrial magnetosheath, *J. Geophys. Res.*, *99*, 6011, 1994.
- Sonnerup, B. U. O., Transport mechanisms at the magnetopause, in *Dynamics of the Magnetosphere*, edited by S. -I. Akasofu, D. Reidel, p77, Hingham, Mass., 1980
- Sonnerup, B. U. O., G. Paschmann, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, and C. T. Russell, Evidence for magnetic field reconnection at the earth's magnetopause, *J. Geophys. Res.*, *86*, 10049, 1981.
- Sonnerup, B. U. O., and J. G. Lyon, On ideal MHD flow past a diamagnetic body, *EOS Trans. AGU*, *76*, S248, 1995.
- Sonett, C. P., and I. J. Abrams, The distant geomagnetic field 3. Disorder and shocks in the magnetopause, *J. Geophys. Res.*, *68*, 1233, 1963.
- Southwood, D. J. and Kivelson, M. G., On the form of the flow in the magnetosheath, *J. Geophys. Res.*, *97*, 2873-2879, 1992.
- Southwood, D. J., and M. G. Kivelson, Mirror instability 1: The physical mechanism of linear instability, *J. Geophys. Res.*, *98*, 9181, 1993.
- Southwood, D. J., and Kivelson, M. G., Magnetosheath flow near the subsolar magnetopause: Zwan-Wolf and Southwood-Kivelson theories reconciled, *Geophys. Res. Lett.*, *22*, 3275-3278, 1995.
- Spreiter, J. R., and Stahara, S. S., A new predictive model for determining solar wind-terrestrial planet interaction, *J. Geophys. Res.*, *85*, 6769-6777, 1980.
- Spreiter, J. R., and Stahara, S. S. *Collisionless Shocks in the Heliosphere: Reviews of Current Research*, AGU, Washington DC, 85-107, 1985.
- Strangeway, R. J., and C. T. Russell, Plasma waves and field-aligned currents in the Venus plasma mantle, *J. Geophys. Res.*, *101*, 17313, 1996.
- Takahashi, K. D., G. Sibeck, P. T. Newell, and H. E. Spence, ULF waves in the low-latitude boundary layer and relationship to magnetospheric pulsations: A multi-satellites observations, *J. Geophys. Res.*, *96*, 9503, 1991.
- Tsurutani, B. T., E. J. Smith, R. R. Anderson. K. W. Ogilvie, J. D. Scudder, D. N. Baker, and S. J. Bame, Lion roars and nonoscillatory drift mirror waves in the magnetosheath, *J. Geophys. Res.*, *87*, 6060, 1982.
- Tsurutani, B. T., D. J. Southwood, E. J. Smith, and A. Balogh, A survey of low-frequency waves at Jupiter: The Ulysses encounter, *J. Geophys. Res.*, *98*, 21203, 1993.
- Wu, C. C., MHD flow past an obstacle: Large scale flow in the magnetosheath, *Geophys. Res. Lett.*, *19*, 87, 1992.
- Wu, B. H., M. E. Mandt, L. C. Lee, and J. K. Chao, Magnetospheric response to solar wind dynamic pressure variations: Interaction of interplanetary tangential discontinuities with the bow shock, *J. Geophys. Res.*, *98*, 21297, 1993.
- Yan, M. and Lee, L. C., Generation of slow mode waves in the front of the dayside magnetopause, *Geophys. Res. Lett.*, *21*, 629-632, 1994.
- Zhang, X. X., P. Song, S. S. Stahara, J. R. Spreiter, C. T. Russell, G. Le, Large scale structures in the magnetosheath: Exogenous or endogenous in origin, *Geophys. Res. Letts.*, *23*, 105, 1996.
- Zhuang, H-C., and C. T. Russell, An analytical treatment of the structure of the bow shock and magnetosheath, *J. Geophys. Res.*, *86*, 2191, 1981.
- Zhuang, H-C., C. T. Russell, E. J. Smith, and J. T. Gosling, Three-dimensional interaction of interplanetary shock waves with the bow shock and magnetopause: A comparison of theory with ISEE observations, *J. Geophys. Res.*, *86*, 5590, 1981.
- Zwan, B. J., and Wolf, R. A., Depletion of solar wind plasma near a planetary boundary, *J. Geophys. Res.*, *81*, 1634-1648, 1976.