On the processes in the terrestrial magnetosheath

2. Case study

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Abstract. We test a new scheme to study the magnetosheath. The scheme uses the solar wind measurements as the input into the gasdynamic convected field model, and the model output is compared with magnetosheath observations. In our four test cases there is a significant overall success in the model prediction. This scheme works better than other methods in magnetosheath studies and is potentially useful for space weather forecasts and nowcasts. The direction of the magnetic field is modeled most accurately. The prediction of the size of the magnetosheath is accurate within a few percent. The predicted thickness of the magnetosheath is accurate up to 90%.

With a double-normalization procedure developed in this study, we are able to separate the processes intrinsic in the magnetosheath from those due to large-scale upstream temporal variations. The test cases confirm the existence of a compressional front one third of the distance from the magnetopause to the bow shock near the stagnation streamline. The magnetosheath density profile near the stagnation streamline is consistent with the models that add a compressional front between the two depletion processes described by the plasma depletion model.

A major unexpected feature is that the magnetosheath flow pattern is very different from that described by the model and may lie by most other models, including MHD models. The magnetosheath flow near the stagnation streamline does not slow down gradually toward the stagnation point. It moves rapidly until reaching a very small region near the magnetopause.

1. Introduction

As discussed in an accompanying paper [Song et al., this issue (hereafter referred to as paper 1), the magnetosheath plays an important role in the solar wind-magnetosphere interaction. In the magnetosheath, the flow is deflected and the shocked interplanetary magnetic field (IMF) changes its configuration. The magnetopause is the ultimate cusp of the flow deflection and field reconfiguration. The bow shock is the agent by which much of the change in solar wind properties occurs. This agent is in turn varies with the solar wind conditions and IMF direction (locally). Too little has been done on the behavior of the magnetosheath plasma because it appears to be turbulent. The processes appear to be nonlinear in a high-beta plasma, which is poorly understood in theory. Furthermore, it is sensitive to the changing solar wind conditions and IMF direction and the processes at the magnetopause. When the upstream conditions change, the magnetosheath changes in response. Therefore, the magnetosheath properties may be well correlated with the upstream solar wind variations. When the upstream conditions are steady, the processes associated with the bow shock become important. These processes include the acceleration of backstreaming ions, the generation of upstream waves [e.g., Luhmann et al., 1988a, Fairfield et al., 1990] and the generation of mirror mode wave downstream of the bow shock [Tu et al., 1982; Shibata et al., 1989; Lacombe et al., 1992; Song et al., 1992b; Anderson et al., 1994; Gary et al., 1995; Johnson and Cheng, 1997]. However, the processes inherent in the magnetosheath are missing in this picture. What are the processes and the properties of the magnetosheath itself? To address this question, observationalists have to face the challenge of separating the magnetosheath processes from the processes caused by the bow shock and by variability in the solar wind, as well as the motion of the magnetopause boundary.

Song et al. [1990] first reported the then unexpected density enhancement near the subsolar magnetopause. This enhancement sits ahead of the depletion layer, where the density decreases just in front of the magnetopause. They interpreted the density enhancements as a slow mode compressional front. However, this interpretation was not totally unambiguous, since temporal enhancements in the solar wind density could also lead to magnetosheath density enhancements. To resolve this ambiguity, Song et al. [1992a] analyzed cases when simultaneous upstream solar wind measurements were available. They developed two techniques to do this. First they found that the clock angle of the magnetic field does not change significantly from the solar wind to the magnetosheath near the stagnation streamline. The correlation between the IMF and magnetosheath clock angles provides the first reliable method to determine the time shift between the solar wind monitor and the magnetosheath satellite. Second, they scaled the solar wind quantities for the plasma and field compression at the bow shock in order to compare them with the magnetosheath quantities. With these two steps the processes in the magnetosheath could be analyzed. The results showed that the compressional front is not caused by changes in the solar wind.

Although these methods provide a good tool to correlate the magnetosheath quantities with upstream ones, there are still ambiguities when the solar wind plasma properties change. When the solar wind varies, the compression at the bow shock may vary too. When the solar wind changes ir speed, the arrival time of different solar wind features may vary.
Using a single fixed scale and time shift may reasonably account for the bow shock compression at one upstream condition but this scale may not work through a whole pass if the solar wind varies.

When an unexpected feature is found in observations, it is common practice to suspect a temporal variation in the external conditions. The first question we need to address is how to determine timing and the properties downstream of the bow shock under varying solar wind conditions. The upstream variations not only cause variations in the downstream conditions but also cause the motion of the bow shock at the magnetopause. The rapid motion of the magnetopause and the bow shock in response to upstream variations can cause a satellite to move rapidly through a relatively gentle magnetospheric density profile, translating a steep density profile in the time series of the observations. Therefore a second question one has to address is where the satellite is in the magnetosphere relative to the magnetopause and bow shock. Well inside the magnetosphere, it is extremely difficult to determine observationally where the bow shock and magnetopause are located. In observational terms, we need to resolve the spatial-temporal ambiguity. In physical terms, we are trying to resolve the intrinsic processes in the magnetosphere. As the compression at the bow shock changes with upstream variations, a third question one has to address is how to estimate the shock jump conditions when the upstream conditions vary.

The present work is designed to address these challenging questions. In paper 1 we outline and justify the scheme we are using. We use the Gustydynamic Convection Field Model (GDCF) [Swap, et al, 1966; Spreiter and Stahara, 1980] to provide the needed reference to timing, the magnetopause and bow shock locations, and shock jump conditions. We use the in situ observations to calibrate these two locations and the shock jump conditions. Once the model prediction is consistent with observations, we establish the validity of the scheme we describe. The model also provides the means for removing the temporal effects so that the time series of observations can be presented in a time-independent coordinate system of the magnetosphere. Since we know what physical processes are included in the GDCF, any systematic differences between the prediction and observation to investigate the physical processes that are not included in the GDCF.

In this paper we present a few test cases. In section 2 we discuss the data used in the study and the intercalibration among them. In section 3 we present four cases to demonstrate the situations and issues we meet in application of the scheme. We use a newly developed double-normalization procedure to remove the temporal effects and provide the spatial density profile of the magnetosphere.

2. Data

In each presented case, the data used are from ISEE 3 as the solar wind monitor and ISEE 2 as the magnetosphere in situ observer. Data from two instruments, a magnetometer and a plasma sensor, on each of the satellites are involved. There is an issue of calibration and intercalibration among these instruments and the derived physical quantities. The systematic differences between the model prediction and the in situ observation can be caused by either or both the inaccuracy in the intercalibration and the physical processes that are not described by the model. Thus we need to understand the effects of possible errors in the intercalibration. One way to assess the possible inaccuracy in intercalibration is to study cases with steady upstream conditions. Under these situations, the effects of possible inaccuracy in intercalibration are most likely to appear as a constant ratio between the predicted and observed quantities. The difference between the observation and prediction but with strong correlation in variations could be caused by the intercalibration errors. Systematic differences between the prediction and observations in different cases where the magnetospheric variations are not associated with solar wind changes are most likely caused by physical reasons instead of intercalibration errors. A deficiency of the prediction of the model, i.e., when the prediction always underestimates the magnetospheric response to the upstream variations, should have a similar appearance to the errors in the calibration. These two may be distinguished by a comparison of the observations with predictions in the regions where the model approximations are mostly satisfied.

In general, the magnetic field measurements [Russell, 1978] can be calibrated accurately in the range of accuracy of in situ study. One of the key plasma parameters in our study is the magnetospheric density. The ion density measured by the ISEE 2 Fast Plasma Experiment (FPE) [Blume et al., 1978] used in this study has been intercalibrated through multiple-satellite, multiple-instrument and physical verification [Song et al., 1991]. Briefly, the density is intercalibrated with plasma frequency measurements; with the electron propagation experiment, which accurately measures the average density between ISEE 1 and ISEE 2 by inter-spacecraft communication; with the ISEE 1 FPE; and with the Vector Electron Spectrometer, and is verified by the magnetohydrodynamic (MHD) momentum equation in combination with electric and magnetic fields measurements. The FPE instrument also measured the plasma temperature and two-dimensional (2-D) velocity in the equatorial plane which are used in this study. Since the FPE was not designed to measure the solar wind, we will not show its measurements when ISEE 2 was in the solar wind. The ISEE 3 solar wind measurements have been calibrated with two IMP 8 solar wind instruments by Petrinec and Russell [1993].

In order to minimize the effects of possible different degradation among involved instruments, we have chosen our

![Figure 1](https://example.com/figure1.png)

**Figure 1. Locations of ISEE 2 in GSE for the four cases studied in this paper.** The magnetopause and bow shock shapes are observed averages [Shue et al., 1998; Forsier et al., 1991]. The thin dashed line with an arrow tail indicates the stagnation streamline when including the aberration effect.
Table 1a. Parameters at Magnetopause Crossing.

<table>
<thead>
<tr>
<th>DOI</th>
<th>Location (Km)</th>
<th>Time (UT)</th>
<th>Time Slot (min)</th>
<th>MP Scale</th>
<th>N_{ew} (10^6 cm^-2)</th>
<th>V_{ew} (km/s)</th>
<th>IMF B_{z} (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78290</td>
<td>(9.4, -2.3, 4.2)</td>
<td>1519</td>
<td>0</td>
<td>-6</td>
<td>4.8</td>
<td>394</td>
<td>1.5</td>
</tr>
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<td>1.5</td>
</tr>
</tbody>
</table>

four test cases from the same season, a total span of 45 days, and from the same pair of the solar wind monitor (ISEE 3) and the magnetosphere in situ observer (ISEE 2). Therefore the temporal variations in the instruments response are minimal.

The GDCF is a single fluid model. The temperature in a single fluid description corresponds to the sum of the temperatures of all species. As was discussed in paper 1, the solar wind temperature used is the ion temperature plus the electron temperature. When the electron temperature measurements are not available (cases 3 and 4 in this study), the nominal electron temperature, 1.4x10^9 K [Newburn et al., 1995], is used. The temperatures used are averaged over 3-D temperatures, \( (T_e + T_i) / 2 \). The temperature of solar wind alpha particles, has been assumed to be 5 times the proton temperature [Feldman et al., 1977], while their concentration has been assumed to be 5% [Feldman et al., 1977].

The magnetosphere electron temperature is about one-tenth to one eight the ion temperature and has been neglected in the comparison.

The temporal resolution for the ISEE 2 data is 2 min averages from 12-30 solar moments and 4-6 field measurements. The original solar wind data are 5-min averages. We interpolate them to 1-min time series. The calculations are performed for every minute but represent temporal variations longer than 5 min in the solar wind.

The locations of ISEE 2 for the four cases studied are shown in Figure 1. The parameters for each case are summarized in Table 1. Two of the cases are near the stagnation streamline, one of the cases is significantly away from the local noon, and the last case is far from the local noon. The four cases are chosen to demonstrate the following situations. The first case shows how the GDCF model works under relatively quiet upstream conditions. The second case was during a period when the upstream conditions underwent major changes. The third case shows that sometimes the model can predict some of the observed features very well but not others. The fourth case shows that the model cannot detect the minor variations that occur between the model prediction and observation. Although the cases can be either inbound or outbound, our discussion for each case and in the discussion section starts with the bow shock moving toward the magnetopause.

3. Cases

3.1. September 17, 1978 (Day 260), Pass

This is pass one of the best documented magnetohshock passes [Song et al., 1990, 1992a, b; Zhang et al., 1996]. As we see later in this work, the new double-normalization technique described in paper 1 resolves some uncertainty in the interpretation of this case. The pass occurred near the stagnation streamline. Figure 2 compares the measurements in the solar wind from ISEE 3 (dashed lines) with those in the magnetosphere from ISEE 2 (solid lines). Since the ISEE 2 FPE instrument was not designed to measure the solar wind, the portion of the measurements in the solar wind is not shown. In this pass, the end of the ISEE 2 plasma quantities marks the bow shock crossing. ISEE 3 data have been shifted by 52 min and plotted in a different scale, labeled on the right, to account for the effects due to the compression of the plasma and field occurring at the bow shock. The solar wind is relatively quiet, and the IMF has a few weak gradual variations during the pass. This case is also used for the intercalibration. With the time shift, some of the IMF variations correlate well with the magnetosphere field variations, but others do not. In general, the y and z components of the magnetic field have the best correlation in the outer and middle sheath, and the x component has the worst correlation. The good correlation means that the clock angle does not change significantly across the bow shock, as pointed out by Song et al. [1992a]. The poor correlation means that the x component is most strongly affected by the bending of the field at the bow shock and the draping of the field over the obstacle. These effects can reverse the age of X. Near the magnetopause, the draping affects the y and z components of the field, and the density and field strength have a poor correlation with their upstream conditions. At the bow shock, the density and the field change in phase as appropriate for a fast mode wave.

The origin of the density enhancements from 1535 UT to 1610 UT has been a subject of debate. It is clear not directly due to a high-density solar wind during the interval because there is no such indication from the solar wind density measurements. There have been suggestions that the density increase is caused by the IMF changes. There has been no analysis indicating that the timing and the magnitude of the IMF rotations are able to generate the measured density structure, especially the outer edge of it. In fact if one tries to use the small (10%) solar wind density difference at 1555 UT in Figure 2 to explain the 50% magnetosphere density difference at 1610 UT, there are two problems. The time shift does not seem to have the needed 10 min flexibility because the field changes at 1530 UT and 1650 UT constrain the shift. The IMF rotation is about 55° around 1555 UT, which is too small to generate any significant density change according to Yan and Lee [1994].

Table 1b. Parameters at Bow Shock Crossing.

<table>
<thead>
<tr>
<th>DOI</th>
<th>Location (UT)</th>
<th>Time (UT)</th>
<th>Sheath Thickness (km)</th>
<th>Temp. (K)</th>
<th>N_{ew} (10^6 cm^-2)</th>
<th>V_{ew} (km/s)</th>
<th>T_{ew} (10^6 cm^-2)</th>
<th>B_{ew} (nT)</th>
<th>M_{ew}</th>
<th>B_{ew}</th>
</tr>
</thead>
<tbody>
<tr>
<td>78290</td>
<td>(13.7, 13.3, 5.2)</td>
<td>1811</td>
<td>-10%</td>
<td>1.2</td>
<td>4.9</td>
<td>395</td>
<td>24</td>
<td>4.0</td>
<td>3.8</td>
<td>2.8</td>
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<tr>
<td>78275</td>
<td>(13.7, 13.3, 5.2)</td>
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</tr>
</tbody>
</table>

* Sheath thickness is defined before the adjustment of the temperature.
Figure 2. The ISEE 2 magnetosheath observations (solid lines) and the ISEE 3 solar wind measurements (dashed lines) on September 17, 1978. From top are the density, velocity, and three components and the strength of the magnetic field. The scales labeled on the left are for the sheath measurements and the v-values on the right are for the solar wind. The solar wind measurements are shifted by 52 min, determined by overall correlation in the field components, to account for the convection time from ISEE 3 to ISEE 2. The ISEE 2 plasma measurements during the solar wind period are shown. The dashed lines are often hidden by the solid lines.

Figure 3 compares the original prediction from GDCAF with the in situ measurements. There is no adjustment made in this run. The predicted magnetopause and bow shock are about 20 min too late; indicating that the predicted magnetosheath is slightly too large. The predicted magnetosheath, using the normalization technique that is described in paper I and later in this paper, is about 10% thinner than observed. Timing of the field variations is reasonably good in the outer and middle magnetosheath. A significant improvement over the simple time shift of the upstream data occurs in the x component of the field. This indicates that the GDCAF is able to describe the draping effect. One of the most notable differences between the observation and prediction is the temperature. The predicted temperature is about 40% less than the observed.

We then conduct a parametric search for the best fit of the observation with the three adjustable parameters described in paper I: the time shift, the size of the dayside magnetosheath and the solar wind temperature. Figure 4 shows our best results. The parameters used in this run are as follows: the time adjustment is zero, i.e. the time in the prediction is exactly the prediction time; the magnetopause location factor is 0.94, i.e. the dayside magnetosheath is 9% smaller than that predicted by the vacuum dipole geomagnetic field balanced by ideal gas solar wind; and the solar wind temperature factor is 2.8, i.e., in order to predict the observed magnetosheath thickness, which is 10% larger than predicted, the upstream Mach number needs to be more than 30% smaller. Here we recall that the Mach number used in the calculation is the fast mode Mach number, as is discussed in paper I. Further discussion concerning the Mach number will be given in section 4. Using the adjusted solar wind temperature, the predicted temperature is similar to that observed in the sheath.

The observed density has a small overshoot just downstream of the bow shock, a significant enhancement in the inner magnetosheath and a depletion in front of the magnetopause. This profile will be further discussed later. The prediction of the x component of the velocity is significantly different from the observation, not only in magnitude but also in its trend. The model predicts a continuous slow down of the flow from the bow shock to the magnetopause. The observation shows that the flow does not slow down until near the magnetopause. This difference, in particular in the trend, cannot be attributed solely to instrument intercalibration. We think that there are qualitatively substantial differences between the physical processes described by the gasdynamics and those that occur in practice, although the gasdynamics can describe some of the observed
features very well. The model predicts that the $y$ component of the velocity changes gradually from near zero to slightly negative from near the bow shock to near the magnetopause. The observed flow actually changes from slightly positive to negative with a significant downward flow enhancement within the density enhancement. Here we recall that the aberration of flow due to the Earth's orbital motion is included in the model. To the Earth's frame, the solar wind comes in from prograde direction. Therefore, near the bow shock, although ISEE 2 was in the prograde side, it was close to the stagnation streamline. Given that the flow divergence increases as the magnetopause is approached and the satellite orbit was further away from the nose into the prograde side, the observed slightly downward flow near the bow shock and a downward flow are understandable. The model seems to slightly underestimate the aberration. The enhanced downward flow downstream of the outer edge of the density enhancement is consistent with the interpretation that the outer edge of the density enhancement is an additional (slow) shock front to the flow [Song et al., 1992a, Southwest and Kivelson, 1992, 1995]. The direction of the flow is more parallel to the field than perpendicular to the field, consistent with the function of the slow mode, which is to convert the pressure from perpendicular to the field to parallel to field as discussed in paper 1 because ISEE 2 FPE instrument did not measure the $y$ component of the velocity, the prediction of the $V_y$ is not shown.

The correlation between the observed sheath field and model prediction for all three components is significantly better than that between the sheath field and either the simple shifted IMF or before the adjustments, indicating that the GDCFIM can be very successful in predicting the field drooping. The prediction of the magnitude of the field is good in the outer magnetosheath. Near the magnetopause, the prediction is not accurate. In front of the magnetopause, the predicted field strength is very high and has been artificially limited in order to balance the magnetospheric field. One thing we emphasize is that although the prediction of the strength is not correct near the magnetopause, the prediction of the direction of the field is rather good.

As was discussed in paper 1, we can use the prediction to normalize the observed quantities to remove the effects of upstream variations and use the normalized distance of ISEE 2 from the magnetopause to remove the time dependence of the satellite's location. Figure 5 shows the normalized quantities for the September 17 case. The top two panels show the density and field clock angle for reference. The normalized distance (third panel) gives the distance of the satellite from the magnetopause normalized by the thickness of the magnetosheath. The magnetopause and bow shock are at zero and one, respectively, in this normalized unit. If the normalized density (fourth panel) is greater (less) than 1, the prediction underestimates (overestimates) the density. The IMF polar angle (fifth panel) is the angle between the upstream

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**Figure 3.** Comparison of the ISEE 2 in situ measurements (solid lines) with the original (without adjustments) GDCFIM prediction (dashed lines) for the September 17, 1978, pass. From top are the density, $x$ and $y$ components of the velocity in GSE, three components of the IMF and strength of the IMF, and the plasma temperature. The magnetopause and bow shock crossings of the satellite are indicated by the arrows labeled with MP and BS, respectively. The ISEE 2 plasma measurements during the solar wind period are shown. The dashed lines are often hidden by the solid lines.
IMF direction and the vector from the Sun-Earth line to the satellite projected onto the \(x-y\) plane. The bottom panel shows the change in the length of a flux tube normalized to the segment in the solar wind; \(\Omega\) is greater than 1 when stretching is more than predicted by the GDCFM and smaller than 1 when there is more shortening. In the GDCFM, there is a small tendency for shortening in the \(x\) direction and significant stretching in the \(z\) direction, which is diverted from the \(z\) axis. The flux tube can be stretched significantly in the \(x-y\) plane as the flow radiates from the \(x-y\) plane and the field is bent. On its orbit, the satellite measures a segment of different flux tubes that are traced along streamlines back to the solar wind; the flux tube could have been stretched or shortened before being measured. Near the magnetopause, the breakdown of the gaseous approach is caused by the infinite stretching of the field lines that drapes over the stagnation point. As discussed in paper 1, the predicted field strength has been limited to the compressed magnetopause dipole field. Therefore, the predicted length near the streamer-belt region is artificially limited in the GDCFM prediction. For this case the satellite moved gradually outward. The small variations in the normalized distance have some positive correlation with the solar wind density, which determines the solar wind pressure and hence the subsolar magnetopause location. The density enhancements near the magnetopause become clear in the normalized density. The IMF polar angle is clearly inversely correlated with the IMF clock angle, the dashed line in the second panel. However, these two will not be the image of each other unless the satellite does not move in the \(x-y\) plane or only moves radially. There is no clear pattern in the length of the field. However, we want to emphasize that the GDCFM describes a highly stretched field near the magnetopause.

Among the normalized quantities, the normalized distance and the IMF polar angle with the solar zenith angle of the satellite which does not strongly depend on the upstream condition unless the solar wind has major directional changes, provide the description of the location of the satellite in a solar wind invariant coordinate system. Since presently our database is not large enough, we are unable to examine the effects of the IMF polar angle. Without knowing the effects of the IMF polar angle, we cannot study the quantities for which the spatial distributions are anisotropic with respect to the IMF direction, such as the length of the field line. The stretching, bending, or shortening of the field highly depend on the location, in the IMF polar coordinates, of the segment of the field being studied. The spatial distribution of the normalized density may be relatively less anisotropic with respect to the IMF direction, although there is still a possible anisotropy [Sonnerup, 1980]. We plot the normalized density versus normalized distance as the dots in Figure 6. The thick solid lines show the bin average. The width of the bins is 0.1. The September 17 case is shown in the top panel. Since this case is very close to the stagnation streamline, we plot several MJID theoretical predictions along the stagnation streamline for reference. Since
Figure 6. The normalized quantities for the September 17, 1978, pass. The top two panels show the ISEE 2 measurements (solid lines) and GDCFM prediction (dashed lines) of the density (N) and the clock angle (θ) of the magnetic field for reference. The next four panels show the normalized distance (ΔD), density (N(norm)), IMF polar angle (θ), and the length of the field (ζ). The adjustment factors are the same as those in Figure 4. The ISEE 2 plasma measurements during the solar wind period are shown.

Figure 6. The density profile for the four cases after the double-normallization procedure. The horizontal axis is the normalized distance from the magnetopause to the bow shock (from 0 to 1). The vertical axis is the normalized density with the predicted density as 1. The dots are observation, and the thick solid lines are bin averages. For the upper two cases when the passes occurred near the stagnation streamline, the density profiles along the stagnation streamline from MHD models are also shown. The thin solid lines, dashed lines and dash-dotted lines are for Wu [1992], Swain and Wolf [1976] and Leer [1964], respectively.
3.2. September 12, 1978 (Day 255), Pass

Like Figure 2, Figure 7 compares the shifted (by 48 min) upstream measurements and the measurements from the magnetosheath for another substorm near the stagnation streamline. During this pass, both solar wind and IMF change dramatically. There is a correlation to a certain degree between the sheath density and solar wind density, and between the sheath field and IMF in the y and z components. However, further careful examination of different parameters of these variations reveals that the fluctuations observed in the magnetosheath cannot be made to match those in the solar wind by a simple shift in time. For example, the highest density peak in ISEE 2 around 2033 UT is associated with the sharpest field rotation in the y component. The corresponding density peak in ISEE 3 data is earlier, but the sharpest By rotation in ISEE 3 is later than that in ISEE 2 data. Similarly, the density peaks in ISEE 2 around 2100 UT and in ISEE 3 around 2047 UT, in case one wants to correlate these two features, correspond to different features in By. Therefore the solar wind features do not simply correlate into the magnetosheath.

We have made the GDCFM run without adjustment. The predicted magnetopause and bow shock are more than half hour later than the real magnetopause and bow shock crossings. The magnetosheath is about 13% thinner than observed. The time shift is not accurate. Similar to the first case, the predicted temperature is less than half that observed.

Figure 8 shows our best run using the GDCFM. The timing adjustment is 12 min, i.e., the solar wind arrives 12 min earlier than predicted. As discussed in paper 1, this can occur when the solar wind monitor is not on the Sun-Earth line and when the solar wind front is not perpendicular to the Sun-Earth line. The magnetopause size factor is 0.95, indicating a smaller dayside magnetosphere. The solar wind temperature adjustment factor is 2.8, the same as the first case. Near 2200 UT, the model predicts a pair of bow shock crossings that are not actually observed. At this time, ISEE 2 was very close to the bow shock, and the small difference is within the uncertainty of the model prediction.

The density overshoot near the bow shock and depletion near the magnetopause can be seen qualitatively although there are temporal fluctuations. The density enhancements observed in the previous case are not obvious in the time series here. As we will show later, they are present but are hidden by the temporal variations. Again, the magnetosheath flow is not slowed down as efficiently as the model prediction, and the observed flow has a downward bias. The magnetic field predicted by the model is much better correlated with the observations than the shifted IMF data.

One significant difference between the prediction and observation is a similar-looking dip in By near 2100 UT in the prediction but shifted by about 10 min in the observation. An almost identical feature also appears in the first case near 1600 UT. Since the time shift has been constrained by other major variations, this difference cannot be removed by using a
different time shift, which will worsen the overall prediction. Therefore this small feature moves relative to the large features. Because the feature arrived later than predicted, it propagates against the flow. We recall that the density peak associated with this feature also shows evidence of its propagation. These delayed features reinforce the argument for propagating processes in the magnetosheath as discussed in paper 1.

Figure 9 shows the normalized quantities for the September 12 case. The satellite took several swings before finally going into the solar wind. The resolution of the code is 20 grid cells along the shock thickness, which converts to 5% in the uncertainty of the satellite location. Near 2200 UT where the prediction shows a pair of bow shock crossings, the satellite is very close to the bow shock within the uncertainty of the model.

After removal of the temporal variations in the solar wind density, the normalized density does not seem to have a clear pattern in the time series. The fourth panel of Figure 9. One may think that the density enhancements observed in the magnetosheath are purely caused by the solar wind density enhancements (M. Van, private communication, 1995). This change when we perform the double-normalization procedure shown in the second panel of Figure 6. In the double-normalization plot, the density profile is almost identical to the first case during which there is no significant solar wind variation: first the density decreases from the bow shock as predicted by the depletion models, then a compressional front appears at near 0.3 with a magnitude double the value before the front, and finally, a second depletion layer occurs.

3.3. October 2, 1978 (Day 275), Pass

This pass occurred slightly away from the Sun-Earth line. As is shown in Figure 10, during the ISEE 2 magnetosheath crossing, there occurred a major solar wind density change and a few oscillations in the IMF. The time shift for ISEE 3 is about 48 min. The correlation of the IMF variations with the sheath field is poorer in both the middle and inner sheath. This makes this case different from the first two.

Figure 11 shows a run using the GDCFM. No adjustment in the time shift is made. The magnetopause scale factor is 1.066. The magnetopause crossing is a few minutes later than predicted. If we use a slightly larger magnetopause scale factor (1.025), which delays the predicted crossing, multiple crossings will be predicted. The temperature factor is 1. The predicted bow shock crossing is near the last observed crossing. The thickness of the magnetosheath is accurate within the model uncertainty of 5%. The predicted temperature is about 30% lower than observed, although the field and density compression is reasonably predicted. Similar to the first case, the z component of the velocity slows down more slowly than predicted and the y component of the velocity gets more kick than the prediction near the magnetopause. Before 0120 UT, the predicted field direction is only poorly correlated with the observed direction, but it improves after 0120 UT. Other than a small region near the magnetopause where the GDCFM starts breaking down, the field strength is relatively well predicted in this case.

The most important information that we try to survey here is that
Figure 9. The normalized quantities for the September 12, 1978, pass in the same format as Figure 5. The adjustment factors are the same as those in Figure 8.

Figure 10. The ISEE 2 magnetosheath observations and the ISEE 3 solar wind measurements on October 2, 1978, pass in the same format as Figure 2. The solar wind measurements have been shifted by 48 min.
with the adjustments the GDCFM can predict noisy features in observations, but in some cases, there are significant irreconcilable differences. In this case, they occur in the direction of the field. In contrast to the next case, these differences seem to be understandable, for example, by arguing that the variations propagate relative to the flow.

During this pass, ISEE 2 initially moved out slowly, as is shown in Figure 12. Near 0130 UT, when the satellite is close to the bow shock, the solar wind pressure decreases, and this decrease brings the satellite back farther from the bow shock. During the crossing, the normalized density is greater than one most of time. This also causes a smaller predicted flux tube length.

This case is slightly away from the stagnation streamline and hence we do not plot the MHD model predictions in the double-normalization plot (third panel of Figure 6). The outer half of the density profile is quite flat. At about 0.4, a weak convection front is formed. It is so weak that one may argue about its existence. Nevertheless, since the front exists in the first two cases and this case is farther from the Sun-Earth line where one may expect a weaker convection front, this weak density enhancement may be the extension of the convection front near the stagnation streamline.

3.4. August 19, 1978 (Day 231), Pass

This pass occurred in the region far away from noon. As expected, shown in Figure 13, the pass took a much longer time. The ISEE 3 data are shifted by 30 min. The sudden drop in the solar wind density and hence the dynamic pressure led to an expansion of the magnetosphere and hence the bow shock. This made ISEE 2 move from the solar wind into the magnetosphere. During the pass, the solar wind is not quite steady but has no major changes. Part of the reason for such a lengthy pass is that the solar wind pressure increased gradually, which pushed the magnetosphere back gradually while the satellite moved inward. The IMF, on the other hand, shows a few very large rotations. There are solar wind data gaps near the time of the bow shock crossing from 0210 to 0220 UT and near 0610-0640 UT.

Figure 14 compares the GDCFM prediction and the observation. The temperature factor is 1.5. The timing adjustment is -3 min, or the solar wind arrived 3 min later than the prediction. The magnetosphere is inflated by 5%. The temperature agrees well with the observation. The densities differ by about a factor of 2. In contrast to the previous cases, the x component of the velocity is slower than predicted. Given the lower density prediction, the higher predicted velocity may lead to a smaller difference in the flux prediction. The field prediction is quite good in both direction and magnitude.

The normalized quantities for the August 19 case are shown in Figure 15. ISEE 2 moved into the magnetosphere gradually. The normalized density is greater than 1 because of the insufficient compression predicted by the model, although we are purged by the adequate compression in the field. Nevertheless, the normalized density is quite steady in the outer sheath. Several density enhancements appear in the second half of the pass.

The time series of the normalized density for the last case indicates a relatively flat (or slightly uptitled) density in the outer sheath and three significant peaks in the middle and
Figure 12. The normalized quantities for the October 2, 1978, pass in the same format as Figure 5. The adjustment factors are 0, 1.006 and 1.

Figure 13. The ISEE 2 magnetosheath observations and the ISEE 3 solar wind measurements on August 19, 1978, pass in the same format as Figure 2. The solar wind measurements have been shifted by 30 min.
inner sheath. In the double-normalization plot (bottom panel of Figure 6) the density appears to gradually increase from the bow shock, to be peaked near 0.3 of the thickness, and then to drop relatively rapidly as the magnetopause is approached. Several density enhancements form near 0.2-0.3, but the average is weighted down by the lower counts.

4. Discussion

4.1. Predictability

We have presented four test cases using the simultaneous upstream measurements and the GDCF to predict the magnetosheath quantities, and then compared the prediction with the local in situ measurements. A similar scheme has also been used to study the magnetosheath of Venus [Luhmann et al., 1986]. Although different quantities have different level of predictability, we see a high degree of overall correlation between the prediction and observations. This is in contrast to the notion that the solar wind and IMF at the L-1 point, where the gravitational force from the Sun equals that from the Earth, can be very different from those near the Earth. Our test cases cover only limited time intervals, therefore we would not be surprised by an occasional breakdown of the correlation, but we think the correlation does exist most of the time. We think this predictability lends support to the idea of using the L-1 point for space weather forecasts or nowcasts. Whether the accuracy of these forecasts is adequate or not depends on users' requirements.

Among the predicted quantities using the GDCF, the direction of the magnetosheath magnetic field is the most successful one. The model handles the draping effects very well. The x component of the field predicted by the model is significantly better than that predicted by conventional simple time shift of the IMF. The model seems to be able to handle large-scale discontinuities very well, but some IMF rotations seem to propagate relative to each other, which has negative effects on the prediction. The velocity is one of the most poorly predicted quantities.

4.2. Timing

As shown in Table 1, in two of our four test cases, the time shifts given by the GDCF, which uses the x component of the solar wind velocity to determine the convection time to the Earth, work very well, and the difference in the time shift in one case is insignificant. A puzzling question is why the GDCF works so well given that the model prediction of the velocity is poor.

4.3. Size of the Dayside Magnetopause

For the two passes that are near the stagnation streamline, the dayside magnetopause needs to be about 5% or 0.5 \textit{Re} inward (see Table 1a). As statistical studies show, the substorm magnetopause location depends on solar wind dynamic pressure and the IMF \textit{Bz}, [e.g. Fairfield, 1971; Pontecorvo et al., 1991; Roelof and Sibeck, 1995; Shue et al., 1997, 1998]. The effect of the dynamic pressure is included in the GDCF, but the \textit{Bz} effect is not. We were expecting that the dependence of the IMF \textit{Bz} would appear in the magnetopause size factor, but it does not appear in these two
cases. For the first case, although the IMF $B_z$ was northward at the time of the magnetopause crossing, it was southward just prior to the crossing. Nevertheless, we may need more cases to study the IMF $B_z$ effects using the model.

The 5% uncertainty in the magnetopause location translates to 100% uncertainty in the solar wind dynamic pressure if the solar wind pressure is the sole source of the uncertainty for the magnetopause location. This seems to be on the upper side of the possible uncertainty for the solar wind measurements. Here we recall that we have included 5% alpha particles. In the GDCFM, the magnetopause location is determined according to the pressure balance between the solar wind dynamic pressure and the vacuum dipole field. The effect of the IMF pressure compared with the solar dynamic pressure is very weak, although it tends to reduce the size of the magnetosphere. The effect of the magnetospheric thermal pressure and ring current tend to scale like the magnetosphere, which is in the wrong direction of what is needed. The offset of the field-aligned currents tends to reduce the substorm distance. However, as we know that the field-aligned currents depend on IMF $B_x$, the effects of the IMF $B_z$ are not noticeable in the two cases. We think that to satisfactorily address this issue, we need more cases.

For the last case, the subaural magnetopause needs to be 5% outward while the IMF $B_z$ was slightly southward. This can be caused by the flaring of the magnetopause. For southward IMF, the magnetopause is closer at the subaural point but further in the flank. Since the crossing occurred in the region far away from the subaural point, the subaural magnetopause location is scaled according to the model, which does not include the effects of the flaring. The actual subaural magnetopause may be closer to the Earth than the model prediction.

4.4. Thickness of the Magnetosheath

As we discussed in Paper 1, the thickness of the magnetosheath in gasdynamic models depends primarily on the Mach number. A higher Mach number results in a thinner sheath. Since the bow shock is a fast mode shock, in order to describe the effects of the magnetic field, we have used the fast mode Mach number based on the direction of the IMF relative to the shock normal at the nose as the Mach number in the GDCFM. We have tested the sonic Mach number and the Mach number based on the perpendicular propagation fast mode, and found that the fast mode Mach number provides the best results. The physical reason for the fast mode Mach number to be better than the sonic Mach number is that it handles both magnetic field and plasma compression at the bow shock. The difference between the perpendicular and nonperpendicular-propagation fast-mode Mach numbers occurs only when the IMF has a significant $B_z$ component. Using a nonperpendicular-propagation fast-mode Mach number produces a slower phase velocity, a larger Mach number and hence a thicker magnetosheath. A piece of evidence to support our use of the nonperpendicular propagation fast mode Mach number is that in our three outward cases, the bow shock crossings occurred after an increase in the magnitude of $\mathbf{B}_z$ (see Figures 2, 7 and 10), and that in the inbound case, the bow shock crossing occurred after a $\mathbf{B}_z$ decrease (see Figure 13). This is consistent with the picture that the magnetosheath is thinner when the magnitude of the $B_z$ is larger, i.e., the direction of propagation at the nose is not perpendicular to the magnetic field. The last case during which multiple bow shock crossings occurred is particularly interesting because the solar wind states are well correlated with the larger $B_z$ values. It is worth mentioning that the difference between varying the direction of propagation of the magnetosonic fast mode wave relative to the field is much smaller than the difference made by our temperature factor.

The thickness of the magnetosheath also depends on the curvature of the obstacle. Therefore the shape of the magnetopause affects the thickness. Since the uncertainty in the size of the magnetopause of the model is very small, its effects on the thickness of the magnetosheath can be neglected.
4.5. Density Profile

As is shown in Figure 6, near the stagnation streamline in the magnetosheath, the density profile is a first gradual decrease from the bow shock, then a compressional front with a magnitude of 2 near 0.3 from the magnetopause, and finally a more rapid decrease before the magnetopause. This profile is consistent with the previous observations [Song et al., 1990, 1992a] and the Southwood and Kivelson [1995] model. This profile confirms the two plasma depletion processes modeled by Zwam and Wolf [1976] but requires an additional compression in between. This profile was first shown on a statistical basis [Song et al., 1990] and now is proved with the rigorous method developed in this study.

The logic for the proof is the following. The new scheme provides a constraint in the correlation between the two series of the solar wind and magnetosheath measurements. This constraint reduces the uncertainty to within 5 min in the timing between the two time series. Therefore the correlation between the solar wind and the magnetosheath measurements is nearly one to one. For each magnetosheath measurement, there is a value based on theoretical calculations. Although the prediction is not completely accurate and physically self-consistent, it obeys the same set of laws throughout each case. The double-normalization procedure, which normalizes at each time the distance of the magnetosheath satellite from the magnetopause to the thickness of the magnetosheath and normalizes the observed value in sheath to the prediction provided by the model according to the upstream value, removes the major temporal variations. Since the density within 30 solar units angle predicted by the GDCFM is close to that of downstream of the bow shock, the normalized electronic density is similar to the density used in most theoretical investigations.

Figure 6 shows first the density profile for a case without significant upstream variations. This case demonstrates that (1) the instruments and scheme work well, and (2) the profile does not depend on solar wind variations, at least not directly on large variations. The next profile in Figure 6 is for an extreme diamagnetism case. This case demonstrates that (1) such wind variations cause predictable magnetosheath variations, and (2) the same density profile exists after removing the temporal variations. Therefore the density profile shown is inherent in the magnetosheath independent of solar wind variations.

In the time series of the magnetosheath measurements, one can readily verify that the field strength is lower than predicted during the times when the density is higher than predicted. According to our definition this is the characteristic of slow mode perturbations. The shape of the slow mode compressional front, its spatial extension, and the conditions for its presence, however, remain poorly understood. It is worth mentioning that the second case seems to have a stronger depletion than the first one while having a lower plasma β. As was shown by Song et al. [1990] and is expected in theory, the slow mode front should be steeper for lower β conditions under which the MHD effects are stronger.

The existence of the compressional front in the magnetosheath adds a major piece of physics not only to the solar wind-magnetosphere coupling but also to the general understanding of how a superdense collisionless magnetized flow interacts with an obstacle.

Away from the stagnation streamline, the compressional front seems to be less prominent. However, the density profile is far from the gasydynamic prediction shown in Figure 4a of paper 1. The density can be a factor of 2 higher than predicted. Part of the underestimation of the density may be related to the underestimation of the flow deceleration in this region. This seems to be a complicated issue: the flow deceleration is

overestimated near the stagnation streamline but underestimated away from that region. Although the prediction of the GDCFM is often excellent in many aspects and gives a good zeroth order structure for the magnetosheath, the model does not describe properly the physical processes in the magnetosheath controlled by the magnetic field.

4.6. Temperatures

One of the major discrepancies between the observation and prediction is the temperature. This issue is closely related to the magnetosheath thickness as discussed above. As shown in Figure 5, using the measured solar wind temperature, often the magnetosheath is thinner and the magnetosheath temperature is lower than observed. An artificial increase of the solar wind temperature thickness the magnetosheath and elevates the predicted sheath temperature, if the reduction in the heating due to the smaller Mach number is less than the effect of the higher upstream temperature. In our parameter range, both the thickness and sheath temperature were improved by this artificial increase in the solar wind temperature. The lowered upstream Mach number reduces the plasma and field compression at the bow shock. This leads to a lower predicted sheath density and field strength. In the first case this lower compression does not worsen the prediction, but in the second case there is a negative effect. In the last two cases the effect is mixed.

We think that the problem with the temperature prediction is due to the non-self-consistency of the method. Our scheme provides a correct handling of the momentum equation, but the energy equation and state equation cannot be handled self-consistently at the same time. The field compression takes some energy from the plasma thermal energy.

4.7. Magnetosheath Flow Velocity

Another major discrepancy in the comparison is the magnetosheath flow velocity. Obviously, the sheath flow behaves very differently from that described by the gasydynamics. Near the Sun-Earth line toward the obstacle, the flow usually does not slow down as efficiently as predicted by the GDCFM but is more efficient in diverting from the stagnation streamline in a narrow region near the magnetopause. Here we note that the MHD description does not help in this regard because MHD models [e.g., Wyg, 1992] is lower than observed. An artificial increase of the solar wind temperature thickness the magnetosheath and elevates the predicted sheath temperature, if the reduction in the heating due to the smaller Mach number is less than the effect of the higher upstream temperature. In our parameter range, both the thickness and sheath temperature were improved by this artificial increase in the solar wind temperature. The lowered upstream Mach number reduces the plasma and field compression at the bow shock. This leads to a lower predicted sheath density and field strength. In the first case this lower compression does not worsen the prediction, but in the second case there is a negative effect. In the last two cases the effect is mixed. The IMF is along the Parker’s spiral, the field kink generated at the bow shock and the distortion of the magnetic field near the magnetopause will produce a dudsock force. This force shifts the stagnation point toward the morning side. The IMF direction for the second case is similar to that of Parker’s spiral. The Vx shift is clear and consistent with the Zhang et al. and Russell et al. model. The first case is less obvious when the IMF is directed both the Parker’s spiral direction and perpendicular to it and Bl is often weak. The inspection of the detailed variations and the differences between the predicted and observed Vx is consistent with the Zhang et al. and Russell et al. model. While this mechanism is useful for explaining the behavior of Vx, it does not help the problem of Vp. When the stagnation point is shifted to the morning side, it is closer to the magnetopause crossings of the two passes, and (see Figure 1) the Vp should be even smaller.
5. Conclusions

We have tested the scheme described in paper 1. We use the solar wind measurements as the input to the GDCFM and compare the model output with magnetosheath observations. In the four test cases there is significant overall success in the model prediction. The model is superior to other methods in magnetosheath studies in terms of correlating the solar wind and magnetosheath features. Using the three parameters introduced, the timing between the solar wind perturbations and the magnetosheath variations is highly constrained. Practically, most of time, there are only a few minutes of uncertainty. This also reduces significantly the uncertainty in interpretation. Although the gaseodynamic model is not ideal for predicting magnetosheath geocorries, it provides a systematic and economic means for such predictions.

The direction of the magnetosheath field is very well predicted, better than by almost all other models in magnetospheric physics. The size of the magnetopause is uncertain within a few percent. The magnetosheath is often about 10% thicker than predicted. The prediction of plasma quantities is less impressive. However, we are able to use the disadvantage of the model to our advantage to study the magnetosheath density profile. With the double-normalization procedure developed in this study, we are able to separate the processes intrinsic in the magnetosheath from those due to large-scale upstream interplanetary waves. We derive a time- independent density profile near the stagnation streamline. It confirms the existence of a compressional front at one third of the distance from the magnetopause to the bow shock near the subauroral region. It is consistent with the models [Song et al., 1992; Southwood and Kivelson, 1995] that add a compressional front between the two departure processes described by the Zwan and Wolf [1976] model. However, little is known about the details of the compressional front. There are two major discrepancies between the observations and model predictions. The first is the component of the velocity, the real magnetosheath flow remains a nearly constant speed toward the magnetopause. The divergence at the magnetopause occurs in a very small region. In contrast, the GDCFM predicts a gradual divergence throughout the whole magnetosheath. We believe that this problem is not due to the non-self-consistency of the gaseodynamic description but may be due to the inadequacy of the fluid description in general for these plasma conditions because MHD models [e.g., Pu, 1992] predict the same gradual divergence. Therefore, the problem is deep rooted and perhaps may not be solved until one has some kinetic description developed. What makes this discrepancy more interesting is the excellent prediction of the magnetic field direction at the same time. The other major discrepancy is the temperature. Using the given solar wind temperature, the predicted magnetosheath temperature is always too low, and the predicted magnetosheath is often thinner. Using an artificially elevated solar wind temperature, both the shear temperature and thickness predictions are improved. We think that this discrepancy is due to the non-self-consistency of the scheme.

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