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Observational aspects of IMF draping around the magnetosphere

Brendan S. Harris
University of New Hampshire, Durham

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Observational aspects of IMF draping around the magnetosphere

Abstract
A key parameter in determining the flow of the solar wind around the magnetosphere is the Alfvén Mach number (Ma) because it determines conditions at the bow shock. High Ma approaches the gas dynamic limit of flow around the magnetosphere, while low Ma implies strong magnetic forces on the flow. We study a long interval of high Ma during the recent pronounced solar minimum 2007--2009, and derive the magnetopause and bow shock shapes from data. We compare our results with models of the magnetopause and properties of the bow shock and find that during this period, the subsolar magnetosheath was 1 Re thinner and the magnetopause is more flared than other models predict. For low Ma, we study Interplanetary Coronal Mass Ejections (ICME) during their northward phase, and present five examples of 34 observed ion accelerations, observed by Geotail and Cluster, in the magnetosheath clue to draping of the IMF around the magnetosphere. Comparing with recent theory, we find good agreement as we investigate their (1) Ma dependence, and (2) their location relative to the east-west terminator.

Keywords
Physics, Fluid and Plasma, Physics, Astrophysics

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OBSERVATIONAL ASPECTS OF IMF DRAPING AROUND THE

MAGNETOSPHERE

BY

Brendan S. Harris

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THESIS

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Thesis director, Charles Farrugia, Research Professor of Physics

Antoinette Galvin, Research Professor of Physics

Dawn Meredith, Associate Professor of Physics

Date
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dependence, and 2) their location relative to the east-west terminator.
INTRODUCTION

The study of the shocked solar wind flow in the magnetosheath has been a longstanding concern, and is important to understand the effect that the solar wind has on the magnetosphere during both normal solar wind conditions (i.e. \(V_{sw} \approx 400 \text{ km/s}, Ma \approx 8 - 12\), and \(T \approx 1.5 \times 10^6 K\)) and the abnormal conditions of the passage of interplanetary structures like Interplanetary Coronal Mass Ejection (ICME). The magnetosheath is a region that is unique in that it represents a transition from the region of plasma that is controlled by the earth’s magnetic field to the plasma connected purely to the processes in the interplanetary medium. The flows within the magnetosheath are of interest for a few reasons. First, magnetosheath flows are related to gas dynamic flows around a rigid body which are studied in rockets and airplanes. These two differ however, since the plasma flow in the magnetosheath is magnetized and additionally depends on the Interplanetary Magnetic Field (IMF). Second, the motion of the magnetosheath can effect bulk particle motion within the magnetosphere through a dragging effect on the boundary of the magnetopause [Axford, 1964]. Third, our work here represents a study of the magnetosheath and adjacent boundaries in two extremes of the solar wind, the effects of which have not been well investigated observationally in the magnetosheath.

To study the magnetosheath and associated boundaries during a period of high Alfvén Mach number \((Ma)\), we take a period in the recent solar minimum where the solar wind occasionally reaches approximately gas dynamic conditions. To study the magnetosheath during low \(Ma\) where magnetic forces dominate and the magnetosheath changes its shape, structure and dynamics, we study the magnetopause and accelerations in ion plasma flow which occur near this region. In summary, our motivations are to understand the
magnetosheath and its nearby boundaries (the bow shock and magnetopause) in two extreme limits of the solar wind within the context of the Alfven Mach number, $Ma$

To understand the dynamics of this region, it is important to first gain a background on the importance of structures associated with the magnetosheath. The most critical structure in determining the dynamics of the magnetosheath is the obstacle that it flows around, the magnetosphere. The magnetosphere is the magnetic field produced by a dynamo within the earth’s core. The magnetosphere acts largely as a dipole to first approximation, where the field lines are given by

$$\vec{B}(\vec{r}) = \frac{\mu_0 m}{4\pi r^3} (2\cos(\theta)\hat{i} + \sin(\theta)\hat{\theta})$$

At the edge of the earth’s control over plasma within the magnetosphere is a structure called the magnetopause. The magnetopause is of great importance in the study of the flow around the magnetosphere because its position is variable due to changes in the upstream interplanetary plasma parameters like density, magnetic field strength and direction, and velocity. Two of the most important quantities in the interplanetary plasma which affect the position and motion of the magnetopause are dynamic pressure, and the Alfven Mach number,

$$p_{\text{dyn}} = \rho v^2$$  
$$Ma = \frac{V_{sw}}{V_a} = \frac{V_{sw} \sqrt{\rho \mu_0}}{B}$$

where $\rho$ is the mass density, $V_{sw}$ is the velocity of the solar wind, $V_a$ is the Alfven speed, $B$ is the magnetic field strength, and $\mu_0$ is the permeability of free space.
The earth's dipole is not a rigid obstacle and therefore interplanetary dynamics alter the shape of the earth's magnetosphere quite dramatically depending on the output of the sun. The position of the earth's magnetopause is controlled by a pressure balance between the earth's magnetic pressure, and the incoming dynamic plasma pressure from the sun defined in Eq 1. The specifics of this process are detailed in subsequent sections, however a simple model for the subsolar point of the magnetopause can be derived by setting the equivalence of the two mentioned pressures and substituting in the equation for a dipole to represent the magnetic field strength of the earth. When the magnetic field strength is multiplied by a constant factor (1.4) representing the compression of the dipolar field lines due to the dynamic pressure of the solar wind, a reasonable determination of the standoff distance to the magnetopause is found.

An example of an outbound magnetopause and bow shock crossing is plotted in Fig 2 from a passage of Geotail through the magnetosheath on 7/25/2001. Geotail is near the nose of the magnetopause on the day side, and low in the $Z_{gm}$ axis. 'Msphere' refers to the magnetosphere, while 'MP' and 'BS' refer to the magnetopause and bow shock respectively. Notice the change in the plasma parameters at approximately 01 25 UT, and 3 05 UT. These vertical lines indicate magnetopause and bow shock crossings by Geotail. Although little deflection of the magnetic field occurs at the bow shock in this example, the magnetosheath is easily discernible from the solar wind by the density $N$, and the $-V_x$ component of the velocity.
Figure 2  'MP' is the magnetopause, and 'BS' is the bow shock for this crossing of the magnetosheath by Geotail on 7/25/2001. Notice the slow field rotation in the $B_y$ and $B_z$ components from the magnetopause to the bow shock, present also in ($\theta_{\text{bs}}$). The $V_x$ component of the flow is denoted in black, the $V_y$ is blue, and the $V_z$ is yellow. The component at the lower end of each panel is considered primary, and each component above it on the $y$ axis corresponds to color with a higher frequency than the previous (according to the light spectrum).

The panels are labeled as follows: $N$ is the proton density in particles per centimeter cubed, $T_{yy}$ and $T_{zz}$ are components of the temperature in eV. $V_{xyz}$ are velocities with respect to $X$, $Y$, and $Z_{\text{gsm}}$ in kilometers per second, $V_{\text{ms}}$ is the magnitude of the velocity in the magnetosheath. $e^{-\text{sunward tailward}}$ are the energy flux with respect to the relevant direction, $B$ is the magnetic field in nanoTesla (nT), $P_m$ is the magnetic pressure in nanoPascals (nPa), $P_p$ is the plasma pressure (nPa), $\beta$ is the ratio of plasma pressure to magnetic pressure, and $\theta_{\text{bs}}$ is the angle between the local magnetic field and the velocity.
vectors.

Energy flux diagrams plotted in panel 5 and 6, are critical to understanding small scale regions on either edge of the magnetosheath. From 00:00 - 01:15 UT we see high energy electrons with a range of regions where their counts are high. This is obviously different from the magnetosheath energies present from 01:30 - 02:45 UT where the energies drop dramatically and the count numbers increase in these regions. From 01:19 - 01:24 we see a transition region form between the magnetosphere and the magnetosheath, where an energy drop occurs followed by a gradient into the magnetosheath values. This region of transition between the magnetosphere and magnetosheath represents a layer called the Low Latitude Boundary Layer (LLBL). We will see that this region is of great importance when studying the magnetopause, and identifying different mechanisms for the accelerations of ions around the magnetopause.

The Solar Wind

The solar wind is a hot, ionized plasma which originates from the sun. There are several types of solar wind which are of importance when studying the problem of flow in the magnetosheath. Fast wind is associated with open magnetic field lines and coronal holes on the sun, and can reach values of 600 - 1000 kilometers per second. Slow wind is associated with semi-closed field lines and a higher density and lower temperature. It is common for slow solar wind to be on the order of 250 - 400 kilometers per second at 1 AU. A cartoon of the sun-earth system is shown in Fig. 3, showing the effect of the solar wind on compressing and interacting with the magnetosphere. The line from the Sun to the Earth is the \(-X_{\text{gse}}\) axis, a coordinate system centered at the earth called the

Figure 3: This image was produced by NASA and is public domain. The source for this image is found at http://sec.gsfc.nasa.gov/popscise.jpg
Geocentric Solar Ecliptic (GSE)

Two configurations important for space weather to consider here are Magnetic Clouds (MC), and Interplanetary Coronal Mass Ejections (ICME) [Neugebauer et al. 1997] which occur as ejections from the surface of the sun and are usually accompanied with magnetic flux ropes [Farrugia et al. 1997]. These are usually accompanied by low $Ma$ in the interstellar medium, and are therefore of interest here since we focus on low $Ma$ to observe its effect on the flow of the magnetosheath near the magnetopause. The passage of an ICME over a spacecraft is evident because of an increase in the magnetic field magnitude, as well as a long and well defined rotation of the IMF. ICMEs are useful for a myriad of spacecraft studies of the interactions of the IMF with the geomagnetic field because the solar wind conditions associated with these structures changes slowly over time. These stable conditions form a 'control' for spacecraft observations that may not occur simultaneously, effectively reducing the uncertainty associated with changing solar wind conditions. Detail is given to all these various types of wind by Cane and Richardson [2010], and the reader is referred here for further information.

An important factor when using the solar wind and its impacts on the earth is something called the correlation length of the solar wind. This refers to the maximum distance perpendicular to the sun-earth line that a spacecraft upstream of the Earth can be used to compare solar wind values. Any distance larger than the correlation length cannot be considered to adequately represent the solar wind at the earth's subsolar point. During average solar wind conditions, the correlation length of the solar wind is approximately 40 - 50 Re in the $\pm Y_{gse}$ direction. During ICME however, the interplanetary medium is more homogeneous, and the correlation length grows to approximately 75 Re.

The Magnetopause

The magnetopause is a relatively thin structure (generally 10 - 1000 km) which separates the plasma controlled by the magnetosphere from that which is connected to the mag-
netic field of the solar wind. Many intriguing turbulent and structural phenomena are associated with the magnetopause, and the reader is referred to “Introduction to Space Plasma Physics” by Kivelson and Russell for an introductory discussion on some of these topics.

An important feature of the magnetopause is its role as a current sheet. This is the result of a finite magnetic shear between the solar wind connected magnetosheath and the magnetic field of the magnetosphere. By Ampere’s law, a curl in the magnetic field produces a ion current layer on the boundary of the magnetopause.

An early observational model for the position of the magnetopause as a function of the $Z_{gsm}$ component of the magnetic field ($B_z$) and the dynamic pressure ($p_{dyn}$) was developed by Sibeck et al. [1991]. The quantity $p_{dyn}$ is chosen because of the magnetopause’s standoff distance depends on a pressure balance between the solar wind and the magnetosphere. $B_z$ in GSM coordinates is chosen because the magnetosphere’s magnetic field points in the $+B_z$ direction on the day side. An IMF pointing in the same direction will reinforce the magnetosphere, while $-B_z$ will erode the magnetosphere through reconnection of field lines, and decrease the standoff distance of the magnetopause. Sibeck et al. established the importance of the solar wind dynamic pressure and the IMF $B_z$ on the standoff distance of the magnetopause empirically, and derived an equation for predicting the global shape of the magnetopause, given in Eq. 3.

$$R^2 + A_0 x^2 + B_0 (\frac{P_0}{p})^{1/6} = C_0 (\frac{P_0}{p})^{1/3} = 0$$

The constant parameters were calculated by the minimization of the scatter of observed magnetopause crossings. The constants are given by, $A_0 = 0.14$, $B_0 = 18.2$, $C_0 = -217.2$, and $p_0 = 2.04$, where $p$ is the upstream dynamic pressure in nPa, given in Eq. 1, and $x$ is the distance along the $X_{gse}$ axis. This model is valid for $p_{dyn}$ from 0.6 nPa - 10
nPa, and $B_z$ from -10 - 10 nT.

Models are continually developing due to the importance of accurately predicting this structure. Knowing the theoretical position of the subsolar magnetopause and shape of the magnetosphere are sometimes useful in comparison to spacecraft observations when there is ambiguity if a spacecraft is within or outside of the magnetopause. A more common use of these models is for theoretical modeling of the earth’s magnetosphere during specific solar wind conditions, which is then used to calculate different parameters (N, B, V) near the magnetopause which depend on the position and flaring of this structure. One prominent model was introduced by Shue et al. [1997]. It was determined by minimizing the scatter of magnetopause crossings after the interplanetary medium parameters were binned according to similar $B_z$ and dynamic pressure. The resulting equation is plotted in the polar coordinate system, and is given by:

$$r = r_0 \left( \frac{2}{1 + \cos(\theta)} \right)^\alpha$$

where $r_0$ and $\alpha$ are given by:

$$r_0 = 11.4 + 0.013B_z(p_{dyn}^{\frac{1}{6}}), \text{ for } B_z \geq 0$$

$$11.4 + 0.14B_z(p_{dyn}^{\frac{1}{6}}), \text{ for } B_z < 0$$

$$\alpha = (0.58 - 0.070B_z)(1 + 0.010P_{dyn})$$

While Shue et al. use $D_p$ to denote dynamic pressure, we use $p_{dyn}$, and have made this substitution in the above equations.

The code for this model is given in Appendix A.1, which produces a post script file of the magnetopause according to given upstream solar wind conditions, and it is written in IDL. IDL stands for “Interactive Data Language”, and runs similar to the script format.
of Matlab. IDL excels in the analysis and creation of images, and is a great tool for high level visualization application. For the code presented in the appendices, all teal text is a comment and should be preceded in the IDL code by a ";;;;" even if the code may overflow onto a subsequent line without an appropriate semicolon preceding the text string. Red text at the bottom of the page denotes the input parameters necessary to run the program which must be input by the user explicitly, or read from an I/O file. Much work was done on these programs, and the reader is encouraged to use this code as open source and open distribution. When implemented however, citation to this document is required.

There are several models in existence which predict the position and shape of the magnetopause, and an overview of several prominent models is made by Safrankova and Nemecek [2002]. Models like Shue et al. [1997, 1998], Petrmec and Russel [1993,1996], and Kunznetsov and Suvorova [1996] use solar wind dynamic pressure and $B_z$ to determine the shape and standoff distance of the magnetopause. Other models like Boardsen [2000] parameterize the shape and location of the magnetopause by dynamic pressure, $B_z$, and the dipole tilt angle which was introduced from the observation that the standoff distance (the point of the magnetopause closest to the sun along the $X_{ps}$ axis) and the tail shifted vertically for similar solar wind conditions but opposite dipole tilt. For a modern comparison of several models in 3 dimensions, the reader is referred to Lin et al. [2010].

None of these models are infallible, and each excels in calculation of the magnetopause for different solar wind input like an increase of the solar wind $V_y$ or $B_x$ for example. If the need arises to calculate the magnetopause theoretically to a very high degree of accuracy given a particular set of solar wind conditions, one should refer to papers like Safrankova and Nemecek [2002] to find which of these models is most statistically accurate for the particular solar wind conditions which are of interest. Since the work done later in this document is observational, calculations of the magnetopause tend to lack the high level
of accuracy required to help identify the differentiation between small regions of interest like the Low Latitude Boundary Layer (LLBL) and the magnetopause. Therefore we do not support our observation by any theoretical position of the magnetopause produced by these models.

A database of magnetopause crossings is found at http://ftpbrowser.gsfc.nasa.gov/magnetopause.html. This observational database consists of several thousand magnetopause crossings, many of which also have the upstream solar wind conditions calculated for use in statistical analyses and comparison of models. This database covers magnetopause crossings spanning from the 1970s to the 2000s.

The Bow Shock

In traditional gas dynamics, shock waves tend to form as collisional entities where particles transfer momentum and energy between themselves through collisions. Dissipation of particle energy at the bow shock causes random motion in the magnetosheath, which increases the temperature. Space plasmas, however, are rarely collisional. This is because collisionless plasmas are used when the system of interest is smaller than the size of the mean free path of the particle. In the case of the solar wind, the density of the plasma is often on the order of $5 \, \text{p cm}^{-3}$, resulting in a mean free path approximately the size of the distance from the earth to the sun. Therefore, any small scale studies of local plasma in the bow shock or the magnetosheath are treated as collisionless.

To understand the dynamics of the bow shock better, we first consider a gas. When a pressure perturbation (sound) is made, that 'information' travels through the gas at the speed of sound. In a plasma, however, there are multiple speeds at which information can travel given the different wave modes. MHD calculates the equivalent of four different 'speeds of information', which are given by the fast and slow Mach number ($M_f$ and $M_s$ respectively), the sonic Mach number ($M_s$), and the Alfven Mach number ($Ma$). These are ratios of the flow speed in the plasma to the corresponding wave mode speed, and
are each useful in their own application, but $Ma$ and $Ms$ are the two most useful in determining bow shock and magnetopause standoff distances.

The earth's bow shock is a structure that forms sunward of the magnetopause which shocks the incoming solar wind. Sunward of the bow shock, the interplanetary plasma is supersonic and superalfvenic, while earthward of the bow shock the flow becomes subsonic and subalfvenic. The bow shock always stands upstream of the object in a position where the ratio of the dynamic pressure to the sum of the magnetic and thermal pressures is sufficient to divert the plasma flow at the subsolar point of the magnetopause. This ratio of pressures is inherent in the definition of the Alfven mach number ($Ma$), defined below:

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

$$Ma = \frac{V_{sw}}{V_A} = \frac{V_{sw} \sqrt{\mu_0 \rho}}{B}$$

The explicit introduction of the magnetic field into equation 9 reinforces the importance that this parameter plays in determining the plasma flow around the magnetosphere. Namely, when the magnetic field is small, $Ma$ is high and magnetic forces do little to impact the plasma flow. In this case, we approach the traditional gas dynamic limit. When the magnetic field is large, $Ma$ becomes small, and magnetic forces dominate the plasma flow. The parameter $Ma$ is given special treatment throughout this document because of these reasons, that it succinctly captures in one parameter the important forces on the plasma flow for given upstream solar wind parameters.

The Rankine-Hugoniot conditions are a system of equations which must be satisfied at the bow shock, and express the conservation laws over this region. These are often called jump conditions, since they represent changes in the plasma parameters upstream and downstream of the bow shock. A condition met at the bow shock is,
\[
\rho_1 u_1 = \rho_2 u_2
\]  

(10)

where \( \rho_1 \) and \( \rho_2 \) is the density and \( u_1 \) and \( u_2 \) are the upstream and downstream velocity (with respect to the bow shock) respectively. This states that the amount of mass flux that passes through the bow shock must be diverted around the obstacle. There are several conditions met at this shock wave which are discussed in most texts about shock wave formation.

An interesting derivation of the relation that the bow shock standoff distance has on the sonic mach number \( M_s \) is given by Farris and Russell [1994], and is included in Appendix 5. It is not included here since it is based off \( M_s \) instead of \( M_a \), which is the parameter that we focus on in this study.

As a spacecraft passes from the interplanetary medium into the magnetosheath, the plasma it encounters undergoes a series of changes. Namely, the temperature and density increase, and the magnetic field jumps and becomes highly oscillatory which is an indication of the mirror instability in the magnetosheath. The most obvious change usually occurs in the \(-V_x\) component of the plasma flow, which drops drastically as the magnetosheath is entered and indicates that the plasma is being slowed down.

As is the case with the magnetopause, the bow shock is often modeled as a three dimensional paraboloid of revolution given in Eq. 4. In gas dynamics, the stand off distance of the bow shock is proportional to the shape of the obstacle. A larger flaring parameter for the object, \( \alpha \), leads to a blunter object and a larger standoff distance. This is important in the high \( M_a \) limit, however in general the standoff distance is much more dependent on the upstream \( M_a \).

Many models exist which predict the standoff distance and the shape of the bow shock with varying success, but since the bulk of our focus later is on the position and
structure of the magnetopause no more consideration will be given here. The paper by Merka et al. [2003] gives a good overview of several models along with their accuracy in predicting the position of the bow shock for various solar wind conditions. Similar to the magnetopause, there is a website which has a database of bow shock crossings. It is available at: http://ftpbrowser.gsfc.nasa.gov/bow shock.html

The Magnetosheath

Compared to the magnetosphere, the magnetosheath is generally characterized by a cool, dense plasma with highly oscillatory magnetic field. The magnetosheath is a perturbation of the solar wind’s plasma which has traveled through the bow shock. For this reason, the plasma in this region is often called “the shocked solar wind”. This can result in several properties like magnetic bottles produced by the mirror instability. This region is crucial for understanding the global effect that the solar wind has on the magnetosphere, and therefore the effect that solar storms may have on earth’s life and environment.

The flow dynamics of this region have been studied many times, and for specific formulations the reader is referred to Spreiter et al. [1966] for a gas dynamic approach, or Alksne and Webster [1974] for a formulation incorporating the magnetic field. In general, the bulk flow speeds of

Figure 4: Geotail’s 7/25/01 crossing of the magnetosheath. 'MP' is the magnetopause, and 'BS' is the bow shock. The angle between the magnetic field and the velocity vectors is $(\theta_{bV})$. Geotail is located at $X_{qsm} = 17.19$, $Y_{qsm} = -3.93$, $Z_{qsm} = -1.44$ Re.
ions in this region are less than those of the solar wind. As the magnetosheath begins to interact with the solar wind downstream of the earth and far in the $\pm Y_{gsm}$ directions however, the magnetosheath speeds up as the bow shock’s influence on the local plasma decreases.

The magnetosheath is bounded on both ends by the bow shock on the sunward side and the magnetopause on the earthward. Close to both of these structures, the flow often changes on small spatial scales. Toward the bow shock, the flow is dominated by the solar wind, and the Rankine-Hugoniot shock jump conditions here. Near the magnetopause, IMF pile up causes an increase of magnetic pressure which exerts a force that counter balances the incoming plasma pressure. Depending on the IMF clock angle (the angle of the solar wind magnetic field between $0^\circ$ - $180^\circ$ of the IMF in the $Y_{gsm} - Z_{gsm}$ plane), the magnetic shear across the magnetopause greatly effects the properties of the magnetosheath near the magnetopause.

There are several changes in the plasma that occur during the passage of a spacecraft through the magnetosheath. Here we will use the same passage of Geotail through the magnetosheath plotted in Fig. 2 for large magnetic sheer. The relevant time frame where Geotail is in the magnetosheath is expanded in Fig. 4. On the right hand side of the plot the bow shock is crossed several times, which is most noticeable from the jumps in density and the change in the $-V_x$ flow speed. The magnetosheath does not change drastically from this initial perturbation at 03:05 and 03:55 UT. Slowly, a rotation of the magnetic field occurs in the $B_z$ and $B_y$, which is reflected in the angle between the velocity and magnetic field $\theta_{bv}$. From 01:23 to 01:28 UT we see a slight drop in the parallel and perpendicular (compared to the magnetic field) temperature compared to the bulk of the magnetosheath, which is a common indicator of a region named the 'magnetosheath transition region' (MSTR) which generally occurs for low magnetic shear [Phan 1994].

The magnetopause crossing is evident at 01:22.5 UT, where the magnetic field $B_z$ jumps drastically. Just before this jump, we see a mixing of the plasma in the electron
energy flux distributions which is identified as the Low Latitude Boundary Layer (LLBL). This is a region where plasma from the magnetosphere and the solar wind (via the magnetosheath) mix and interact. The positive temperature gradient here is due to the mixing of these plasmas.

Outside the magnetopause however, the plasma in the MSTR is quite different from the bulk of the magnetosheath. Namely, the temperature, $\beta$ and density is lower, while the magnitude of the magnetic field is greater (not pictured but evident from the increase in $B_z$). The specific properties of this region near the magnetopause for high (>60°) and low (<45°) magnetic shear are discussed in detail by Phan et al. [1994]

**Plasma Depletion Layer**

On the day side of the magnetosphere, a structure called the Plasma Depletion Layer (PDL) can form in the magnetosheath prior to an inbound crossing of the magnetopause. Under northward IMF this region is the same as the previously mentioned magnetosheath transition region (MSTR), which is a barrier where magnetic pressure dominates in the magnetosheath near the magnetopause. This region is likely to form for IMF $B_z$ north, where the magnetosphere is reinforced by IMF field lines and the magnetic shear across the magnetopause is low. As IMF field lines are draped over the front of the magnetosphere, they cause an acceleration of the plasma, as well as an increase in the total magnetic field and a decrease in the density. Thus the name, Plasma Depletion Layer which emphasizes the reduction of density observed in this region. The PDL is a special case of the day side magnetosheath transition region, but these two are sometimes used interchangeably.

The formation of the PDL is a purely MHD phenomena, and is not present in the original flow formulations given by Spierer et al. [1966]. Specifics of the MHD theory and observation regarding this region are found in Zwan and Wolf [1976], and Farrugia et al. [1995]. These papers explain the properties of the PDL and how these affect energy.
and momentum transfer to the magnetosphere, as the plasma in the magnetosheath approaches the magnetopause. Alternately named the 'Magnetic barrier region' in Farrugia et al. [1995], Erkaev et al. [1988], its sunward boundary is defined as a region outside of the magnetopause where the thermal pressure is less than or equal to the magnetic pressure, $P_p \leq P_m$. This requires that $\beta \leq 1$ in the magnetic barrier region. This definition reflects the formation of a magnetically dominated region of flow outside of the subsolar magnetopause where the magnetic pressure ($P_m$) is greater than the plasma pressure ($P_p$).

Curiously during low $Ma$, with our previous definition of the magnetic barrier region, theoretically this region can extend from the magnetopause to the bow shock when the magnetopause is modeled as a tangential discontinuity. This implies that for large magnitudes of magnetic field strength, which generally occurs during ICME or MC's, the entire magnetosheath's plasma flow is dominated by magnetic forces.

To understand this process, it is useful to think of a magnetic field line as a tube, which in many ways is an accurate analogy. Plasma is bound to magnetic field lines due to the 'frozen in' condition. This means that everywhere plasma travels, it will drag the
magnetic field lines with it, and vice versa. As these magnetic field lines 'tubes' approach the magnetosphere and begin to drape across it, the portion of the field line which does not get slowed down by an interaction with the magnetosphere continues ahead, pictured in Fig 5. This creates a tension in the magnetic field line due to its forced curvature which is evident in the first term on the right hand side of Eq 11

$$\mathbf{J} \times \mathbf{B} = (\mathbf{B} \cdot \nabla)\mathbf{B} - \nabla \left( \frac{B^2}{2\mu_0} \right)$$

(11)

This tension forces of the cross sectional area of the magnetic 'tubes' to decrease. As these tubes are 'squeezed' they force plasma away from this region at a rate greater than can be compensated for by additional particle pile up due to incoming magnetic field lines. This produces a stagnation line flow perpendicular to the magnetic field lines and results in a net depletion of density. In this region, magnetic tubes 'pile up' and increase the magnitude of the magnetic field. More explanation of the theory behind field line draping and the PDL, as well as observation is given in subsequent sections.

**Plasma Flow**

The flow within the magnetosheath has been studied many times, an early example of which is discussed in Spreiter [1966]. The first models of flow past the magnetosphere used the upstream flow approximation that the Alfvén Mach number was high, resulting in conditions that were similar to those of the Gas Dynamic (GD) limit. Since this was already a problem which was well understood due to the study of flow around rockets during the 1960s, the velocity flow field was then solved around the theoretically predicted shape of the magnetosphere. Then, the magnetic field lines were solved as they were convected with the known velocity field from the GD solution (according to the frozen-in condition) using the MHD Faraday induction equation. This was then able to reproduce
important results like the Chapman Ferriero magnetopause shape. This approach came to be known as the gas dynamic convected field or GDCF model.

The point in the center of a blunt object where GD requires the velocity field flow to approach zero is called the stagnation point. Since Spitzer first solved the flow of the velocity field around a blunt object and then later convected the magnetic field lines along with the flow, the boundary condition that the velocity field approaches zero at the stagnation point caused an increase in density and a decrease in magnetic field strength to be predicted here [Spitzer et al. 1966]. This however is not what actually occurs in the subsolar region [Lees et al. 1964]. To solve for the magnetic field and density parameters in this region, a different approach is required where the magnetic field and velocity flow vectors can be solved simultaneously. The tools to do this can be found in the language of MHD.

One example of an MHD approach is called the magnetic string equations. These are based on a set of curvilinear coordinates \((\alpha, \xi, \tau)\) first introduced by Podovkin and Semenov in 1977. This is a coordinate system where magnetic field lines take on a simple 'line' configuration during its passage past the magnetosphere despite the somewhat difficult geometry that this object presents. The \(\alpha\) coordinate changes along the straight magnetic field line, \(\tau\) changes along flow streamlines, while the coordinate \(\xi\) is the electric potential. With the assumption that the plasma has infinite conductivity, the \(\xi\) coordinate is conveniently constant along both magnetic field lines and stream flow lines. The \(D(\Pi, y, z)\) and \(D(\alpha, \xi, \tau)\) are Jacobian transformations from the coordinate in the numerator to those in the denominator:

\[
\left(\frac{\partial^2 l}{\partial \tau^2} - \frac{1}{Ma^2} \frac{\partial}{\partial \alpha} \left(\rho \frac{\partial l}{\partial \alpha}\right)\right) + \frac{D(\Pi, y, z)}{D(\alpha, \xi, \tau)} = 0 \quad (12)
\]

The magnetic string equations can be thought of as a evolution of the traditional \(\vec{j} \times \vec{B} - \nabla \rho\) MHD momentum equation. Commonly used parameters \(V\) and \(B\) are given.
by the following Jacobian transformations,

\[
\vec{V} = \frac{\partial (\tau, y, z)}{\partial \tau} \\
\vec{B} = \rho \frac{\partial (\tau, y, z)}{\partial \alpha}
\]  

while the transformation from \((x, y, z)\) into \((\alpha, \xi, \tau)\) represents the conservation of mass

\[
\frac{1}{\rho} = \frac{\partial (\tau, y, z)}{\partial (\alpha, \xi, \tau)}
\]

An excellent description of this formulation as well as its impact on the magnetic barrier region can be found in Erkaev et al. [1988] The theory will not be considered further, but observational analysis for the remainder of this document will be compared to the work done using this formulation [Erkaev et al. 2011] for accelerated plasma flows near the magnetopause for IMF \(B_z\) north which are thought to be the result of field line draping.

Petrinec et al. [1997] studied the angle between the velocity vector and the local magnetic field \(\theta_{bc}\) throughout spacecraft motion through the magnetosheath. They have shown that in general as the magnetopause is approached on an inward pass of the magnetosheath, the local magnetic field and the velocity vector become perpendicular, regardless of its orientation at the boundary of the bow shock when the IMF is pointing north. Others have also shown that it is common to observe a slow rotation in the magnetic field from bow shock to magnetopause, effectively reducing the plasma pressure buildup on the nose (stagnation point) of the magnetosphere.

From Fig. 2, an obvious rotation of \(\theta_{bc}\) occurs from the bow shock to the magnetopause. Interestingly, the plasma velocity vector reverses the rotation that we would expect as the plasma approaches the magnetopause, becoming more parallel to the magnetic field lines. This is most likely the result of the shear angle (and consequently large clock angle) between the magnetosheath and the magnetosphere, which causes altered
flow dynamics from those of low shear when the IMF points north.
OBSERVATIONS OF HIGH $MA$: SOLAR CYCLE MINIMUM 2009

In a COSPAR 2010 study on the long and extended solar minimum by Farrugia, Harris, et al., the position of the bow shock and magnetopause were of great interest given the dearth of interplanetary ejecta from the sun, the low $p_{dyn}$ and high $Ma$, and the low kinetic and magnetic energy densities. A distinguishing feature of magnetic clouds and ICMEs is the low $Ma$. $Ma$ is critical in determining the position of the bow shock according to the previous explanation, so the lack of low $Ma$ solar wind conditions in this extended solar minimum presents the opportunity to study the average position of the bow shock and magnetopause as the solar wind begins to approach a gas dynamic limit (high $Ma$). This solar minimum, which ranged from 2007 - 2009 was one of the longest and most prolonged solar minimum in recent memory [Farrugia et al. 2010], presenting us with an ideal data set.

In this study, we used the OMNI spacecraft to identify the time frame of the minimum

**Figure 6**  The indicated region is that of the lowest magnetic energy ($E_B$) for solar minimum 2009, $E_{kin}$ is the kinetic energy of the solar wind.
magnetic and kinetic energy density output from the sun, in order to minimize the effect that the sun’s plasma would have on the Earth’s magnetosphere [Farrugia, Harris et al. 2010]. The range selected for the magnetopause and bow shock crossings was from March 24 - June 26th, 2009, and this data set is available upon request. The region of interest is indicated in Fig. 6.

There are several definitions that are used by physicists to identify the lowest and highest point of the solar cycle. Traditionally, physicists interested in the heliosphere have used the sunspot number as an indicator of solar activity. Therefore some define the lowest point of solar minimum to occur accordingly. Since we are interested in the impact of the sun on the earth, we take the minimum kinetic and magnetic energy density of the solar wind, because it is the sun’s plasma that directly impacts the position of the bow shock, magnetopause, and other terrestrial phenomena.

In the third panel, we see why this time frame is useful for our study of Ma’s effect on the magnetosphere. During this time there was roughly a lower limit of 10 on the Ma, which indicates that the interplanetary magnetic field’s effect on the magnetosphere was minimized. This time range included a few MCs and ICMEs that are noted in Cane and Richardson [2010], but any crossings that were found during the period in which ejecta occurred are not used to maintain this as a high Ma dataset. To determine the solar wind conditions during this period, parameters were averaged from the OMNI spacecraft at 5 minute data points, and is found in table 1. The data are corrected for aberration due

![Figure 7: In three dimensions, the observed bow shock and magnetopause crossings. Notice the low height of the Themis and Cluster orbits off the ecliptic plane. Magnetopause crossings are orange, and all bow shock crossings are black.](image)
Table 1  Average and standard deviation of solar wind parameters 3/24/09 - 6/26/09. Of note here is the relatively high \( M_a \) and the relatively low \( P_{dyn} \) to the motion of the earth around the sun. The angle of rotation is given by the following equation.

\[
\theta = \tan^{-1}\left(\frac{V_{earth}}{V_{sw}}\right)
\]  

(15)

If multiple magnetopause or bow shock crossings were observed within a half hour, the two times were averaged and the resulting position is plotted. In the usual way, each data point has been rotated, or "aberration", to account for the speed of the solar wind and the motion of the earth around the sun before fitting. Using the \( X_{gsn} \) velocity of the solar wind and the tangential component of the earth’s orbit velocity, \( V_{earth} \), around the sun which is approximately 29.66 km/s.

The data fitting on these crossings is done using the AMOEBA fitting routine available in IDL, which completes a multidimensional minimization of a user-specified function. AMOEBA uses the downhill simplex method which was discussed in detail by Nelder and Mead [1965]. The function chosen for minimization was of the same form used by Fairfield [1971] and Sibeck [1991], and given in Eq. 16.

\[
0 = y^2 + Axy + Bx^2 + Cy + Dz + E
\]

(16)

The source code for this fitting routine is found in Appendix A 2, and the fitting parameters of the solar minimum bow shock and magnetopause are given in Table 2 with the corresponding Fairfield parameters.

**Solar Minimum Magnetopause**
Table 2  Fitting parameters for solar minimum 2009 bow shock and magnetopause against Fairfield 1971.

<table>
<thead>
<tr>
<th></th>
<th>$BS_{\text{Smn}}$</th>
<th>$BS_{\text{Fairfield}}$</th>
<th>$MP_{\text{Smn}}$</th>
<th>$MP_{\text{Fairfield}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0252449</td>
<td>0.0296</td>
<td>-0.126130</td>
<td>-0.0942</td>
</tr>
<tr>
<td>B</td>
<td>0.4061</td>
<td>-0.0381</td>
<td>0.0245140</td>
<td>0.3818</td>
</tr>
<tr>
<td>C</td>
<td>-0.457631</td>
<td>-1.280</td>
<td>0.671697</td>
<td>0.498</td>
</tr>
<tr>
<td>D</td>
<td>40.3743</td>
<td>45.644</td>
<td>21.0455</td>
<td>17.992</td>
</tr>
<tr>
<td>E</td>
<td>-663.475</td>
<td>-652.10</td>
<td>-248.203</td>
<td>-240.12</td>
</tr>
</tbody>
</table>

To compile this dataset, we take Cluster and Themis in the period 3/24/09 - 6/26/09 since this corresponds to the minimum magnetic energy density apparent in Fig. 6. In Fig. 8 the empirical magnetopause is plotted against a classic observationally based magnetopause compiled by Fairfield in 1971. We used the Themis and Cluster spacecraft to compile this data set, resulting in a total of 198 unambiguous magnetopause crossings. There were few spacecraft far downtail during this period, therefore the bulk of the data represented ranges from 15 to -20 Re.

There are two interesting features of the fitted magnetopause plotted (blue) against Fairfield (red). First, the standoff distance on the $X_{\text{gse}}$ axis is noticeably larger, than that of Fairfield. This is most likely due to the decrease in dynamic pressure observed during this quiet solar minimum. A typical solar wind dynamic pressure ranges from 2 - 3 nPa, but for this period of solar minimum we have calculated an av-

Figure 8: Solar minimum magnetopause (blue) against Fairfield 1971 (red) in the $X - \sqrt{y^2 + z^2}$ plane.
verage dynamic pressure of only 1.31 nPa. According to previous observation [Sibeck et al. 1991], theory and modeling (Eq. 4 - 5), this decrease is dynamic pressure leads to a larger standoff distance of the magnetopause, and an increase in the flaring parameter \( \alpha \), both of which are observed here in comparison to the Fairfield curve.

Unfortunately little is known about the solar wind parameters which caused the magnetopause position for the Fairfield curve since there was no consistent upstream solar wind monitor at that time. In cases where the bow shock positions are compared with upstream data, it is possible to use solar wind parameters measured by the bow shock observing satellite shortly after an outbound (or before an inbound) crossing of the bow shock [Merka 2003]. In the case of magnetopause crossings however, in the time it takes for the spacecraft to cross the magnetosheath, the solar wind parameters have a high probability of changing from the time that the magnetopause crossing was observed. Therefore it is not possible to use the same spacecraft that observes the magnetopause to obtain a measurement of the upstream solar wind conditions.

In Fig. 9 we have plotted the fitted solar minimum magnetopause against the models presented in chapter 1 in section 3. Both models are valid for the solar wind dynamic pressure that of interest shown in table 1.
Interestingly, both magnetopauses underestimate the flaring of the magnetopause, however this may be the result of the lack of data on magnetopause crossings beyond -30 Re downtail for the period of interest. Of the two, the Sibeck et al. model is closer to properly calculate the flaring, despite its horizontal offset. Both the Sibeck et al. and Shue et al. magnetopauses underestimate the stand-off distance by ≈ 1Re, which represents 9.2%. This is a substantial distance for an offset, and demonstrates why we do not use theoretical magnetopause models to validate arguments of spacecraft position with respect to this structure. This ≈ 10% underestimation is a common problem with these two models, and a result that we independently verify here.

Solar Minimum Bow Shock

The same period used for the solar minimum magnetopause is used to calculate the solar minimum bow shock. It is plotted against the original Fairfield [1971] curve in Fig. 10. The relatively high $Ma$ and the relatively low $p_{\text{dyn}}$ imply a compression of the bow shock [Farris and Russel, 1994] to balance the magnetic and plasma pressures in the subsolar region in front of the magnetosphere. This is expected in the gas dynamic limit, and should be noticeable here in our plot.

Surprisingly, the decrease in the standoff distance from the magnetopause for the bow shock is not observed here. This is because there are two opposing forces during this period of solar minimum. The high $Ma$ causes the bow shock to move earthward, but the low dynamic pressure during this period causes the bow shock to move out since the magnetopause is also moving away from the earth. The result is that the bow shock seemingly stays in the same position compared to Fairfield, however the magnetosheath’s thickness (distance from bow shock to magnetopause) is much smaller during this period of solar minimum compared to Fairfield. The main difference between the our figure and that of Fairfield’s is the change in the flaring. The solar minimum bow shock is less flared than Fairfield, which is the result of high $Ma$. On average, we found that the
stand off distance of the bow shock from the magnetopause was 1 Re less (or 25% of the
typical subsolar magnetosheath thickness) for this period of quiet solar minimum, but
was mostly the result of a reduction of the magnetopause standoff distance.

A small asymmetry is observed near the terminators of the bow shock. The dusk side
crosses $X_{y_{se}} = 0$ at 26.5 Re in the plane, while the dawn side crosses the terminator at
25.56 Re on the dawnside, and 25.97 on the dusk side. This asymmetry is small however,
and not likely indicative of any noteworthy features in the shape and structure of the
bow shock.

The nose of the minimized function describing the bow shock is at 14.35 Re. This
 corresponds to a magnetosheath thickness of 2.72 Re. The ratio of the nose to the
dawnside terminator is 0.561, and 0.553 compared to the dusk side terminator. The
standoff distance of the bow shock divided by the standoff distance of the magnetopause
is 1.23.
Figure 10  Solar minimum bow shock (blue) in the $X - \sqrt{y^2 + z^2}$ plane against Fairfield 1971 (red)
OBSERVATIONS OF LOW MA: DRAPING FOR IMF $B_Z$ NORTH

Over the past 20 years, work has been done on accelerations of bulk ion flow within the magnetosheath, especially those which exceed the speed of the solar wind. There is a consensus that these accelerations due to IMF draping across the magnetosphere (Fig. 5) tend to occur close to the magnetopause, and are not associated with the entire magnetosheath [Petrinec et al. 1997, Chen et al. 1993, Lavraud et al. 2007]. There are several theories which explain these accelerations, however, little observational work has been done on this subject. To our knowledge, there are less than 5 demonstrated examples of IMF draping all given by different authors, and accompanied by different theoretical framework. Our work here is to establish a groundwork for observation of these events by identifying a methodology, and producing a dataset to be used in future study of this subject. We identify 34 examples of accelerations in the magnetosheath which are likely the result of IMF draping around the magnetosphere, and do statistical analysis to determine global features of these accelerations. Reconnection is an important agent in the acceleration of particles within the LLBL [Dungey et al. 1961], but generally occurs for large clock angles or high magnetic shear. Our focus however, will remain on accelerations which are not related to reconnection.

To exclude reconnection as much as possible, we choose events for which the possibility of reconnection on the day side magnetosphere was minimized. In general, we only present events where the Interplanetary Magnetic Field (IMF) pointed strongly north. Physically these accelerations can occur for IMF configurations which are dominated by the $\pm Y_{gsm}$ and $-Z_{gsm}$ components, but given the high possibility for reconnection to
occur with these field configurations, our examples focus on $B_z$ north where reconnection at low latitudes is much less likely. In order to exclude reconnection further, care has been taken to ensure that these flows occurred in the magnetosheath, instead of the magnetosphere where accelerated flows are often seen if related to reconnection [Sonnerup et al. 1981]. Reconnection is possible at the poles of the earth’s magnetic field poleward of the cusp for IMF $B_z$ north, causing us to closely inspect the position and structure of the magnetopause in each of our examples if they occur substantially off the ecliptic plane.

Historically, there has been several different attempts to systematically characterize the transition regions between the magnetosheath and the magnetosphere for $B_z$ north [Phan et al. 1994, Fuselier et al. 1995, Sibeck et al. 1990, Petrinec et al. 1997, Chen et al. 1993]. Most of these analyses agree that tailward on the magnetopause, the definition of magnetosheath, LLBL and MSTR is sufficient. On the day side magnetopause however, this classification becomes more subtle with introduction of the Plasma Depletion Layer (PDL) [Sibeck 1990], and the possibility of reconnection at either pole producing additional regions such as the Magnetosheath Boundary Layer (MSBL) [Fuselier et al. 1995]. The most important parameter however in understanding the formation of transition regions is the magnetic shear across the magnetopause. For magnetic shear that is low (<30 deg) the Plasma Depletion Layer often forms on the day side magnetopause where magnetic field lines drape across the magnetosphere and depletes the local plasma of particles as magnetic flux tubes are tightened and stretched. For high magnetic shear however (>60 deg), the transition region between the magnetosheath and the magnetosphere is disrupted, causing a decrease in its size [Phan et al. 1994]. We focus here on small IMF clock angles and therefore low magnetic shear across the magnetopause.

The theoretical problem that was present in PDL regions is the finite, non-zero density and non-infinite magnetic field as the stagnation point is reached [Pudovkin and Semenov 1977]. With the introduction of a stagnation line flow where the direction of plasma
flow is perpendicular to the magnetic field, there is no need to associate these structures on the boundary of the magnetosphere with mass flux transfer across the magnetopause.

Recently, several theories give predictions about the strength of ion accelerations that occur due to IMF draping. In 2007, Lavraud et al. did a global simulation of hot ion speed during a period of simulated low Ma. They used an observational event on 11/25/01 seen by Cluster, which we also briefly study here, to substantiate their results. This event was found during a period of extreme IMF Bz north, and was found to exceed the speed of the solar wind by 60%.

Recently Erkaev et al. [2011] produced very interesting calculations on the speed of the plasma flow due to draping during periods for IMF Bz north. This theory predicts accelerations due to draping globally on the surface of the magnetopause for a given upstream Ma that reach to values of 60% greater than the speed of the solar wind, but suggest this as a cutoff for accelerations due to IMF draping. The detailed nature of the predictions in this theory are highly relevant to our work here, since we study many accelerations which occur during a variety of Ma.

Methodology

Presented here are five events for which the speed of the bulk ion flow within the magnetosheath exceeded that of the solar wind. As a primary dataset, we have used the Cane
and Richardson [2010] ICME list from 1997 - 2009, examining every magnetopause crossing by the Geotail Cluster, and Themis spacecraft during the northward-pointing phase of the ICME. We present here a nonexclusive dataset of IMF field line draping events because of the complex dynamics of the magnetopause during the passage of ICME, which leads to difficulty in exactly identifying the signatures of IMF field line draping as an acceleration mechanism. Although many more accelerations were observed than are noted here during this period, they have not been included because they did not satisfy the guidelines set forth here.

Our methodology for identifying accelerations due to draping is a combination of techniques used by Lavraud et al [2007], Sonnerup et al [1981], and Rosenqvist et al [2007] among others. First, we choose events for which the possibility of reconnection on the day side magnetosphere was minimized, and focus mainly (with few exceptions) on an IMF clock angle <45 degrees. Next, we try to exclude accelerations observed high off the ecliptic plane where it is possible to observe a flow burst due to reconnection poleward of the cusp. Then, we calculate the flows parallel and perpendicular to the local magnetic field lines. Flows parallel to the magnetic field lines are often characteristic of reconnection-induced flows which occur in the LLBL and earthward of the magnetopause [Rosenqvist et al 2007], however flows perpendicular to the magnetic field lines tend to be associated with IMF field line draping. Next, we use the magnetic field parameters in conjunction with the plasma temperature and density to identify the magnetopause, as well as the ion and electron energy flux distributions. After these tests, if there was still doubt about the region in which the acceleration occurs, we perform a Walen test according to Sonnerup et al [1981] which identifies the plane of minimum variance (of the magnetic field), and determines the probability that an acceleration is related to reconnection. This was developed to observe reconnection-related flows, and fails in the cases where accelerations are due to draping. A few parameters of interest when studying these flows are shown in table 3.
An example of an orbit by one of the spacecraft used in this study is given in Fig. 11. This demonstrates that the coverage of the magnetosheath by Cluster, Themis and Geotail extends from roughly 3 Magnetic Local Time (MLT) through 21 MLT. There is potential of covering more MLT in the magnetosheath with spacecraft far down tail of the terminators on the boundary of the magnetopause, however no data is available in this region for our spacecraft of interest.

Cluster, Themis, and Geotail spacecraft magnetopause crossings during ICMEs and Magnetic Clouds (MC) identified by Cane and Richardson [2010], represent the bulk of the ion accelerations studied here. ICMEs and MCs were chosen because of their characteristically low Alfvén Mach number in comparison to average solar wind conditions and strong magnetic field. As noted by Chen et al. [1994] and Phan et al. [1994] there also seems to be a correlation between acceleration of ions and the passage of magnetic flux ropes which will be discussed later in more detail.

Song et al. [1990] subdivides the LLBL into two regions, the outer boundary layer (OBL) and the inner boundary layer (IBL). In general the OBL is earthward of the magnetopause and connected to the ionospheric field lines, however during reconnection events on the magnetosphere it is possible for the field lines to open in the OBL and connect to the IMF in the magnetosheath [Sonnerup and Siebert 2003]. The IBL is strongly coupled to the magnetosphere and represents a region of mixing between the solar and magnetospheric plasmas, which is invoked to explain the temperature gradient observed in the IBL and OBL. This is evident in the electron and ion energy flux diagrams.

<table>
<thead>
<tr>
<th>IMF clock angle</th>
<th>θ_{by}</th>
<th>Layer</th>
<th>acceleration max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draping Reconnection</td>
<td>0° - 180°</td>
<td>≈ 90°</td>
<td>magnetosheath</td>
</tr>
<tr>
<td></td>
<td>&gt; 60°</td>
<td>≈ 180°, 0°</td>
<td>LLBL / Msphere</td>
</tr>
</tbody>
</table>

Table 3: These are some of the important parameters that distinguish between draping and reconnection related ion accelerations in the ecliptic plane. Note that reconnection can occur at the poles of the magnetosphere during small clock angles. θ_{by} is the angle between the B and V vectors. V_{sw} is the speed of the solar wind.
We use these definitions to identify regions earthward of the magnetopause through our study of the nearby region where IMF draping accelerations are thought to occur.

**Event 1 - Geotail 3/25/02.**

To ensure that our methodology is effective, we will now apply it to a more straightforward instance of IMF field line draping where there is little ambiguity with the position of the magnetopause. Here we see an outbound passage of Geotail through the LLBL into the magnetosheath on 03/25/2002, plotted in Fig 12. Geotail has a position of \( X_{gsm} = -11.69, Y_{gsm} = -16.64, Z_{gsm} = -1.52 \) at 07:12 UT. The clock angle throughout much of the time Geotail is in the magnetosheath is 55 degrees, which is only slightly higher than our ideal conditions. We rank the certainty of this measurement as '2' in table 4, which indicates that this is acceleration is well defined in the magnetosheath, and has a high probability of being caused by IMF line draping.

This event is considered to occur with a high degree of confidence because of three major factors mentioned previously. Namely, it is in agreement with all our initial requirements (low off the ecliptic plane, and for low clock angle), it occurs outside of the magnetopause, and the bulk ion flow during the acceleration occurs perpendicular to the local magnetic field. We know that the magnetopause is crossed at 07:04 UT, where a sharp decrease in density correlates with the formation of a temperature gradient and a drastic change in the magnetic field, therefore accelerations due to reconnection or Maxwell stresses are not suspect. The ion plasma flow from the LEP (Low Energy Particle) on Geotail reached a speed 20% greater than the speed of the solar wind, which is evident from panel 6. We are sure this was not the result of a short passage into the solar wind because of the proximity of this flow to the magnetopause, as well as the discontinuity of the magnetosheath \( B_z \) value with that of the solar wind plotted in panel 8. Additionally, the energy flux distribution, and comparison of magnetosheath temperature, \( V_y \) and \( V_z \) components of the velocity field and density are other parameters.
Figure 12: Event on 3/25/02. N is the density in $\text{cm}^{-3}$, Temperature is measured in eV, $V_x, y, z$ are measured in km/sec, $V_{par}$ and $V_{perp}$ are the flows parallel and perpendicular to the local magnetic field $V_{sh}$ and $V_{sw}$ are the magnitude of the velocity of the magnetosheath and solar wind respectively. $B_x, y, z$ are measured in nT, $\beta$ is the ratio of the plasma and magnetic pressures, $P_p$ and $P_m$ respectively, where $\theta_{iv}$ and $\theta_{IMF}$ are the angle between the local magnetic field and the ion velocity and the solar wind IMF clock angle respectively.
often used to distinguish between magnetosheath and the solar wind. For identification of accelerations which occur at the bow shock, there are additional techniques one should to distinguish the solar wind from the magnetosheath, some of which are explained in Chen et al. [1993]. Conversely, the IMF clock angle changes minimally over the bow shock, and is another good parameter to use to identify the magnetosheath from the magnetosphere.

Interestingly, the flow perpendicular to the magnetic field extends throughout the entirety of Geotail’s time in the magnetosheath. We derive this conclusion from the fact that $\theta_{bw} \approx 90^\circ$. This extended structure is indicative of a stagnation streamline flow downtail of the terminators ($X_{gsm} < 0$). We will see that this occurs fairly often in accelerations which occur in the magnetosheath on the boundary of the magnetopause.

The increase in $P_p$ (denoted in red) results in a increase in $\beta$ from 07:03 - 07:04 UT. Although not indicated on Fig. 12, there is a decrease in temperature and density from 07.05 - 07.10 UT which is indicative of the MSTR for low magnetic shear [Phan 1994].

**Event 2 - Geotail 04/13/1998**

An acceleration on 4/13/1998 observed by Geotail from 05:15 - 06:00 UT at $X_{gsm} = -18.5$ Re, $Y_{gsm} = 19.9$, $Z_{gsm} = 6.0$, is plotted in Fig. 13. Although the plasma parameters appear to fluctuate, there are distinct crossings of the magnetopause where the magnetic field, density and temperature jumps occur in phase with one another. Reconnection is very unlikely to occur given the latitude and the solar wind conditions found for the time of these crossing, as the two accelerations seen here occur at clock angles between $1^\circ$ and $25^\circ$. The maximum acceleration observed here reaches a value of 28% greater than the speed of the solar wind.

The regions have been defined as magnetosheath (Msh), and the Low Latitude Boundary Layer (LLBL). As the magnetopause is crossed, the temperature increases, the density decreases, and the magnetic pressure increases ($P_m$). This is typical of magnetopause
Figure 13  Event on 4/13/1998
crossings, where a gradient forms in the aforementioned values

By using the Cane and Richardson list of ICMEs as a basis for our dataset, we have confined ourselves to a difficult series of crossings because of the complex nature of the study of the magnetopause during the passage of flux ropes associated with ICME. This is an example of how this study of draping requires close examination of the plasma parameters, where the magnetopause crossings are not typically as straightforward as our initial example on 7/25/01 in Fig. 2
Event 3 - Geotail 8/20/2006

![Graph of various parameters over time]

Figure 14  Event on 8/20/06  Notice the parameter \( \theta_{bv} \) which is plotted at the bottom with the clock angle of the IMF \( \theta_{ib} \). \( \theta_{bv} \) is constant through the entire magnetosheath leading up to the first magnetopause crossing at 11:45 UT. This is an indicator of the stagnation streamline flow, usually associated with the PDL on the nose of the dayside of the magnetopause.
This particular event is of great interest given the length of time that Geotail observes an acceleration which reaches a speed of 27% greater than the speed of the solar wind. A similar event is presented by Rosenqvist et al. [2007], where the duration of the accelerated flow is on the order of 15 minutes, whereas most accelerations we have studied are on the order of 2 - 5 minutes. These accelerations are often short lived because they typically are identified next to the magnetopause where the draping effect is strongest, and the probability of a spacecraft skimming the magnetopause during a low $Ma$ period (where the transition region between the magnetosheath and the magnetosphere increases in size), is decidedly low. Geotail crosses the magnetopause at $X_{gse} = -14.7$ Re, $Y_{gse} = 15.6$ Re, $Z_{gse} = -16.3$. We give this acceleration a confidence rating 1, meaning somewhat confident, because it has all the signatures of draping yet remains relatively high off the ecliptic plane.

The increase in density observed at 11:30 is not due to any region transition between the magnetosheath and the magnetosphere, instead it is the result of changing parameters in the upstream solar wind. When observing these examples, it is important to remember that the magnetosheath acts globally as a perturbation of the solar wind by the bow shock, and therefore reflects changes in the solar wind parameters. Notice that this event also represents a stagnation streamline flow ($\theta_{bo} \approx 90$) on the boundary of the magnetopause downstream of the terminators.

**Event 4 - Cluster 11/25/01**

To help us compare our events with known examples of draping, we now study the acceleration observed by the Cluster 3 spacecraft on November 25, 2001. The position of Cluster is near the ecliptic plane at $X_{gse} = -3.32$ Re, $Y = 18.75$ Re, $Z = 1.68$ Re. This event was studied in detail by Lavraud et al. [2007], and the reader is referred here for more detailed information on the specifics of certain calculations. Similar to Lavraud et al., we calculated a time delay of approximately 39 minutes, and identified
the magnetopause crossing near 09 12 UT. Here the magnetosheath bulk ion flow reaches a speed 61% greater than the speed of the solar wind, and it is given a confidence rating of 2. The plasma parameters are displayed in Fig. 15.

Using a Multi-spacecraft discontinuity analysis technique [Gosling et al. 2002], Lavraud et al. found a thickness of a few Re for the magnetosheath boundary which hosted the acceleration event after calculating a magnetopause normal velocity with a lower limit of 400 km/s. However, given the magnetopause motion of approximately 11 km/s given by Phan et al. [1994] for normal solar wind conditions, this represents a large departure from typical values observed. A likely contributing factor in observation of these accelerations is the increase in thickness of the MSTR near the magnetopause during low MA (it scales in size proportional to $\frac{1}{Ma^2}$, [Farrugia et al. 1995]), resulting in a better observed profile of the thin acceleration region as it passes over the spacecraft.

The deflection in the magnetic field occurs before (09 12 5) the temperature, energy flux and density gradient begin (09 17). Often, the placement of the magnetopause corresponds to the start of this temperature, density and energy flux gradient. Here, the indicated position of the magnetopause by Lavraud with the deflection of the magnetic field places the magnetopause well earthward of what many of the plasma parameters would otherwise indicate. The region between the vertical lines in Fig. 15 is very similar to a part of the LLBL called the Outer Boundary Layer (OBL). This placement of the magnetopause earthward of the temperature gradient increase is an important point in the dissemination between the acceleration events which are classified in the magnetosheath versus the OBL, because the OBL is generally considered to host only accelerations which are the result of Maxwell stresses (a fundamentally different acceleration mechanism).

Interestingly, this event lacks a build up of magnetic pressure on the boundary of the magnetopause that is observed in other events. The strict definition of the magnetopause seems somewhat ambiguous because $N$, $B$, $T$, $\theta_b$, $\theta_{bs}$, magnetic and plasma pressure, and $\beta$ do not vary in a systematic way over the magnetopause for all solar wind conditions,
Figure 15  The plasma parameters for the event on 11/25/01 observed by Cluster. 'Msh' refers to the magnetosheath, while 'Msphere' refers to the magnetosphere. The left most vertical line indicates Lavraud's placement of the magnetopause [2007]. Another line is included to indicate where the temperature, density, and energy fluxes (Fig 16) reach their asymptotic magnetosheath levels.
Figure 16: The plasma parameter overview for the entire event, note the independent acceleration at 8:21.
and again may change out of phase [Chen et al. 1993]. Especially when the Alfvén Mach number is very low, the bow shock moves upstream and weakens which can result in altered plasma flow compared to the high $Ma$ limit on the boundary of the magnetosphere. In event 5, we study the implication of the magnetopause placement with respect to the plasma and magnetic field parameters.

On the left side of Fig. 16, the reader will notice another ion acceleration which exceeds the speed of the solar wind at approximately 08:25 UT. Similar to the event seen just a short while later, this acceleration occurs very close to the magnetopause, and reaches a value of about 22% greater than the speed of the solar wind. For this example, the higher of the two accelerations occurs during the contraction of the magnetosphere which may be caused by the release of IMF lines piled up on the front of the magnetopause, and could account for the reason that magnetic pressure pile-up is not seen during the larger of the accelerations at 9:12.5 UT.

This acceleration also shows the difficulty of exactly predicting the value of the acceleration given that these two events occurred close to the same $X, Y, Z_{gsm}$ position and at similar solar wind $Ma$ and dynamic pressure. Cluster’s position during the acceleration at 8:25 was $X_{gsm} = -3.46$ Re, $Y_{gsm} = 18.13$, $Z_{gsm} = -4.76$ while the event at 9:12 was at $X_{gsu} = -3.32$, $Y_{gsm} = 18.75$, $Z_{gsm} = 1.68$ suggesting that local topology on the magnetopause may also play a role in the maximum acceleration observed. Therefore, it is difficult to quantitatively identify the absolute maximum velocity of the acceleration that could be observed at a given position for a given $Ma$. Additionally, it is of interest that $\theta_{bo} \approx 90$ indicates the presence of a stagnation line flow both before and after the largest acceleration at 09:12 UT.

**Event 5 - Geotail 5/30/01**

So far we have studied events with a confidence rating 1 or 2 meaning that these accelerations are considered to be the result of IMF field line draping to a relatively high degree...
of confidence  Let's now consider an event with an initial confidence rating '0', to see what specifically casts doubt on these events.

The event studied here was observed by Geotail on May 30, 2001 at position $X_{gsm} = -10.36$, $Y_{gsm} = 25.73$, $Z_{gsm} = 12.77$ Re from 20:30 - 24:00 UT during an inbound passage. This crossing occurred at relatively high latitude compared to the ecliptic plane, presenting unique challenges compared to IMF field line draping and reconnection accelerations which occur near the ecliptic plane. The most important accelerations occur at approximately 21:00 UT, 21:36 and 23:25 UT which are plotted in Fig 17.

It is clear by the temperature and density profiles that these three events were also accompanied by crossings of Geotail over the magnetopause. The bulk direction of the acceleration occurs tangent to the magnetopause in the $-X_{gsm} + Y_{gsm}$ direction. By Fig 17, one can see that the second and third accelerations occur almost completely in a direction perpendicular to the magnetic field. This is a good first indicator that the acceleration is occurring outside of the magnetopause and is most likely due to field line draping. The first acceleration, however, tends to be largely in a direction parallel to the magnetic field.

**21:39 UT**

To justify the origin of this flow, a correct identification of the magnetopause is critical since this flow exceeds the speed of the solar wind by 77% at its maximum. Because accelerations up to 60% greater than the speed of the solar wind are predicted by theory, this could possibly represent an experimental departure from theoretical prediction. It is not uncommon for the density, temperature and magnetic field data to be slightly out of phase, where the magnetic field indicates that the magnetopause is crossed at approximately 21:40 UT with a sharp change in the $B_x$ and $B_y$ components. This then suggests that the acceleration is occurring within the magnetopause, however the oscillations in the magnetic field data before this jump seems to suggest the presence of magnetosheath.
Figure 17  The Plasma and B field parameter overview for 5/30/01
Figure 18  The Plasma and B field for the first two events. The crossing is divided into Magnetosheath (Msh), Outer Boundary Layer (OBL), and Inner Boundary Layer (IBL).
The energy flux distributions are critical to understanding the dynamics and the change that occurs from magnetosphere at 21 25 to magnetosheath at 21 55, and are plotted in Fig. 19. The tailward electron flux distributions go through three distinct regions, magnetosphere (MS) from 21 20 - 21 29 5 UT, IBL from 21 29 5 - 21 35, OBL from 21 35 - 21 40 and Msh from 21 40 - 21 50. 21 40 UT also corresponds to a sharp change in the tailward ion flux distributions, which leads one to agree with the previous definition of Msh, BL and MS. This time of 21 35 - 21 40 however does correspond well with an increase in density and a local decrease in temperature, both of which are indicators that Geotail is leaving the BL and entering the Msh.

In Fig. 19 we have also included the O/H and He++/H ratios at the noted energies. Despite the different origins of the particles (solar wind in the magnetosheath and the earth’s magnetosphere for the BL), curiously there is no noticeable change in the composition. Therefore, observation of the ratios of ions is not a legitimate means of identification of the magnetopause. If additional parameters are sought however, temperature anisotropy and calculation of the magnetic field angle to the \(+Z_{\text{gse}}\) axis have been shown as effective tools [Phan et al. 1994].

As Geotail enters the IBL at 21 29 5 from the magnetosphere the density increases, the temperature decreases and the total magnetic field jumps and slowly begins to oscillate, which is an indication of the mirror instability. Entrance into the IBL also results in a decrease of the sunward proton energy flux distribution, and a mixing of similar energy ions moving tailward. This suggests that a semi-isotropic plasma is present, as the energy flux is very similar for all directional components. Isotropy is no longer present however when Geotail leaves the IBL and enters the OBL at 21 35. At this point the plasma becomes strongly directionalized in the antisunward direction, as the sunward and dawnward flux drop out. It is here that the acceleration occurs, and therefore it is our chief region of interest. The duskward and tailward flux begins at a relatively high energy compared to the magnetosheath at 21 35, rapidly decreasing to magnetosheath
Figure 19  The energy energy flux and particle ratio overview for the first events
values at 21:40 where the magnetopause is breeched. The increase of temperature over
the magnetosheath is generally accepted to be the result of the mixing of plasma from
the magnetosheath with the magnetosphere. Although a small amount of plasma mixing
occurs on the inner edge of the OBL, the vast majority occurs in the nearby IBL where
the plasma reaches near isotropy.

At 21:31 in the IBL we see a drop off of the plasma pressure which increases upon entry
into the OBL at 21:35. The OBL maintains this increase in plasma pressure which ends as
the Msh is entered at 21:40. For a field of 9 nT, and a velocity of 300 km/s present in the
OBL, the gyroradius of a proton is approximately 0.05 Re. We calculate that Geotail is
moving approximately 0.033 Re/minute, which is on the order of a gyroradius per minute.
At large $Z_{gse}$ the OBL is expected to increase [Sonnerup and Siebert 2003], supporting
why this region is so well defined in this example. It is clear from the energy flux and
plasma parameters that the OBL is dominated by magnetosheath particle populations
here. Although theoretically it is considered uncommon for the OBL to contain open
field lines, this has been observed many times [Sonnerup and Siebert 2003]. Given the
high correlation between magnetosheath plasma and that of the OBL, we consider the
field lines to be open in this example, requiring that reconnection is occurring on the
magnetopause.

Since the OBL region is small ($\approx 0.2$ Re), it is likely that the acceleration earthward
of the magnetopause is within one or two gyroradius of the magnetopause. Current
models [Sonnerup and Siebert 2003] suggest this acceleration is due to Maxwell stresses
in the magnetopause away from a local X line but require local quasisteady reconnection
nearby, a scenario that is unlikely here given the structure of the IBL and OBL. Despite
its identification in the OBL, flows perpendicular to the local magnetic field suggest IMF
field line draping as an acceleration mechanism, which is substantiated by the oscillations
in the B field and clock angle during the time of the acceleration. Before an absolute
determination of the nature of this event, we will study the first acceleration that occured
21:00 UT

This event is noticeably different from the acceleration which occurs at 21 39, but reaches a similar speed of 75% greater than the speed of the solar wind. The outer boundary layer seems dominate here, while the inner boundary layer exists for a very short time and contains high energy ion traveling in the tailward direction mixing with high energy ions traveling in the sunward direction. This signature is present in the energy flux distributions in Fig. 19. The latter event has a distinct region from 21 29 5–21 35 where the ion energy flux turns sunward, but the remains at a relatively low energy for an extended period of time. The energies then increase in a distinct drop at the transition from magnetosphere to IBL present at 21 29 5. For the event at 21 00, we see a gradient of tailward flux energy distributions, which abruptly turn sunward at 21 01 through this region of turbulent mixing identified here as the IBL. No distinct jump in temperature or density is present here like the transitions from magnetosheath to OBL in the event on 21 39 instead a gradient forms in all of these parameters.

A rotation of the magnetic field is observed from 20 52 - 20 57 which is either associated with a change of the IMF parameters during this period, or a transition of Geotail from the open field lines of the magnetosheath to the closed field lines of the magnetosphere. This region is also accompanied by an increase in temperature and ion energy flux, leading us to believe this rotation in the field represents the latter. This then places the acceleration within the confines of the closed magnetic field lines of the magnetosphere, supporting the general interpretation that ion flows parallel to the local magnetic field are related to reconnection or some acceleration mechanism other than IMF field line draping. The maximum acceleration at 21 00 then is dismissed since it occurs in the IBL, and the maximum plasma speeds occur parallel to the local magnetic field.
At first upon observing the symmetry of the accelerations occurring near the boundary of the magnetopause, one may incorrectly assume that these flows are due to the exact same acceleration mechanism. We have shown through our methodology that this is not the case. The first acceleration is shown to occur within the IBL, with flows parallel to the local magnetic field. Therefore reconnection somewhere along the magnetopause is suspected among other acceleration mechanisms, and is outlined theoretically in Sonnerup and Siebert [2003]. The second acceleration however, which has the same signature as the third, is shown to occur in the OBL and perpendicular to the local magnetic field, and therefore we suggest that draping is a possible acceleration mechanism.

**Discussion of 5/30/01**

Given the high correlation between the second acceleration on 5/30/01 and the main acceleration on 11/25/01, one may incorrectly determine that both of these events are due to the same acceleration mechanism. Although the second acceleration in the event on 5/30/01 occurs mostly perpendicular to the local magnetic field, its placement in the OBL at high latitude and the magnitude of the acceleration do not pass the criteria to be recorded in our list of events. The Walen test [Sonnerup et al. 1981] for the second acceleration on 5/30/01 was inconclusive, and which is another reason it is not included in our subsequent analysis.

There seems to be some ambiguity about the exact positioning of these accelerations within the the magnetosheath or OBL depending on the upstream solar wind conditions and the latitude of the crossing. We are certain however that any accelerations that occur in the IBL cannot be associated with IMF field line draping, and are likely the result of reconnection somewhere along the magnetopause. Given the methodology set forth, we determine that any acceleration that occurs in a plasma depleted region like that of 11/25/01 which satisfies all our previous requirements is the result of IMF draping, and will be included in table 4 with an appropriate confidence rating.
Comparison with Theory

As magnetic field lines pass over the magnetosphere, they are stretched and distorted. This process is commonly referred to as field line draping, and a pictorial representation is given in Fig 5. This draping effect creates a tension force on the magnetic field lines similar to stretching a rubber band, causing the local plasma that carries the field line into the magnetosphere to be accelerated. The steady state MHD momentum equation is given by

$$\vec{v} \cdot \nabla \vec{v} = \vec{J} \times \vec{B} - \nabla \vec{P}$$

(17)

Where the left term on the right hand side represents the force Lorentz force (sum of magnetic pressure and tension), while the term on the right is the gradient of the thermal pressure. During low $Ma$, the magnetic tension dominates and therefore becomes central to understanding the bulk of these acceleration events. To compare the events seen here, the magnetic string approach of Erkaev et al. [2011] is used, and the reader is referred here for more information.

Physically, the theory showed that the gradient of the pressure on the day side of the magnetosphere will reinforce the curvature force, causing the particles to accelerate. Near the terminators ($X_{\text{ge}}$), this curvature force will reverse direction and oppose the pressure gradient force. Far downstream of the terminators on the magnetopause, the curvature force will dampen the peak speed due to draping accelerations. Therefore we identify the maximum plasma speed due to draping where the sum of all forces is equal to zero, which the theory predicts should occur just tail-ward of the terminators. Table 4 is a list of acceleration events, which represents a non-exclusive survey of the Cane and Richardson ICME list from 1997 - 2009 for Geotail. Cluster and Themis.
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<td>13:43</td>
<td>8.95</td>
<td>5.19</td>
<td>67.5</td>
<td>2</td>
<td>CL</td>
</tr>
<tr>
<td>21</td>
<td>6</td>
<td>2009</td>
<td>11.9</td>
<td>1.28</td>
<td>5.05</td>
<td>0.63</td>
<td>05:27</td>
<td>-6.54</td>
<td>-7.61</td>
<td>79.0</td>
<td>1</td>
<td>CL</td>
</tr>
<tr>
<td>27</td>
<td>6</td>
<td>2009</td>
<td>12.19</td>
<td>1.14</td>
<td>12.1</td>
<td>1.07</td>
<td>06:04</td>
<td>0.28</td>
<td>0.05</td>
<td>29.8</td>
<td>2</td>
<td>CL</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>2009</td>
<td>17.21</td>
<td>1.20</td>
<td>8.07</td>
<td>1.80</td>
<td>19:11</td>
<td>-3.46</td>
<td>-6.99</td>
<td>44.2</td>
<td>2</td>
<td>CL</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>2009</td>
<td>17.70</td>
<td>1.15</td>
<td>7.80</td>
<td>1.80</td>
<td>19:08</td>
<td>-3.32</td>
<td>-6.85</td>
<td>75.0</td>
<td>1</td>
<td>CL</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2010</td>
<td>4.95</td>
<td>1.15</td>
<td>12.5</td>
<td>2.80</td>
<td>06:31</td>
<td>2.08</td>
<td>-0.11</td>
<td>80.8</td>
<td>1</td>
<td>CL</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2010</td>
<td>6.15</td>
<td>0.91</td>
<td>14.2</td>
<td>2.01</td>
<td>11:10</td>
<td>9.99</td>
<td>-8.70</td>
<td>85.0</td>
<td>2</td>
<td>CL</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>2010</td>
<td>16.9</td>
<td>0.96</td>
<td>12.6</td>
<td>1.50</td>
<td>09:53</td>
<td>5.70</td>
<td>-9.76</td>
<td>69.8</td>
<td>1</td>
<td>CL</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2010</td>
<td>23.0</td>
<td>0.93</td>
<td>9.37</td>
<td>2.28</td>
<td>10:10</td>
<td>5.56</td>
<td>-10.72</td>
<td>8.5</td>
<td>2</td>
<td>CL</td>
</tr>
</tbody>
</table>

Table 4: V% refers to the percentage by which the hot ion plasma in the magnetosheath exceeded that of the solar wind. The 'Rate' column is a qualitative number given to the certainty of each event. 0 = uncertain, 1 = moderately certain, 2 = certain. The average standard deviation of the ratios $\sigma_r = 0.04$, due to the variation of the upstream solar wind velocity around the time of interest.
Erkaev et al. [2011] numerically integrated the magnetic string equations given in Eq. 12, in the section on plasma flow in the magnetosheath in chapter 1. The maximum magnetosheath velocity ratio to solar wind as a function of the $X_{gs}$ normalized by the curvature of radius of the subsolar magnetopause is determined through a numerical solution to these equations, and is given in Fig. 20. The magnetopause is calculated using the Shue et al. [1998] model. This plot represents the maximum acceleration predicted for different $Ma$, labeled in the plot. The largest accelerations from this theory are expected tailward of the terminators at $X_{gsm}/R_0 = -0.4$, and for $Ma \to 1$.

When the position and ratio are plotted for various $Ma$ in the theory, the general trend of Fig. 20 was present. The effect here that $Ma$ has on the speed at which the solar wind is exceeded is immediately evident theoretically. In Fig. 21, we have plotted our observational points with respect to the ratio in which the ions exceed the speed of the solar wind, and $Ma$. Overlaid on Fig. 21 is the theoretical maximum velocity ratio for a given $Ma$ (Blue) as well as the line of best fit for the observational points (red). These two differ by a vertical offset, but otherwise the trends are very similar. The offset is expected because the theory predicts the absolute maximum ever observed in a given position, which would be extremely difficult to reproduce observationally because of the varying magnetopause distance from the earth, and the effect local topology on the magnetopause has on the maximum speed observed.

These speeds as a function of their position have been evaluated for different MLT, and are plotted in Fig. 22. This figure confirms the theory that

![Figure 20: The vertical Axis is the maximum ratio predicted. The horizontal axis is related to distance, and the terminator $X_{gsm} = 0$ is denoted by the vertical dotted line. The numbers on the curve are the upstream Alfvén Mach number.](image)
these accelerations are smaller in magnitude on the day side of the magnetosphere, and higher accelerations are observed further downstream on the magnetopause. It is evident that there is a hole in Fig 22 from 15-18 UT. The lack of data here is curious since we tended to find few events in this region despite looking for them explicitly. Perhaps accelerated flows due to draping here do not exceed the speed of the solar wind, and are therefore easier to overlook.

Gosling et al. [1986] found accelerations in the boundary layers which exceeded the speed of the magnetosheath by a factor of 2, and existed for several hours. These are considered to be related to reconnection and are otherwise unimportant to this study besides the asymmetry in the observation of these events. Few accelerations of this kind were found on the dawnside (6-12 MLT) of the magnetosphere, and instead tended to dominate the duskside (12-18 MLT). This is the opposite situation that we have found here, where we have observed a lack of IMF field line draping accelerations from 15-18 MLT. To our knowledge, this asymmetry between IMF field line draping and reconnection accelerations has never been observed. We suggest that this asymmetry is due to the motion of the earth around the sun in the ecliptic plane, on average exposing more of the dawnside of the magnetosphere to direct contact with the solar wind.

Figure 21. The maximum acceleration predicted by Erkaev et al. [2010] (blue) against the fit to the observed data (red). This represents all MLT, thus the scatter of points.
Discussion

In general, the magnetopause can be identified by a decrease in density, an increase in temperature, a decrease in $B$ fluctuation, a rotation of the magnetic field, an increase in the magnitude of the magnetic field, an increase in Beta, an increase in the temperature anisotropy parameters, a change in the $B$ zenith angle, and a change in the angle between the $B$ and $V$ vectors among other parameters for the low shear magnetopause. Although the magnetospherically connected LLBL is often presented as a sharp transition which occurs at and earthward of the magnetopause, it is quite common for some of these plasma parameters not to be met, and other to be out of phase with one another by a few minutes [Chen 1993]. This is the difficulty in identification of the region of acceleration due to the complex motions of the magnetopause during ICME. Therefore, the major parameters we have used to identify the magnetopause has been the temperature, and the electron and proton flux distribution, since electrons have a small gyroradius and are closely tied to the magnetic field lines. By a combination of all these parameters along with the ion and electron energy flux distributions, we have identified all of the following events as occurring within the magnetosheath.

Although accelerations due to draping may be caused by an IMF pointing in the $-Z_{gsm}$ or strictly $Y_{gsm}$ directions, as was expected large clock angle (>60 degrees) is unfavorable to IMF field line draping because high shear across the magnetopause increases the possibility of the magnetopause reconnection.
After studying these five events, we are in a better position to understand the region in which these accelerations are occurring. The events on 5/30/01 and 11/25/01 show that although the magnetic field parameters change slightly between these two events, these events share many of the same plasma parameters. Therefore any events that are similar to 5/30/01 are added to table 4.

![Figure 23: The maximum acceleration observed per MLT per MA](image)

The three most important parameters in our study of IMF draping accelerations has been MLT, and $Ma$. Using the normalized values for the ratios against $Ma$ (Fig. 21), and the unnormalized ratios against MLT (Fig. 22), we have numerically approximated our results in Fig. 23 using a downhill gradient method and our two previously fitted functions for the Vratio dependence on MLT and $Ma$. This represents the maximum ratio observed against $Ma$ and MLT, which would underestimate a similar theoretical plot for the reasons outlined in the last section. In agreement to the theory of Erkaev et al. [2011], we found that the maximum ratios were observed downstream of the terminators. Interestingly, accelerated flows do not appear bounded by their distance downtail (large MLT), which is evident in Fig. 23.

Using the Cane and Richardson ICME list increases the probability of observing an increased size of the PDL, given the low $Ma$ generally associated with ICME. By Farrugia
et al. [1997], we know that this region of transition scales in size as:

$$\delta \alpha \frac{1}{M_e^2}$$

and is of interest to us since the plasma parameters observed in these accelerations is often similar to those of the PDL. Because magnetopause compresses and expands in all the noted events, the spacecraft sees a wider profile of the magnetosheath transition region compared to a stationary crossing and therefore can still witness an acceleration event despite the small space associated with the MSTR. Additionally, the region of increased magnetic field strength and decreased density seems to occur globally in the magnetosheath near the magnetopause, and its size and properties as a function of downtail distance will be the topic of future study.

This process of field line draping is also valid for IMF south and strongly in the $Y_{gsm}$ direction, however these examples have not been studied here (with the occasional high clock angle in table 4) given the opportunity to inadvertently include a reconnection related flow. The analysis done here is sufficient to differentiate between reconnection and field line draping flows for IMF south, making sure that mass flux over the magnetopause does not occur, and to pay close attention to the energy flux of both electrons and ions to ensure that the flow does not occur within the magnetosphere.

**Conclusion**

After surveying the Cane and Richardson ICME list from 2007 - 2009 for Geotail, Cluster and Themis we have determined that bulk ion accelerations in the magnetosheath which exceed the speed of the solar wind for $B_z$ north are relatively rare for flows which are unambiguously not related to reconnection. During most passages of spacecraft through the magnetosheath however, it is not uncommon for an acceleration due to field line draping to be observed near the magnetosheath/magnetopause boundary. The likelihood that
the acceleration will exceed the speed of the solar wind however, is small and generally associated with ICME or Magnetic Clouds (MC)

These flows represent a group which cannot occur in the bulk of the magnetosheath, but instead always occur in the transition region between the magnetosphere and the magnetosheath. By observing the electron signatures of this transition region, it is evident that this region is notably different from the magnetosphere, and slightly different from the bulk of the magnetosheath. There are therefore three regions near the boundary of the magnetopause which are of interest, the Magnetosphere, the magnetosheath, and the transition region between the two. This transition region shares many of the properties of a layer of depleted plasma with a decreased particle density and temperature compared to the rest of the magnetosheath. However, the local plasma $\beta$ in this region is not always lower, and the total magnetic field is not always greater than the bulk of the magnetosheath, which are the defining parameters for a PDL on the dayside magnetosphere [Farrugia et al. 1995]

The initial hypothesis is therefore supported that as the IMF lines are draped on the magnetosphere, the tension in the field lines and the pressure gradient force in the magnetosheath accelerate the plasma as the magnetic flux tube cross sectional area is reduced. We have shown that magnetic field line draping is sufficient to explain the observed accelerations in the magnetosheath that are not related to reconnection. In this regard, our methodology has proven effective in making distinction between bulk ion accelerations due to reconnection and IMF draping. The structure of ICME magnetic flux tubes is well defined, and their compression as they are draped over the magnetosphere is most likely the reason so many strong acceleration events are seen during the passage of magnetic clouds and ICMEs. The IMF draping then creates a small transition region similar to the Plasma Depletion Layer (PDL) between the magnetosheath and the magnetosphere globally on both the day and night side magnetosphere. Commonly used plasma parameters and calculation of magnetic shear were insufficient to exactly
identify the causes for variable magnetic field and $\beta$ values between examples, which is not unexpected given the variety of PDLs that have been identified for low and high shear magnetopauses [Fusehei et al 1991, Hall et al 1991]. Therefore more analysis is necessary to fully understand this acceleration region globally.

We found that these flows tended to be perpendicular to the local magnetic field. Regardless of the IMF clock angle in the $Y - Z_{\text{gsm}}$ plane crossing the bow shock, Phan et al. [1994] found that as the magnetosheath nears the magnetopause there tends to be a slow rotation of the velocity vector to be tangent with the local magnetic field. This is expected from theoretical predictions of flow around the magnetosphere and is substantiated by our observations as well. By invoking a simple conceptual model for solar wind particle repulsion against the magnetopause, it is evident that particles associated with these flows are of solar wind origin and are being reflected by the magnetopause during expansions and compressions of the magnetopause.

On the question of the origin of these accelerated particles, it is obvious that pure particle counts of different species would be insufficient to identify the differences in composition of the magnetosheath and the magnetosphere given the sharp drop in density over the boundary of the magnetopause. Interestingly, ratios of these particle counts were also insufficient to warrant an exact answer to this question. The energy flux however, leads us to believe that these accelerated particles are in fact of solar wind origin and are not leaked across the magnetopause from the magnetosphere. These events therefore do not correspond to mass flux transfer across the magnetopause, which is substantiated by the common occurrence of stagnation line flows. The theoretical problem that was present in PDL regions is the finite non-zero density and non-infinite magnetic field as the stagnation point is reached [Podovkin and Semenov 1977]. With the introduction of a stagnation line flow theoretically, there is no need to associate these structures on the boundary of the magnetosphere with mass flux transfer across the magnetopause.

Since this acceleration region is similar to a Plasma Depletion Region, Farrugia [1995]
has shown that the thickness of a PDL scales proportional to \( \frac{1}{Ma^2} \). Therefore accelerations which exceed the speed of the solar wind are not generally seen for high \( Ma \) or high shear magnetopause where the transition region is deconstructed. This is exactly the case that Lavraud et al. [2007], Petrinec et al. [1997], Rosenqvist et al. [2007], and Chen et al. [1993] studied.

Through comparison with a modern theory of field line draping to investigate these accelerations [Erkaev et al. 2011], we find good agreement with observation. However, we add the caveat that the passage of magnetic flux ropes associated with low magnetic shear and \( Ma \) is a highly desirable condition for draping associated accelerated flows to occur. Because of the flows’ proximity to the magnetopause and since many passes the ion and electron signatures were accompanied by a crossing of the magnetopause, it is possible that local topology and ion-cyclotron instability on the boundary of the magnetopause is an additional trigger mechanism for the accelerations. Local waves on the magnetopause such as the Kelvin-Helmholtz instability can cause strong local turbulence leading to particle accelerations. Further study of the exact triggers of accelerations due to local topology on the boundary of the magnetopause and quantization of the magnetosheath transition region for both the day and night side magnetopause continues to be ongoing.
Further Considerations

Now that this dataset is compiled, we have taken the first step to systematically identify and understand accelerations of magnetosheath plasma due to IMF draping through statistics associated with observations. This data set then can be used as the basis for much future work in understanding this phenomenon.

First, by using the Cluster crossings, one can determine the speed of the expansion and compression of the magnetopause in each of these examples. There is ambiguity about the true thickness of this region, and a systematic study of this region would do much to explain the physical size of this region for different latitude, and for different solar wind $P_{\text{dyn}}$ and $Ma$ since these parameters have been shown to impact the size of the PDL (where we believe these flows to occur). We have extended this definition of PDL or ‘Magnetic barrier region’ globally on the boundary of the magnetopause, since this region was previously only defined on the day side. A study of this region and its connection to stagnation line flows globally on the magnetopause would be a very interesting topic which is not well understood. More study needs to be done on the structure of this region, and its shape, structure and size dependence on the distance down tail on the magnetopause.

The thickness and stable velocity parameters obtained from this study during stagnation line flows can be used to make a contour plot for varying $Ma$’s to compare with Lavraud et al [2007], and other global simulations. Also, Eikaev et al [1988] predicts the size of these magnetic barrier regions (MSTR) analytically, and these calculations could be used to compare with the statistical results of this study of the global structure of the magnetic barrier (a.k.a PDL or ‘MSTR’).

Next, a systematic study of the plasma properties of this region would be interesting to compare with the magnetosheath transition region of Phan et al [1994]. Here, it would be useful to normalize the parameters in the acceleration region to that of the nearby magnetosheath and identify the parameters which indicate a spacecraft entrance.

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into the MSTR, since the earthward end of this region tends to be bounded by the magnetopause. This would be very useful to help statistically identify the magnetosheath transition on the boundary of the magnetopause globally, and obtain a concrete definition of the magnetopause compared to the MSTR, which has not yet been done. One component of this would be to study the stagnation line flows (which we have shown here) away from the subsolar point of the magnetopause, where these flows have traditionally been shown to occur.

In our study, we have found a relatively large acceleration at high $Ma$ and $P_{dyn}$. It has been shown previously that the MSTR forms away from the subsolar point during high $P_{dyn}$, which may help to explain the possible inversion of $V_{sh}/V_{SW}$ at the high end of the $Ma$ spectrum in Fig. 21. The simultaneous effect of $Ma$ and $P_{dyn}$ on the MSTR is not well known, and determining the size and the max plasma speeds in this region as a function of $Ma$, $P_{dyn}$ and MLT, would perhaps give interesting results.
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Sonnerup, B. U. O., The reconnecting Magnetopause, In: B. M. McCormac Editor, Magnetospheric Physics, 1976


Sonnerup and Siebert (2003), Earth’s Low-Latitude Boundary Layer, *Geophys. Mon.*, 133, Copyright 2003 by the AGU, 0.1029/133GM02
APPENDICIES
APPENDIX A PLOTTING THE SHUE 1997 MAGNETOPAUSE

with Shue et al. (1997) Magnetoopause for normal solar wind conditions

angle = findgen(l000) * 0.04 - 0.20
alpha = (0.58 - 0.01 * Bzo) * (1.0 + 0.01 * pdyn)

r_0 = (11.4 + 0.013 * Bzo) * (pdyn^(-1/6.6))

r_sc = (asb(yge)/yge) * sqrt(yge^2 + zge^2)
r_space = sqrt(xgsm^2 + ygsm^2 + zgsm^2)
theta_space = atan(sqrt(Ygsm^2 + Zgsm^2)/Xgsm)
r_shue = r_0 * (2/(1 + cos(angle)))^alpha
r_shue_sc = r_0 * (2/(1 + cos(theta_space)))^alpha

print, r_0
print, alpha

plot, r_shue, angle, POS = [0.001, 0.50, 0.82, 0.999]; polar, xrange = [20, -40], yrange = [30, -30], ystyle = 1, xstyle = 1, xtitle = 'X (Re)', ytitle = '(Y!U2!N + Z!U2!N)!U1/2!N (Re)'

List of parameters:
Bzo = solar wind Magnetic field Z component
x y z ge = Spacecraft xyz components
pdyn = dynamic pressure in nPa (Eq.1)
timeb = the time of the spacecraft
timeo = time of the solar wind monitor
APPENDIX B MAGNETOPAUSE FITTING VIA AMOEBA

This program fits the x curve for the magnetopause, specifically for solar minimum day.

FUNCTION FUNC, P
COMMON FUNC_XY, X, Yp1
bx = (P[0]*X+P[2])/2.0
RETURN, MAX(ABS((Yp1 + bx)^2 - bx^2 + P[1]*x^2 + P[3]*x + P[4]))
END

COMMON FUNC_XY, X, Yp1

INCLUDE the basis set size of the data file.

vect = fltarr(4,191)
openr, 51, '/Users/brendan/IDL/Solarmin_mppause_y.dat'
readf, 51, vect

Calculating the columns of the data file, position of the spacecraft and velocity of Sun. Load for each
X = vect(0,*)
Y = vect(1,*)
Z = vect(2,*)
Sw = vect(3,*)

close, 51

velocity of Earth around the sun is 'v' from we.

V = 29.66

speed of velocity of solar wind, km/second

S = (moment(Sw,sdev = standard_deviation, /nan)
T = ATAN(V/S[0])

A rotation of the x and y-directional sqrt(y^2 + z^2)

Xp = x*cos(T) - y*sin(T)

Yp1 = [abs(y)/yp]*sqrt(y^2 + z^2)

R = AMOEBA(1.0e-4, SCALE=[0.1,0.4,0.2,2,0,0.1], P0 = [-0.0, 0.4, 0.5, 18.0, -240.0],
FUNCTION_VALUE=fval)

Check for convergence.

IF N_ELEMENTS(R) EQ 1 THEN MESSAGE, 'AMOEBA failed to converge'
PRINT, 'Coefficients ', r, $

Function value (max error): ', fval[0]

set_plot/ps
device_filename='solarmin_mppause_y.ps'
device_bits = 8, font_size=11, /times
device/inches/color, xsize = 8.5, ysize = 11 0, xoffset = 0 0, yoffset = 0 0
loadct, 39

xsz = 4.0*100
ysz = 7.0*100
xcor = 0.5*100
xcorl = 2.8*100
xlen = 6.0000*100
ylen = 1.0000*100
ycor = 1.0*100
ycorl = 6.5*100

The lower position vector gives the lower left and upper right coordinates in the image, XN, YN.

position = [xcor/xsz,ycor/ysz,xcorl/xsz,ycorl/ysz]
!!p.chartthick = 4.0
!x.thick = 1.5
!y.thick = 1.5
plot, xp, yp1, psym=4,$
xrange = [-20, 15], yrange = [-30, 30], ystyle = 1, xstyle = 1, thick = 3, $
title = 'Solar Min 09 Magnetopause: +y', ytitle = 'Sgn(Y)*SQRT(Y^2 + Z^2) in Re', $
xtitle = 'X (Re)', xticklen = 0.05, yminor = 5, xminor = 5, $
POS = position, $
SUBTITLE = 'Coeff A=-0.0306878, B=0.507914, C=-1.32091, D=1.90558, E=-287.020, Max Error 91.837'

!The subroutine plotting subroutine

!gx = (r[0]*x + r[2])/2.0
!oplot, x, -gx + sqrt(gx^2 - r[1]*X^2 - r[3]*X - r[4]), color = 250, thick = 3, psym = 5
!oplot, X^2 - r[1]/r[2] - r[3]*X - r[4], color = 60, thick = 3, psym = 5

theta = fltarr(16)
rl = 1.0
theta = (pi/180.0)*(30.0)*findgen(16)
!plot, r1*cos(theta), r1*sin(theta), color = 60, thick = 3
!Plotting lines, x = -0 and y = 0
!plots, [0, 0], [-30, 30], linestyle = 2
!plots, [-20, 15], [0, 0], linestyle = 2
!device, /close

End

List of parameters:
XY, Z = position of the spacecraft observing MP/BS crossing
Sw = speed of the solar wind
APPENDIX C BINNING DATA / REMOVING 'NAN'S

A subroutine to remove nan from your dataset, in this case for less than or equal to 12

Note this can also be used for removing 'nan' from your dataset.

\( b = [8,9,10,11,12,13,14,15,16] \)
\( Nn = n\text{.elements} (b) \)
\( c = \text{fltarr}(1,Nn) \)
\( d = \text{fltarr}(1,Nn) \)

```
for i = 0, n\text{.elements}(b)-1 do begin
  if b[i] le 12 then c[i] = b[i]
  else d[i] = b[i]
  if b[i] le 12 then d[i] = 'nan'
  else c[i] = 'nan'
endfor
```

Listing the binned vectors by taking end print the mean
\( c\text{.avg} = \text{moment}(c,\text{sdev} = c\text{.dev}/\text{nan}) \)
\( d\text{.avg} = \text{moment}(d,\text{sdev} = d\text{.dev}/\text{nan}) \)

print, 'c avg is', c\text{.avg}[0], c\text{.dev}
print, 'd avg is', d\text{.avg}[0], d\text{.dev}
end
APPENDIX D OBSERVATIONAL GEOTAIL TEMPLATE

EXAMPLE: 16° 25.02
Range: 6° - 8° Year: 7 30 50 min guess
Display: 1: Go to http://telluric.gsfc.nasa.gov/
2: Click on link Public Data
3: Select spacecraft geostationary and Auxiliary and magnetic field is particles and plasma
4: Choose GE.FDA.JAB.MGF GE.FDB.E.E.F.MGF, GE.FDA.2STC.LEP, GE.FDB.2STC.LEP.
OMNI HIO 1M
5: Select the final output parameters
6: Geostationary data needed Bx, By Xrup, z, Ge, Bz, Vx, vz, Density, Temp, GF, 401
OMNI I Data needed: Bx, By, Density, Temp, Vx, vz, Xrup, z, OMNI

Name the data file: OMN\{date\}_1.0\{OMN\}_2.0\{OMNI\}.dat; and
OMNI, OMNI.dat. Both dat files used!
This will produce a file named "GF.\{date\}_1.0\{OMN\}_2.0\{OMNI\}_401.dat", as specified by the "data entry below"

HIGH BLEVELING. If you receive a message about a vector of value being out of range,
then change the time delay guess you made, because you may have landed on a "X.X".

NOTE: Be sure that the GF spacecraft file is active.

CHANGE GF DATABASE PARAMETERS FOR EACH \{date\}
TIME = 0. ELEMENTS IN THE DATA FILES
OMNI = 241
LEP = 1178
MAGFIELD = 4725
When "date" in "\{date\}_1.0\{OMN\}_2.0\{OMNI\}.
\{date\} = '03.25.02'
The start of the X-range?
xrng1 = 6.5
The end of the X-range?
xrng2 = 8.0
What is the length of the increments on the x-range in minutes? "\{date\}_1.0\{OMN\}_2.0\{OMNI\}.
incl = 15
What is the hour of the event?
hour = 7
What is the minute of the event?
min = 30
When is your guess for the time delay in minutes?
guess = 50
Time = \{hour\} + \{min\} + \{guess\}
xxyohr1 = 7
xxyomin1 = 4
xxyohr2 = 7
xxyomin2 = 34

\{date\}_1.0\{OMN\}_2.0\{OMNI\}.
xxyotime1 = xxyohr1 + xxyomin1/60.
xxyotime2 = xxyohr2 + xxyomin2/60.
General the number trick
if incl eq 5 or 10 or 15 then xmin = 5
if incl eq 20 or 60 then xxmin = 4
if incl eq 30 then xxmin = 6
mc = incl60.
xrng = [xrng1,xrng2]
set_plot('ps')
device, filename = 'GE:' + date + '.ps'
device, bits = 8, font_size = 11, /times
device, /inches, /color, xsize = 8.5, ysize = 11, xoffset = 0, yoffset = 0
loadct, 39
vect4 = fltarr(17, OMNI)
openr, 51, '/Users/brendan/IDL/BZ_north/''+date+'.' OMNI.dat'
readf, 51, vect4
close, 51
dayo = vect4(0,*)
montho = vect4(1,*)
yearo = vect4(2,*)
houro = vect4(3,*)
mino = vect4(4,*)
seco = vect4(5,*)
timeo = houro + mino/60 + seco/3600
Bxo = vect4(6,*)
Byo = vect4(7,*)
Bzo = vect4(8,*)
vxo = vect4(9,*)
vyo = vect4(10,*)
vzo = vect4(11,*)
np = vect4(12,*)
tempo = vect4(13,*)
Xo = vect4(14,*)
Yo = vect4(15,*)
Zo = vect4(16,*)
vpo = sqrt(vxo*vxo+vyo*vyo+vzo*vzo)
bo = sqrt(bxo*bxo+byo*byo+bzo*bzo)
vect.vpo = fltarr(1, OMNI)
vect.vpo(0,*) = vpo
openr, 52, '/Users/brendan/IDL/bz_north/''+date+'.'ion.dat'
readf, 52, vect1
close, 52
dayp = vect1(0,*)
hourp = vect1(3,*)
minp = vect1(4,*)
secp = vect1(5,*)
timep = fltarr(1, LEP)
timep = hourp+minp/60+secp/3600
np = vect1(6,*)
temppyy = vect1(7,*)
temppzz = vect1(8,*)
tempp = vect1(7,*)*vect1(8,*)
Vxp = vect1(9,*)
vyp = vect1(10,*)
vzp = vect1(11,*)
convert from cv to kelvin
temppp = sqrt(temppyy^2 + temppzz^2)*11604.505
vp = sqrt((vxp*vxp+vyp*vyp+vzp*vzp))
vect3 = fltarr(12, MAGFIELD)
openr, 54, '/Users/brendan/IDL/BZ_north/`+date+`_B.dat'
readf, 54, vect3
close, 54

dayb = vect3(0, *)
hourb = vect3(3, *)
minb = vect3(4, *)
secb = vect3(5, *)
timeb = hourb + minb/60 + secb/3600
bx = vect3(6, *)
by = vect3(7, *)
bz = vect3(8, *)
XGE = vect3(9, *)
YGE = vect3(10, *)
ZGE = vect3(11, *)
b = sqrt(bx*bx+by*by+bz*bz)

vect5 = fltarr(262, FLUX)
openr, 55, '/Users/brendan/IDL/BZ_north/`+date+`_flux.dat'
readf, 55, vect5
close, 55

dayf = vect5(0, *)
monthf = vect5(1, *)
yearf = vect5(2, *)
hourf = vect5(3, *)
minf = vect5(4, *)
secf = vect5(5, *)
timef = hourf + minf/60 + secf/3600

e = vect4(6:264, *)
esunward = vect5(6:37, *)
eduskward = vect5(38:69, *)
etailward = vect5(70:101, *)
edawnward = vect5(102:133, *)
psunward = vect5(134:165, *)
pduskward = vect5(166:197, *)
ptailward = vect5(198:229, *)
pdawnward = vect5(230:261, *)

esunward2 = fltarr(FLUX, 32)
etailward2 = fltarr(FLUX, 32)
eduskward2 = fltarr(FLUX, 32)
edawnward2 = fltarr(FLUX, 32)
psunward2 = fltarr(FLUX, 32)
pduskward2 = fltarr(FLUX, 32)
pptailward2 = fltarr(FLUX, 32)
pdawnward2 = fltarr(FLUX, 32)
for i = 0, 31 do begin
for j = 0, FLUX-1 do begin
esumward2[j, i] = esumward[i, j]
eduskward2[j, i] = eduskward[i, j]
etailward2[j, i] = etailward[i, j]
edawnward2[j, i] = edawnward[i, j]
psunward2[j, i] = psunward[i, j]
pduskward2[j, i] = pduskward[i, j]
pailward2[j, i] = pailward[i, j]
pdawnward2[j, i] = pdawnward[i, j]
endfor
endfor
dor i = 0, 30 do begin
y[i] = 100 + 1300*i
endfor
time0 = fitarr(1,32)
for i = 0, 30 do begin
y[i] = 100 + 1300*i
endfor
time0_0 = time0 + guess/60.
xsw = vect4(14, where(time0 eq time0_0))
Vsw = vect4(9, where(time0 eq time0_0))
timesec = (xsw-XGE)^*6378)/\Vsw
timehou = timesec/60
timehou = timehou/60
time_alt = timehou/60
hoursw = hour(time0)
minsw = time0 - hoursw*60.
printvect = intarr(2,1)
printvect[0, *] = hoursw
printvect[1, *] = minsw
for i = 0, OMNI-1 do begin
print, time0_alt
Vpsh = interpol(vp, timep, time0_alt)
bl = interpol(b, timeb, time0_alt)
by = interpol(by, timeb, time0_alt)
bz = interpol(bz, timeb, time0_alt)
b_int = interpol(b, timeb, time0)
bp = interpol(bpx, time0)
by_int = interpol(by, timeb, time0)
bz_int = interpol(bz, timeb, time0)
bp = interpol(b, timeb, time0)
vpr = (bp * bx_int + by_int + bp * by_int + bp * bz_int)/(bp * bp)
vperp = sqrt(vp^2 - vpr^2)
THETA_BV = acos((vpx*bx_int+vpy*by_int+vz*bz_int)/(vp*b_int))*(180/pi)
THETA_BV = acos((vpx*bxo+vpy*byo+vzo*bo)/(vpo*bo))*(180/pi)
\[
\text{thetab} = \cos(bz/b) * (180/\pi)
\]

\[
\text{clock\_angle} = \arccos(bz/b) * (180/\pi)
\]

\[
\text{clock\_angle} = \arctan(\abs(Byo)/bzo) * (180/\pi)
\]

\[
\text{clock\_angle} = \arccos((\abs(bzo)/\abs(bzo)) * \sqrt{(byo^2 + bzo^2)}) * (180/\pi)
\]

\[
\byy = \abs(by)
\]

\[
\bbb = bx/b
\]

cone = 57.2958 * \cos(\bbb)

\[
\text{pdyn} = 1.6726e-5 \times \text{vpo}\times \text{vpo} \times \text{no} \times \left(1 + 4 \times 0.04\right)
\]

\[
\text{pp} = \text{np} * \left(1 + 4 \times 0.04\right) \times \text{tempp} * 1.3807e-8
\]

\[
\text{pno} = \text{no} \times \text{tempo} \times 1.3807e-8
\]

\[
\text{pt} = \text{pp} + \text{pm}
\]

\[
\text{pto} = \text{pno} + \text{pno}
\]

\[
\beta = \frac{\text{pp}}{\text{pm}}
\]

\[
\betao = \frac{\text{pno}}{\text{pno}}
\]

\[
\text{ma} = \frac{(\text{vpo}\times \sqrt{\text{no} \times \left(1+4\times 0.04\right)})}{(21.812 \times \text{bo})}
\]

\[
\text{ms} = \frac{\text{vp}}{\text{cs}}
\]

\[
\text{mms} = \frac{\text{ma} \times \text{ms}}{\text{ms} + \text{ma} \times \text{ma}}
\]

\[
\text{Vsh\_Vsw} = \text{vpsh}/\text{vpo}
\]

\[
\beta_{int} = \text{interpol}(\beta, \text{timep}, \text{timeo}\_alt)
\]

\[
\text{TBV} = \text{interpol}(\text{theta\_bv}, \text{timep}, \text{timeo}\_alt)
\]

\[
\text{vpo\_avg} = \text{moment}(\text{vect\_vpo}(0, \text{where}(\text{timeo eq timeo}\_2)-5: \text{where}(\text{timeo eq timeo}\_2)+5), \text{sdev} = \text{sigmav})
\]

\[
\text{clk\_avg} = \text{moment}(\text{clock\_angle}(0, \text{where}(\text{timeo eq timeo}\_2)-5: \text{where}(\text{timeo eq timeo}\_2)+5), \text{sdev} = \text{sigmac})
\]

\[
\text{MA\_avg} = \text{moment}(\text{ma}(0, \text{where}(\text{timeo eq timeo}\_2)-5: \text{where}(\text{timeo eq timeo}\_2)+5), \text{sdev} = \text{sigmam})
\]

\[
\text{pdyn\_avg} = \text{moment}(\text{pdyn}(0, \text{where}(\text{timeo eq timeo}\_2)-5: \text{where}(\text{timeo eq timeo}\_2)+5), \text{sdev} = \text{sigmap})
\]

print, 'Time Delay:', timemin

print, 'Projected time for SW monitor at time of event:', printvect

print, 'Average Solar wind speed : STD dev ', \text{vpo}\_avg[0], \text{sigmav}

print, 'Average clock angle : STD dev ', \text{clk\_avg}[0], \text{sigmac}

print, 'Average MA : STD Dev ', \text{MA\_avg}[0], \text{sigmam}

print, 'Average Pdyn : STD dev ', \text{pdyn\_avg}[0], \text{sigmap}

print, 'In-vec', 'Beta of the calculated parameters in the console', 'moment', 'print'

RatioMatrix = fltarr(10, OMNI)

ratioMatrix(0, *) = dayo

ratioMatrix(1, *) = montho

ratioMatrix(2, *) = yearo

ratioMatrix(3, *) = timeo_alt

ratioMatrix(4, *) = Vsh\_vsw
ratiomatrix(5,*) = MA
ratiomatrix(6,*) = pdyn
ratiomatrix(7,*) = clock_angle
ratiomatrix(8,*) = tbv
ratiomatrix(9,*) = beta_int
:print, ratiomatrix

NNN = floor((xrng2-xrng1)/ 25)
:print, ' Lx.tickv =', NNN
xv = fltarr(1,NNN+1)
for i = 0, NNN do begin
  xv[i] = xrng1 + (i*inc)
endfor
:print, 'NNN: ', NNN
:print, 'Xv: ', Xv

xval = xv

:p.charsize = 1.1
!P.charthick = 4
!x.thick = 2
!y.thick = 2
xsz = 8.5*100
ysz = 11.0*100
xcor = 1.0*100
xcorl = 7.5*100
xlen = 6.0000*100
ylen = 1.1000*100
!x.range = xrng
!xticks = NNN
!xticks = NNN
ycor = 9.6*100
ycorl = 10.5*100

yrng = [min(np),Max(np)]
!y.range = yrng
plot, timep, np, /noerase, ystyle = 1, $
yytitle = ', ytitle, '

pcharsize =0.01,xticklen =0.10, $
xtickv =xval, $
psym=-4,symsize =0.01, yrange = yrng, $
xminor =xxmin, xrange =xrng,thick = 2,$
position = [xcor/xsz,ycor/ysz,xcorl/xsz,ycorl/ysz]
oplot, timeo, npa, color = 250, thick = 3
plots, [xyotime1,xyotime1], [min(yrng),max(yrng)], color = 120, thick = 3
plots, [xyotime2,xyotime2], [min(yrng),max(yrng)], color = 120, thick = 3
!p.noerase = 1
ycor = 8.65*100
ycorl = 9.55*100

yrng = [min(temppyy), max(temppyy)]
!y.range = yrng

plot, timep, temppyy, /ylog, ystyle = 1, yrange = yrng,$
ytitle = 'V'Lpexp!N' $
\text{xchaisize} = 0.002, \text{xticklen} = 0.10,$
\text{xtickv} = xval, \text{thick} = 2, $
\text{yrang} = yrng, \text{ytickv} = yval, \text{ymnor} = 5, $
\text{xmmor} = xxmin, \text{range} = xrng, $
\text{position} = [xcor/xsz, ycor/ysz, xcorl/xsz, ycorl/ysz]

\text{plot}, [xyotime1, xyotime1], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{plot}, [xyotime2, xyotime2], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{p noerase} = 1
\text{ycoi} = 4.85*100
\text{yco1} = 5.75*100

\text{ying} = \text{mm}(vp), \text{max}(vp)
\text{yiange} = \text{mm}(vng)
\text{yrange} = \text{mm}(vng)

\text{plot, timep, vp,$}
\text{ytitle} = 'V'Lsh !N(V'Lsw!N)',$
\text{xchaisize} = 0.01, \text{xticklen} = 0.10,$
\text{xtickv} = xval, \text{thick} = 2, $
\text{yrang} = yrng, \text{ytickv} = yval, \text{ymnor} = 2, $
\text{xmmor} = xxmin, \text{range} = xrng, $
\text{position} = [xcor/xsz, ycor/ysz, xcorl/xsz, ycorl/ysz]
\text{oplot, timeo_alt, vpo, color} = 250, \text{thick} = 3
\text{plot}, [xyotime1, xyotime1], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{plot}, [xyotime2, xyotime2], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{p noerase} = 1
\text{ycor} = 3.90*100
\text{yco1} = 4.80*100

\text{ying} = \text{mm}(by), \text{max}(by)
\text{yiange} = \text{mm}(by)

\text{plot, timeb, by,$}
\text{ytitle} = 'B'Lx !N(B'Ly!N)',$
\text{xchaisize} = 0.01, \text{xticklen} = 0.10,$
\text{xtickv} = xval, \text{thick} = 2, \text{xtickv} = yval, \text{ymnor} = 4, $
\text{xmmor} = xxmin, \text{range} = xrng, \text{yrang} = yrng $
\text{position} = [xcor/xsz, ycor/ysz, xcorl/xsz, ycorl/ysz]
\text{oplot, timeb, by, color} = 60 \text{ thck} = 3
\text{plot}, [xyotime1, xyotime1], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{plot}, [xyotime2, xyotime2], [mm(ying), max(ying)], \text{color} = 120, \text{thick} = 3
\text{p noerase} = 1
\text{ycoi} = 2.95*100
\text{yco1} = 3.85*100

\text{yrng} = \text{mm}(bz), \text{max}(bz)
\text{yiange} = \text{mm}(bz)

\text{plot, timeb, bz,$}
\text{ytitle} = 'B'Lz !N(B'Lsw!N)',$
\text{xchaisize} = 0.01, \text{xticklen} = 0.10,$
xtickv = xval, thick = 2, 

yrng = ying, ytickv = yval, ymmnr = 5, 

xmmnr = xminrôrange = xing, 

position = [xcoi/xsz,ycori/ysz,xcorl/xsz,ycorl/ysz] 

oplot, timeo_alt,bzo, color = 250, thick = 3 
plots, [xyotime1,xyotime1], [min(ying),max(ying)], color = 120, thick = 3 
plots, [xyotime2,xyotime2], [min(ying),max(ying)], color = 120, thick = 3 

p noeiase = 1 
ycor = 2.00*100 
ycor1 = 2.90*100 

yrng = [min(beta),max(beta)] 

yrange = ying 

set yticks = 0 for logarithmic plots 

vticks = n_elements(yval)-1 

plot, timep beta, /ylog, $ 
ytitle = '4b SP'Lp'N P'Lm $ 

xcharsize = 0.001, xticklen = 10, $ 

xtickv = xval, thick = 2, yrange = ying, ystyle = 1; $ 

ymin = xmin, yrange = xing, $ 

position = [xcori/xsz,ycori/ysz,xcorl/xsz,ycorl/ysz] 

oplot, timep, pm color = 60, thick = 3 

oplot, timep, pp, color = 250, thick = 3 

plots, [xyotime1,xyotime1], [min(ying),max(ying)], color = 120, thick = 3 

plots, [xyotime2,xyotime2], [min(ying),max(ying)], color = 120, thick = 3 

p noeiase = 1 

eycor = 1.05*100 
ycor1 = 1.95*100 

yrng = [180 0] 
yval = [180, 135, 90, 45, 0] 

vticks = n_elements(yval)-1 

plot, timep, ThetaJBV, $ 
ytitle = T'lvbn (T'LeclBNv'N) $ 

xcharsize = 1, xticklen = 0.10, subtitle = 'UT', $ 

xtickv = xval, thick = 2, $ 

yrange = ying, ytickv = yval, ymmnr = 2, $ 

xmmnr = xmin, xrange = xing $ 

position = [xcoi/xsz,ycori/ysz,xcorl/xsz,ycorl/ysz] 

oplot, timeo_alt, clock_angle, color = 250, thick = 3 

plots, [xyotime1,xyotime1] [180,0], color = 120, thick = 3 

plots, [xyotime2,xyotime2], [180,0], color = 120, thick = 3 

device, /close 

end
APPENDIX E RESOURCES

Below is a list of online resources that are very useful for observational study of astrophysical plasmas.

Plotting data online
http://cdpp-amda.ces.h-DDHTML/index.html (only available on Internet Explorer and Firefox browsers)

Plotting data online and downloading data files
http://cdaweb.gsfc.nasa.gov/

Orbits
http://sscweb.gsfc.nasa.gov/

Day of Year conversions

Greek letters in IDL
http://www.astro.washington.edu/docs/idl/cgi-bin/getpro/library08.html?GREEK

Checking Latex code online
http://www.texify.com/links.php

Other LaTeX references
http://www.atopproblemsolving.com/Wiki/index.php/LaTeX Layout

A bunch of fun space weather resources
http://space.nice.edu/ISTP/

A database of magnetopause crossings is found at
http://ftpbrowser.gsfc.nasa.gov/magnetopause.html

A database of bow shock crossings
http://ftpbrowser.gsfc.nasa.gov/bow_shock.html
Here we derive the standoff distance of the bow shock by Farris and Russell based off the sonic mach number $M_s$. $M_s$ is used more traditionally in gas dynamics and describes the ratio of the speed of the gas compared to the speed of the sonic speed in the gas. In gas dynamics, the standoff distance of the bow shock to a rigid obstacle is given by Eq 19, where $\rho_1$ and $\rho_2$ are the upstream and downstream density respectively, $D$ is the radius of the obstacle, and $\Delta$ is the shock distance from the object

$$\frac{\Delta}{D} = 1 + \frac{\rho_1}{\rho_2}$$

(19)

The density ratio is related to the upstream sonic mach number and the ratio of specific heats $\gamma$ by

$$\frac{\rho_1}{\rho_2} = \frac{(\gamma + 1)M_s^2}{(\gamma - 1)M_s^2 + 2}$$

(20)

Therefore the standoff distance of the bow shock, $D_{BS}$, in comparison to that of the obstacle, $D_{OB}$, is given in Eq 21. This has been shown to effectively predict the standoff distance of the bow shock in the high $M_s$ limit where the flow approaches the gas dynamic relations. However, as $M_s$ (and $Ma$) become small, the bow shock is observed to move far upstream. When $M_s$ ($Ma$) approaches one, the flow speed is equal to the speed of an Alfven wave (or the Alfven speed $V_A$), and the shocking of the upstream flow is no longer needed because it is already 'subsonic' in comparison to $V_A$. Therefore, the bow shock no longer exists at $Ma, M_s = 1$

$$D_{BS} = D_{OB}[1 + \frac{1}{\gamma + 1}(\gamma - 1)\frac{M_s^2 + 2}{(\gamma - 1)M_s^2 + 2}]$$

(21)

To ensure that this occurs, a new relation is needed for the bow shock standoff distance. Therefore the substitution of Eq 22 into Eq 20 is made. This forces the bow shock to move upstream as $M_s$ increases.

$$\frac{M_s^2}{1 - M_s^2} \rightarrow \frac{\gamma - 1}{\gamma + 1}$$

(22)

$$D_{BS} = D_{OB}[1 + \frac{1}{\gamma + 1}(\gamma - 1)\frac{M_s^2 + 2}{(\gamma + 1)(M_s^2 - 1)}]$$

(23)

Finally, we arrive at a relation for the upstream standoff distance for the bow shock given in Eq 23. This relation is important because it gives us the proper limiting behavior of the bow shock for both high and low $M_s$ (and $Ma$), which is of great use in modeling the position of the bow shock for given upstream conditions. As is the case with the magnetopause, the bow shock is often modeled as a three dimensional paraboloid of revolution given in Eq 4. In gas dynamics, the standoff distance of the bow shock is dependant on the shape of the obstacle. A larger flaring parameter for the object, $a$, leads to a blunter object and a larger standoff distance. This is important in the high $M_s$ limit, however in general the standoff distance is much more dependant on the upstream $M_s$.

This derivation is likely more accurate than simply a conceptual picture. It has been shown that in taking the gas dynamic flow equations, a simple substitution of $Ma$ in the place of $M_s$ reproduces many of the qualitative results in MHD theory [Farrugia 1995].