## CONDITIONS AT THE MAGNETOPAUSES OF JUPITER AND SATURN AND IMPLICATIONS FOR THE SOLAR WIND INTERACTION

by

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Conditions at the magnetopauses of Jupiter and Saturn and implications for the solar wind interaction

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The nature of the solar wind interaction with the giant outer planets, Jupiter and Saturn, has not been well described or understood, due to limited measurements of the plasma conditions and magnetic fields at the magnetopauses of these planets. At Earth this interaction can be examined in depth with local spacecraft and measurements from the planet's surface. It is accepted that large-scale reconnection between the draped interplanetary magnetic field and planetary magnetic field is the dominant method by which the solar wind imparts mass and momentum to the terrestrial magnetosphere. When reconnection is suppressed, due to a parallel magnetic field configuration, viscous processes at the magnetopause mediate the interaction. At the outer planets, the environments in which this interaction takes place differ significantly from the terrestrial case, due to the changes in the solar wind with radial distance, along with the larger sizes of the magnetospheres and internal plasma sources at the moons Io and Enceladus.

Using idealized models of the magnetosheath and magnetosphere magnetic fields, plasma densities, and plasma flow, I test for the steady state viability of processes mediating the interaction between the solar wind and the jovian and kronian magnetospheres. The magnetopauses are modeled as asymmetric paraboloids with variable asymmetry. I test where on the magnetopause surface large-scale reconnection may be affected by either a shear flow or diamagnetic drift due to a pressure gradient across the magnetopause boundary. I also test for the onset of the Kelvin-Helmholtz instability. I find that while the onset of reconnection is highly sensitive to changes in solar wind and magnetosphere conditions at both planets, the Kelvin-Helmholtz instability on the dawn flanks of these magnetopauses is active independent of changes in these conditions. I use a hybrid code simulation to explore how changes in solar wind and magnetosphere conditions affect the growth rate of the Kelvin-Helmholtz instability as well as transportation of mass and momentum across the magnetopause boundary.

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## CHAPTER 1 INTRODUCTION

The study of space plasmas allows the scientific community to examine environments and interactions that cannot be replicated in the laboratory setting. The interaction between the solar wind plasma and magnetic field and the Earth's magnetic field has been studied in depth. Evidence of this interaction is visible from the surface of our planet via the aurora, and many spacecraft orbit Earth to investigate this interaction locally. Efforts to understand this interaction have led to developments in the theory of magnetic reconnection, as well as an understanding of instabilities that can develop at plasma boundaries.

At the giant planets Jupiter and Saturn the magnetopause boundary, where the interaction between the planet and the solar wind takes place, has properties that vary significantly from the terrestrial magnetopause boundary. These planets have larger magnetic dipole moments than Earth's dipole moment, as well as local sources of plasma (Io at Jupiter and Enceladus at Saturn); both of these fundamentally change the interaction of the solar wind with these planets and create phenomena that differ from the terrestrial case. Additionally, the solar wind undergoes changes as it travels from Earth to the outer planets. Understanding the nature of this interaction at Jupiter and Saturn allows us to broaden our knowledge of plasma boundaries in a space physics context. Limited spacecraft measurements and observation capabilities, however, have inhibited the ability of the scientific community to investigate and describe these interactions.

### The Solar Wind

state.

At  $\sim 1.5 \times 10^8$  kilometers from the Earth, the sun's influence is still felt on our day-to-day life. The sun produces a stream of ions and electrons, known as the solar wind, that enters interplanetary space at a nominal speed of  $\sim 400$  km/s. The solar wind is governed by Maxwell's equations and the fluid equations. Maxwell's equations are:

Gauss' law, 
$$\nabla \cdot \mathbf{E} = \frac{\rho_c}{\varepsilon_0} \tag{1}$$

Gauss' law for  
magnetisim
$$\nabla \cdot \mathbf{B} = 0$$
(2)Faraday's law of  
induction, $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ (3)

and Ampere's law, 
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$
(4)

where  $\rho_c$  is the charge density, **E**, **B**, and **J** are the electric field, magnetic field, and current density,  $\mu_0$  is the magnetic permeability in free space, and  $\varepsilon_0$  is the electric permittivity. The fluid equations for a charge neutral plasma of ions and electrons are:

2

the continuity  
equation,  
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{5}$$
$$\rho \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right) \mathbf{V} = \mathbf{J} \times \mathbf{B} - \nabla \mathbf{P} + \rho \mathbf{g}$$
(6)  
momentum  
equation,  
$$\rho \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right) \mathbf{V} = \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{\mu_0} - \nabla \left(\frac{B^2}{2\mu_0} + \mathbf{P}\right) + \rho \mathbf{g}$$
(6)  
and equation of  
$$\mathbf{P} \propto \rho^{\kappa} \tag{7}$$

2

where **V** is the bulk fluid flow velocity, **P** is the pressure tensor, **g** is the gravitational acceleration,  $\rho$  is the mass density and  $\kappa$  is the polytropic index.

The solar wind carries with it the magnetic field that emerges from the sun. This magnetic field, called the interplanetary magnetic field (IMF), and the plasma that makes up the solar wind interact with the planets and other bodies as they travel outward from the sun through interplanetary space. The IMF is assumed to be frozen-in, meaning that the plasma carries the magnetic field, because the gradient length scales are larger than the ion gyroradius ( $r_i = mv_{\perp}/q_iB$ ) and the plasma is taken to be infinitely conducting, such that Ohm's law simplifies to

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}.$$
 (8)

 $\langle 0 \rangle$ 

The IMF at Earth's orbit is oriented in a direction nearly parallel to the plane of the Earth's orbit around the sun, but at an angle of  $45^{\circ}$  relative to the line between the sun and the Earth. The magnetic field has a north-south component that can change direction randomly. As the distance from the sun increases, the properties of the solar wind plasma and IMF change. The solar wind density decreases with radial distance as  $1/r^2$ , as does the radial component of the magnetic field strength. The azimuthal component of the IMF falls off as 1/r. A detailed derivation of these relations can be found in *Hundbausen* [1995].

The angle of the IMF with radial direction changes due to the spiral motion of the magnetic field lines as they are dragged outward from the rotating Sun, as shown in Figure 1. The properties of the solar wind at the orbits of Earth, Jupiter, and Saturn, are summarized in Table 1. The solar wind properties at Earth are based on observation (reported in *Hundhausen* [1995]), while the properties at Jupiter and Saturn are based on scaling the terrestrial values.



Figure 1: Schematic of solar wind flow outward from the sun and resulting magnetic field structure (from *Kivelson* [1995], adapted from *Parker* [1963]). As the solar wind flows outward at ~400 km/s (arrows), the magnetic field lines connected to the rotating sun spiral outward.

	Earth (1 AU)	Jupiter (5.2 AU)	Saturn (9.5 AU)
Electron density [cm <sup>-3</sup> ]	7.1	0.26	0.079
Flow speed [km/s]	400	400	400
Magnetic field [nT]	7.0	1.3	0.74
Spiral angle (with radial direction)	45°	80°	85°

Table 1: Solar wind properties at Earth, Jupiter, and Saturn. Properties at Earth are observed, while values at Jupiter and Saturn are based on scaling laws.

#### The Terrestrial Magnetosheath and Magnetosphere

The solar wind plasma is collisionless – the mean free path between collisions is greater than the scale size of the system. Collisionless plasmas, when forced to undergo rapid changes in density, temperature, magnetic field strength, or speed, can develop a shock. When the solar wind is slowed from super-sonic to sub-sonic speeds, as happens when it approaches an obstacle such as a planet, a shock forms in front of the planet called the bow shock. A ratio of the plasma speed to the speed of sound, at which information is transmitted through the plasma, known as the Mach number, M, can be defined. Upstream of the planet's bow shock, the Mach number of the solar wind M > 1 and downstream M < 1. While the plasma conditions differ significantly on either side of the bow shock, the downstream conditions are dependent on the upstream conditions. Assuming conservation of mass, momentum, and energy across the shock leads to the Rankine-Hugoniot jump conditions, which relate the upstream to downstream conditions.

Downstream of the bowshock there is the magnetosheath, where the solar wind flows around the obstacle created by the Earth's magnetic field. The inner boundary of the magnetosheath is defined by the magnetopause, a current sheet separating the solar wind flow from the planet's region of influence, the magnetosphere. The magnetosphere is well constrained by the solar wind on the sunward side of the planet, but behind the planet, the magnetosphere can stretch back for several Earth radii ( $R_E$ ). The plasma flow streamlines in the terrestrial magnetosheath, derived from the Gas-Dynamic-Convected-Field (GDCF) model of *Spreiter* [1966], are shown in Figure 2. This is a fluid model of gas flow around an obstacle, which includes the convection of the magnetic field through the flow assuming that the magnetic field is frozen in to the flow, thus ignoring all magnetic forces. This model does not accurately describe the conditions right near the nose of the magnetopause, where flow becomes stagnated and magnetic forces begin to dominate, however it is still useful for understanding the general flow structure, density patterns, and draping of the magnetic field in the magnetopause. *Kallio & Koskinen* [2000] used the GDCF approach to develop a semi-empirical model of the terrestrial magnetosheath, allowing for variation in magnetosheath and magnetopause shape and symmetry.



Figure 2: Streamlines for supersonic flow past the terrestrial magnetopause (left) and plasma density contours (right). From *Walker & Russell* [1995], adapted from *Spreiter* [1966]. A gas dynamic convected field model is used, which combines a gas flow past the magnetopause with a convected magnetic field.

The magnetopause, the boundary between the magnetosheath and the magnetosphere, is a current sheet across which the plasma and magnetic field can change state. On the magnetosheath side of the terrestrial magnetopause the plasma population is predominately protons and electrons, and the magnetic field is the IMF that is draped over the magnetopause. On the magnetosphere side, the plasma is less dense, and the magnetic field results from the planetary dipole. The main sources of the plasma in the magnetosphere are the solar wind and the planet's ionosphere. At Earth, the magnetopause has a thickness of several hundred kilometers [*Berchem & Russell*, 1982], ~10 r; a magnetopause thickness on this scale has also been observed at Jupiter [*Sonnerup et al.*, 1981].

The size of the magnetopause and magnetosphere cavity that it encases is determined by a balance of the pressures on either side of the magnetopause. The distance between a planet and the nose of the planet's magnetosphere, also called the subsolar point, is known as the standoff distance. At Earth, the standoff distance is determined by balancing the solar wind dynamic pressure and the planetary dipole magnetic field pressure,

$$\rho_{SW} v_{SW}^2 = B_{MS}^2 / 2\mu_0 \tag{9}$$

where the subscripts SW and MS indicate solar wind and magnetosphere respectively. The plasma pressure in the magnetosphere is not included in this pressure balance because the plasma pressure is much smaller than the magnetic pressure.



Figure 3: Magnetic field lines in the noon-midnight meridian plane at Earth. Field lines are labeled to indicate the magnetic latitude at the earth. The earth's dipole is parallel to the  $Z_{GSM}$  axis. The solar wind flows in the  $-X_{GSM}$  direction. From *Wolf* [1995], originally from *Tsyganenko* [1982].

The simplest model of the magnetopause assumes that the magnetic fields and plasma flows normal to the surface are zero; this state is often referred to as a closed magnetopause. The magnetic field in the terrestrial magnetosphere is shown in Figure 3. The field is generally dipolar in structure, confined by the magnetopause on the dayside (sunward of the planet) and stretched out in the magnetotail behind the planet. For a dipole magnetosphere magnetic field,  $B_{MS} \propto r^{-3}$ , so Equation (9) implies that the standoff distance varies with solar wind dynamic pressure to a power of -1/6.

Parameters describing the terrestrial magnetosphere, as well as the magnetospheres of Jupiter and Saturn, are summarized in Table 2.

	Earth (1 AU)	Jupiter (5.2 AU)	Saturn (9.5 AU)
Planetary radius [km]	6,371	71,492	60, 330
Magnetic moment $[M_E]$	1	20,000	580
Spin axis tilt angle	23°	3°	26.73°
Magnetic axis tilt angle	10.8°	9.7°	<1°
Expected magnetopause distance	11 R <sub>E</sub>	45 R <sub>J</sub>	21 R <sub>s</sub>
Observed magnetopause distance	10 R <sub>E</sub>	60-90 R <sub>J</sub>	21-25 R <sub>s</sub>
Spin Period	24 hrs	10 hrs	10.5 hrs
Orbital Period	1 yr	11.9 yrs	29.5 yrs

Table 2: Magnetosphere properties at Earth, Jupiter, and Saturn

### The Solar Wind Interaction at Earth

The description of the terrestrial magnetosphere thus far has been of a closed magnetosphere– the case when the plasma flows and magnetic fields normal to the magnetopause surface are zero. The dynamics of the magnetosphere, however, are influenced by the interaction of the magnetosphere with the solar wind, and so there must be some way to "open" the magnetosphere to the solar wind. *Dungey* [1961] proposed that if the draped IMF and planetary magnetic field at the subsolar point reconnect, the planetary magnetic field will be dragged tailward by the solar wind flow. The magnetic field of the magnetosphere, now opened to the solar wind rather than connected to the planet at both north and south pole, eventually reconnects in the magnetotail. This process, known as the Dungey cycle, is shown schematically in Figure 4.



Figure 4: Schematic of the Dungey cycle from *Hughes* [1995]. The numbered magnetic field lines show the succession of configurations of the geomagnetic field as it reconnects with the IMF at the subsolar point. The inset shows the position of the feet of the numbered field lines at the northern ionosphere, the polar flows, and the region of active aurora.

For simplicity, the IMF has been drawn as southward, antiparallel to the planet's dipole field. In reality, the IMF is highly variable. In fact it is the variability of the IMF that supported Dungey's theory. *Fairfield* [1966] showed that geomagnetic activity was modulated by the north-south component of the IMF (relative to Earth's dipole field). When the IMF turns northward, and the magnetic fields on either side of the magnetopause are symmetric, reconnection at the subsolar point and the Dungey cycle are suppressed, though reconnection can still occur at high latitudes.

The process of reconnection is the basis for the Dungey cycle model of the solar wind interaction. A simplified schematic for reconnection is presented in Figure 5. A current sheet exists between two oppositely directed magnetic fields – like the magnetopause current sheet between the magnetosheath and magnetospheric magnetic fields.



Figure 5: Schematic of reconnection between two oppositely directed magnetic fields. There is an X-line of neutral magnetic field. In the diffusion region the magnetic field lines are no longer frozen-in to the plasma flow.

There is an inflow of plasma from both sides of the current sheet. The inflow flux must be matched by an outflow flux, and an X-line that is magnetically neutral is created. The magnetic fields from either side of the current sheet connect to each other in the central diffusion region, where the frozenin condition is violated. The plasma is ejected from the X-line region in a direction parallel to the reconnecting magnetic field. From energy conservation, the electromagnetic energy inflow to the reconnection region must equal the energy of the plasma outflow,

$$\frac{\rho v_0^2}{2} = B^2 / 2\mu_0$$

$$v_0^2 = \frac{B^2}{\rho \mu_0} = V_A^2$$
(10)

where  $V_A$  is the Alfven speed, the speed at which information travels along the magnetic field, and  $v_0$  is the plasma outflow speed from the reconnection region. Reviews of magnetic reconnection can be found in *Priest & Forbes* [2000] and *Pudovkin & Semenov* [1985].

Since Dungey's original proposal of a large-scale interaction between the solar wind and the magnetosphere, there have been numerous observations that support the theory. Observations of accelerated plasma flows, assumed to be the outflow from the reconnection site, have been made at Earth's magnetopause [*Sonnerup, et al.*, 1981]. Additionally observations of a normal component of the magnetic field are taken to be clear signatures of reconnection. In a closed magnetosphere, the normal component of the magnetic field is zero. When a normal component is present, there is a connection between the magnetosheath and the magnetosphere. Reconnection observations have been made for both a northward and southward component of the IMF, however the frequency of reconnection events decreases with southward IMF. A complete literature review of reconnection at the terrestrial magnetopause is beyond the scope of this thesis; the introductory paragraphs of *Trattner et al.* [2012] have a review of the current state of the field for reference.

An alternative description of the interaction of the solar wind with the terrestrial magnetosphere was developed by *Axford* [1961]. In this model, solar wind plasma crosses the magnetopause boundary through viscous interactions, such as diffusion and the Kelvin-Helmholtz (KH) instability. Through these viscous interactions, the magnetosphere flow can affect the magnetosphere flow and momentum. The KH instability is a shear flow-driven instability. Vortices that mix the plasma develop at the interface between the two plasma populations.

Reconnection mediated by the instability can then occur in several different ways, leading to plasma transport across the magnetopause boundary. At the early stage of development of the instability, compression of the magnetopause current layer can lead to reconnection if there are antiparallel in-plane components of the magnetic field on either side of the magnetopause [*Nakamura et al.*, 2006]. The vortices can twist and compress the magnetic field, causing reconnection in the plane of the vortices [*Nykyri & Otto*, 2001]. In addition, the vortices can twist the magnetic fields, causing reconnection at high latitude that can lead to the transport of momentum and plasma, as shown in the sketch on the right of Figure 6 [*Otto*, *A.*, 2008].

The criterion for destabilization is

$$[\mathbf{k} \cdot (\mathbf{v_1} - \mathbf{v_2})]^2 > \frac{n_1 + n_2}{4\pi m_0 n_1 n_2} [(\mathbf{k} \cdot \mathbf{B_1})^2 + (\mathbf{k} \cdot \mathbf{B_2})^2]$$
(11)

where **k** is the wave vector, **v** denotes velocity, *n* is the number density,  $m_o$  is the ion mass, **B** is the magnetic field, and the subscripts refer to the two regions across the boundary [*Hasegawa*, 1975]. A magnetic field component in the same plane as the shear flow can stabilize the KH instability, through the magnetic tension force, as indicated on the right side of Equation (11). It has been shown that when the IMF has a southward component, the Dungey cycle dominates the interaction of the solar wind with the magnetosphere, while when the IMF has a northward component, viscous interactions dominate this interaction.



Figure 6: Illustration of basic geometries for the KH instability at the magnetosphere flank from *Otto* [2000] (left). In (a) the wave vector is in the equatorial plane where the velocity shear is and the magnetic fields have small parallel (in plane) components. In (b) the wave vector has a component out of the plane. An illustration of the KH mode at the magnetospheric boundary is shown in (c). On the right is a sketch of the twisting of the magnetic fields that leads to reconnection at high latitudes (indicated by blue circles). The reconnection occurs in a KH stable region. The green arrows indicate the region of KH activity, where the vortices form, as shown in (c) on the left. [Delamere & Bagenal, 2010].

### The Magnetospheres of Jupiter and Saturn

There are many differences between the magnetospheres of the outer planets and the terrestrial magnetosphere, as outlined in Table 1 and Table 2. The outer planets are much larger than

Earth. While the internal planetary magnetic field is predominately dipolar in structure, as at Earth, the magnetic dipole moment is much greater at Jupiter and Saturn. However the magnetic field at the planets surfaces in the equatorial plane is only 10 times greater at Jupiter, and is actually smaller than at Saturn than at Earth, due to the larger size of these planets. The magnetosphere cavities are also much larger than at Earth.

A predominate difference between the outer planets and the terrestrial magnetosphere is the presence of internal plasma sources at the moons of Io (Jupiter) and Enceladus (Saturn). These plasma sources increase the plasma pressure in the equatorial region, so that Equation (9) is no longer valid, and the contribution of the plasma pressure in the magnetosphere must be included in the pressure balance to determine the magnetopause standoff.

In Jupiter's magnetosphere, the close proximity of the moon Io, at 5  $R_j$  (jovian radii), to the planet causes extreme tidal heating in the moon. This heating leads to Io being the most volcanic body in our solar system, losing ~ 1 ton/s of neutral material, mostly sulfur and oxygen. This material is ionized and forms a plasma torus near Io's orbit. Due to the rapid rotation of the planet, the plasma is confined to the centrifugal equator, defined by the farthest position from the planet along the magnetic field lines. The plasma spreads out through the magnetosphere due to an interchange instability, forming a plasmasheet. This instability is driven by the centrifugal force on the plasma at Io's orbit and the pressure gradient between the plasma-dense flux tubes and the less-dense flux tubes of the outer magnetosphere. The currents, which are required to maintain corotation of the plasma as it spreads outwards, distort the magnetic field, and outside of ~10  $R_j$  the field is no longer dipolar as it is at the Earth. Figure 7 is a schematic of the jovian magnetosphere. The non-dipolar nature of the magnetic field at both noon and midnight is apparent, as is the presence of the plasmasheet (collocated with the current sheet). The structure of the magnetic field will be discussed in more detail in Chapter



Figure 7: Schematic of the jovian magnetosphere showing the noon-midnight meridian (top) and equatorial cross-section (bottom). From *Khurana, et al.* [2004]. M indicates the magnetic axis direction;  $\Omega$  is the planet's spin axis direction. The cushion region is a region of less dense plasma; the origin of this region will be described in more detail in Chapter 2.

The presence of the dense plasmasheet in the jovian magnetosphere results in a cycle of plasma ejection down the magnetotail that is not present in the relatively plasma deficient terrestrial magnetosphere. This cycle was described in *Vasyliunas* [1983] and is pictured in Figure 8. As the plasma rotates with the planet and moves outwards, the field lines are stretched down the magnetotail until the plasmasheet thins to the point that reconnection can occur between the magnetic fields above and below the plasmasheet. Plasma blobs are released down the tail, and the now empty magnetic field lines rotate around into the dawn sector.



Figure 8: Schematic of the Vasyliunas cycle, showing the escape of plasma down the jovian tail via reconnection. The equatorial plane is shown on the left, the noon-midnight meridian is shown on the right. The arrows indicate the direction of plasma flow; the solid lines indicate the magnetic field. The plasma is corotating with the planet inside the dashed line. Outside of this line, centrifugal forces become too large and the magnetic X-line is formed, where reconnection occurs, as shown on the right [*Vasyliunas*, 1983].

At Saturn there is an additional plasma source at the moon Enceladus, located at 4  $R_s$  from the planet's center. Enceladus ejects water vapor from geysers in its southern hemisphere; approximately 100 kg/s is ionized forming a plasma torus and plasmasheet, similar to what was seen at Jupiter. This

plasmasheet distorts the magnetic field, however because it is less massive than the plasmasheet at Jupiter, the field is distorted less. The plasmasheet at Saturn has been observed to have a bowl like structure, shown in Figure 9. This structure is attributed to solar wind forcing on the highly tilted spin and magnetic axes of the planet [*Arridge et al.*, 2008].



Figure 9: Schematic illustrating the distortion of the plasmasheet in Saturn's magnetosphere from *Arridge et al.* [2008]. (B) shows a three-dimensional view of the distorted plasmasheet.

#### The Solar Wind Interaction at Jupiter and Saturn

At the terrestrial magnetopause, the roles of large-scale steady-state reconnection via the Dungey cycle and viscous interactions such as the Kelvin-Helmholtz instability are expected to vary depending on the north-south component of the IMF. The roles of both these processes have been extensively studied at Earth. At the outer planets, it cannot be assumed that the Dungey cycle is active in the same way, or that viscous interactions will necessarily be viable. The magnetic fields on either side of the magnetopauses of Jupiter and Saturn are weaker than at Earth. Whereas at Earth there is a

significant north-south component of the IMF, parallel/anti-parallel to the planet's dipole, at Jupiter and Saturn the IMF is oriented almost entirely in the orbital plane. Additionally, and perhaps most significantly, there are significant sources of plasma in the jovian and kronian (Saturnian) magnetospheres which create a high pressure plasmasheet in the equatorial regions of both planets.

There is a vast amount of evidence showing the properties of the solar wind interactions at Jupiter and Saturn are different than the properties at Earth. The size of Jupiter's magnetosphere is not what is expected based on the balance of pressures at Earth. At Jupiter, consideration of the magnetosphere plasma pressure is necessary in order to determine the magnetopause standoff distance. It then is reasonable to hypothesize that the plasma may affect the solar wind interaction in a way it does not at Earth.

In addition, evidence of reconnection has been sought at both planets. Flux transfer events (FTEs), short-lived reconnection events with a signature of a normal component to the magnetopause, were observed at Jupiter's magnetopause by the Pioneer and Voyager spacecraft [*Walker & Russell*, 1985]. These events were infrequent and very short lived; no evidence of steady-state reconnection was observed. Transit times from the subsolar point to the planet are of the order of many hours, on the time scale of the rotation of the planet [*McComas & Bagenal*, 2007]. The large size of the magnetosphere and rapid rotation of the planet make it difficult to imagine a global process that is able to be steady state. At Saturn observations of accelerated flows, indicative of the outflow from reconnection sites, were searched for and not found [*Lai et al.*, 2012]. This led *Lai et al.* [2012] to conclude that reconnection does not play a large-scale role in the interaction of the solar wind with Saturn's magnetosphere.

In contrast, the high shear flows at Jupiter and Saturn's magnetopause, due to the plasmasheets rotating with the planets and the solar wind flow in the magnetosheaths, create conditions necessary for the shear-flow-driven Kelvin-Helmholtz instability to be active. A model for



Figure 10: Schematic of solar wind interaction with Jupiter's magnetopause from *Delamere*  $\mathcal{O}$  Bagenal [2010]. Inside ~60 R<sub>J</sub> (the Alfvèn radius) the plasma flow is corotational. Beyond ~60 R<sub>J</sub>, radial outflow combines with rotation. Beyond ~80-100 R<sub>J</sub>, blobs of plasma detach and are shed down the tail of the magnetosphere. Strong velocity shear across the magnetopause drives the viscous interaction on both flanks.

the viscous interaction at Jupiter was proposed in *Delamere & Bagenal* [2010]; a schematic for this model is shown in Figure 10. In this model, beyond ~60 R<sub>1</sub>, radial outflow combines with rotation to

produce a spiral flow. Beyond  $\sim$ 80-100 R<sub>J</sub>, blobs of plasma detach as in the Vasyliunas cycle. Viscous interactions happen along the entire magnetopause boundary, but in particular far behind the planet where the shears on both flanks are large.

At Saturn there has been observational evidence of Kelvin-Helmholtz vortices on the dawn flank [*Masters, et al.,* 2009; *Wilson et al.,* 2012; *Masters et al.,* 2010]. Additionally, parameters from the Saturnian magnetopause have been input to hybrid-code simulations and the boundary has been shown to be KH unstable [*Delamere et al.,* 2011].

#### Outline of this thesis

In this thesis, I will use models of the plasma state and magnetic field at the magnetopauses of Jupiter and Saturn to explore the solar wind interaction at these planets. The models will be steadystate and idealized, but will allow for the analysis of whether large-scale reconnection, as in the Dungey cycle, can occur. I will also investigate how conditions at the magnetopause affect the onset of the Kelvin-Helmholtz instability. Many of the results regarding the solar wind interaction (Chapters 2-5) at Jupiter have been published in *Desroche et al.*, [2012], and presented at numerous conferences. The results regarding the solar wind interaction.

Chapter 2 describes the models employed in this study. These are the models that are used to describe the plasma flow, plasma density, and magnetic field on either side of the magnetopause boundaries at both planets.

Chapter 3 presents a study of the effect of the velocity shear across the magnetopause boundary on the onset of large-scale reconnection. I show that the large shears at the magnetopauses can, under certain constraints, restrict the onset of reconnection by inhibiting the plasma flow outward from the X-line region. Chapter 4 presents a study of the effect of a diamagnetic drift on the onset of large-scale reconnection. The diamagnetic drift is a fluid drift caused by a gradient in the plasma pressure across the magnetopause boundary. The drift convects the reconnection X-line; when the drift is larger than the plasma outflow speed, reconnection is suppressed.

Chapter 5 presents an analysis of the onset of the Kelvin-Helmholtz instability at the magnetopauses of Jupiter and Saturn. The high shear flows at both planets leads to a boundary that has significant regions of instability.

Chapter 6 describes a hybrid code simulation that is used to model the Kelvin-Helmholtz instability. The effect of variations in magnetic field and plasma conditions on either side of the boundary on the development of the Kelvin-Helmholtz instability vortices is explored.

Chapter 7 discusses the implications of my findings on future observations at both planets. Outstanding questions and implications for future work are also discussed.

## CHAPTER 2 MODELS EMPLOYED IN THIS THESIS

In this section I outline the models utilized to describe the conditions on either side of the magnetopause boundaries at Jupiter and Saturn. I begin by describing the coordinate systems, magnetopause shapes, and geometry. I employ a grid of points on the magnetopause surface as the basis of our models of the magnetic field, plasma flow, and plasma density in the magnetosphere and magnetosheath. Outputs from these models are used to evaluate how the conditions at the magnetopause affect steady-state large-scale reconnection and the onset of the Kelvin-Helmholtz instability.

Figure 11 provides an example of how model output is displayed on the magnetopause surface. For illustration, I have plotted plasma density in the magnetosheaths at the magnetopause surfaces of Jupiter (top) and Saturn (bottom) derived from the model of *Erkaev et al.* [1996] and *Farrugia et al.* [1998] described later in this chapter. The color-contoured surface is a two-dimensional projection of the paraboloid magnetopause surface. I use Jupiter-Solar-Orbital (JSO) coordinates throughout this paper when discussing Jupiter, with  $\hat{x}$  sunward,  $\hat{y}$  duskward, and  $\hat{z}$  normal to the planet's orbital plane. Grid lines are placed on the surface every 10 Jupiter radii (R<sub>j</sub>) along the X-axis for reference. The subsolar point is at ~92 R<sub>j</sub> and the plots continue tailward of the planet to -40 R<sub>j</sub>. In Figure 11 the interplanetary magnetic field (IMF) clock angle, the angle from the positive Z-axis, is 85°, and the magnetopause is highly oblate, with a ratio of the radii of curvature of 2. The asymmetry of the magnetopause will be discussed later in this chapter.



Figure 11: Plasma density in the magnetosheath at Jupiter's magnetopause surface (top) and Saturn's magnetopause surface (bottom). The color-contoured surface is a two-dimensional projection of the paraboloid magnetopause. At Jupiter, the JSO coordinate system is used, with X sunward (out of the plane), Z normal to the planet's orbital plane and Y perpendicular to both. Grid lines are placed on the surface every 10  $R_J$  along the X-axis for reference. In this case the magnetopause is highly asymmetric, with the polar axis much smaller than the equatorial axis in the noon meridian plane. The KSO coordinate system is employed at Saturn, with axes defined as at Jupiter. Gridlines are placed on the surface every 5  $R_s$ .

When discussing Saturn, I employ the Kronian-Solar-Orbital (KSO) coordinate system, with axes orientated as with the JSO coordinate system. Gridlines are placed on the surface plots of Saturn's magnetopause every 5  $R_s$ , and the magnetopause is oblate, with a ratio of the radii of curvature of 1.5. The subsolar point is at ~25  $R_s$ , and the plot continues tailward of the planet to -30  $R_s$ .

#### Magnetopause shapes at Jupiter and Saturn

In steady state a balance of the total external pressures and internal pressures determines the standoff distance of a magnetopause. The presence of a dense plasmasheet in the magnetosphere can result in a boundary that is highly responsive to the solar wind. While the terrestrial magnetopause standoff distance varies with the solar wind dynamic pressure to a power of -1/6, as would be expected with a dipolar magnetosphere magnetic field, at Jupiter it is shown to vary to a power of -1/4 to -1/5 [*Slavin et al.*, 1985; *Huddleston et al.*, 1998; *Joy et al.*, 2002] and at Saturn it is shown to vary to a power of -1/5 [*Kanani, et al.*, 2010].

Joy et al. [2002] combined spacecraft observations of Jupiter's bow shock and magnetopause boundary with magnetohydrodynamic (MHD) simulations to find a bimodal probability distribution of the magnetopause standoff distance of 63 and 92 R<sub>J</sub> corresponding to a compressed and expanded magnetopause boundary respectively. The solar wind dynamic pressures and associated errors corresponding to these distances are 0.306 (+0.108, -0.078) nPa (compressed) and 0.039 (+0.020, -0.014) nPa (expanded). I have restricted the jovian portion of this study to the expanded standoff distance,  $L_0$ , of 92 R<sub>J</sub>, because the magnetosphere magnetic field model I employ, discussed later in this chapter, only includes an expanded shape for the magnetopause, and does not include a variable magnetopause boundary. *Achilleos et al.* [2008] also reported a bimodal probability in the magnetopause standoff distance at Saturn, with normal distribution means at ~22 R<sub>s</sub> and ~27 R<sub>s</sub>. Again, due to the constraints of the magnetosphere magnetic field model, I am restricted to one standoff distance of ~25 R<sub>s</sub>.

While few direct observations of the high-latitude boundary at either planet have been made,  $Engle \Leftrightarrow Beard$  [1980] combined an equatorial current sheet based on Pioneer 10 observations at Jupiter with a dipole planetary field to create an idealized magnetic field model. Using the requirement that the magnetic field normal to the magnetopause boundary is zero, the magnetopause currents and the shape of the magnetopause necessary to close the magnetic field were calculated. They found that Jupiter's magnetopause shape was considerably flatter than would exist with only the dipole field, however they did not quantify the flattening.

Slavin et al. [1985] studied bow shock and magnetopause crossings from Pioneer 10 and 11 and Voyager 1 and 2 and found that at both Jupiter and Saturn the bow shock was closer to the magnetopause everywhere than predicted by gas dynamic modeling with a magnetopause that is axisymmetric about the X-axis. They concluded that the magnetopauses of Jupiter and Saturn must be flattened in shape, extended in the equatorial plane relative to the polar plane. This shape is thought to be due to the effect of increased centrifugal forces in the plasmasheets of Jupiter and Saturn. *Stahara et al.* [1989] included a non-axisymmetric magnetopause boundary in a gas dynamic convected field model. They varied the ratio, A/B, of the major (equatorial) to minor (polar) axes in the noon meridian plane, and found a ratio of ~1.75 to be consistent with the observed jovian bow shock location, and a ratio of ~1.25 to be consistent with the observed Saturnian bow shock location. The shapes of the magnetopause used in this thesis, based on this work, are described by

$$X = L_0 - \frac{Y^2}{2R_Y} - \frac{Z^2}{2R_Z}$$
(12)

with L<sub>0</sub> the magnetopause standoff distances of ~92 R<sub>j</sub> (Jupiter) and ~25R<sub>s</sub> (Saturn), R<sub>Y</sub> = 89 R<sub>j</sub> (Jupiter) and 34 R<sub>s</sub> (Saturn) determined from the average width of the magnetopause in the equatorial plane, and X, Y, and Z are all given in planetary radii. R<sub>Y</sub> and R<sub>z</sub> are the radii of curvature at the subsolar point, and are related to the major and minor axes in the noon meridian plane by R<sub>Y</sub>/R<sub>z</sub> = (A/B)<sup>2</sup>. Equation (12) describes a paraboloid that is flattened but does not include an east-west asymmetry. In order to explore how the onset of large-scale reconnection and the Kelvin-Helmholtz instability are affected by the magnetopause shape, I consider cases of  $(A/B)^2 = 1.25$ , 1.5, and 2 at Jupiter.  $(A/B)^2 = 1.25$  is the most symmetric shape, close to the terrestrial case of  $(A/B)^2 \approx 1$ .  $(A/B)^2$ = 2 is the most asymmetry of  $(A/B)^2 = 2.5$ . The magnetopause shape determined in *Stabara et al.* [1989] for Jupiter is even more oblate than the cases considered here, however I chose to use shapes that were not quite as extreme due to the lack of observational evidence confirming the *Stabara et al.* [1989] shape. At Saturn, I model the paraboloid as having a degree of asymmetry of  $(A/B)^2 = 1.5$ , which is the shape closest to the results of *Stabara et al.* [1989].

#### Model of conditions in the magnetosheaths of Jupiter and Saturn

It is necessary to develop a model of the solar wind flow around the magnetopause in order to understand the nature of the interaction between the solar wind and the magnetospheres of Jupiter and Saturn. A description of the plasma conditions (plasma flow, density, temperature, and pressure) and magnetic field draping in the magnetosheath permits the investigation of how large-scale reconnection and the Kelvin-Helmholtz instability are affected by these conditions. I use outputs from the MHD calculations of *Erkaev et al.* [1996] and *Farrugia et al.* [1998] to describe conditions in the magnetosheaths of Jupiter and Saturn. The deviation of the magnetopauses from axisymmetry results in variations in the magnetosheath flow from what is observed in the terrestrial magnetosheath. *Erkaev et al.* [1996] and *Farrugia et al.* [1998] investigated the nature of a 3-D magnetohydrodynamic (MHD) flow around a non-axisymmetric magnetopause. The magnetopause boundary used in their calculations is modeled as a tangential discontinuity with the shape described as in Equation (12) and the Rankine-Hugoniot jump conditions taken at the bow shock boundary, which is modeled as a hyperboloid. Pressure balance at the magnetopause is given by the Newtonian 'approximation' [*Petrinec & Russell*, 1997]. In this approximation the total pressure along the magnetopause is given by

$$P_M = p^{(0)} \cos^2 \phi \tag{13}$$

where  $p^{(0)}$  is the pressure at the subsolar point and  $\phi$  is the angle between the normal to the magnetopause and the direction of the unperturbed solar wind flow.

In the *Erkaev et al.* [1996] and *Farrugia et al.* [1998] MHD model (called the Erkaev model for the remainder of this thesis), the solar wind plasma is modeled as an electrically neutral, perfectly conducting (nondissipative) fluid. Maxwell's equations and the fluid equations (Equations 1-7) are the basis for the model, with the assumptions of charge neutrality and zero electric field force in the momentum equation. These equations are cast in terms of magnetic string equations, a procedure which is described in more detail in *Erkaev et al.* [1996]. They found the orientation of the IMF upstream of the bow shock significantly affects the properties of the magnetosheath as a consequence of the deviation from axisymmetry,. The asymmetry of the magnetopause causes a systematic rotation of the magnetic field in the magnetosheath towards the normal to the orbital plane. This is a result of increased plasma acceleration out of the equatorial plane and over the polar region of the magnetosphere, due to the streamlined shape of the boundary. As the asymmetry of the magnetopause increases, the degree of rotation also increases.
In addition, they found that the magnetic field in the magnetosheath exerts a strong influence on the plasma flow in the vicinity of the magnetopause. The magnetic tension force accelerates the plasma in a direction perpendicular to the magnetic field lines, causing the plasma flow streamlines at the magnetopause to curve away from the magnetic field lines. A stagnation line develops along which the plasma flow is zero. The direction of this stagnation line is dependent on the direction of the magnetic field at the magnetopause in the magnetosheath [*Erkaev et al.*, 2012]. The development of this line is independent of the asymmetry of the magnetopause. In the case of an axisymmetric magnetopause, the stagnation line is coplanar with the IMF, however the magnetopause asymmetry rotates this line as it does the magnetic field [*Farrugia et al.*, 1995].

Additionally, a magnetic barrier region, also called a plasma depletion layer, is found to develop near the magnetopause, through which the plasma density decreases, due to the compression of the magnetic field in the magnetosheath [Zwan O Wolf, 1976]. The thickness of this magnetic barrier/plasma depletion layer along the sun-planet line (X-axis in JSO/KSO coordinates) is dependent on the IMF orientation for the case of the asymmetric magnetopause shapes. Both the plasma depletion layer and the acceleration of plasma perpendicular to the stagnation line/magnetic field direction have been observed at Earth [*Biernat et al.*, 2000], and there is evidence for the plasma depletion layer at Jupiter [*Richardson*, 2002].

The results of Erkaev model calculations are used in this paper to describe the conditions in both Jupiter and Saturn's magnetosheaths. The calculation results are given along streamlines from the bowshock to the magnetopause surface. These results are then interpolated onto the magnetopause surface using the IDL routine GRIDDATA, and a 2-D grid with dimensions corresponding to the X-axis and an angle,  $\alpha$ , where  $\alpha = \tan^{-1}\left(\frac{z}{r}\right)$ . Resolution is 0.1 R<sub>J</sub> (R<sub>s</sub>) along X and 1° in  $\alpha$ . Based on measurements of typical solar wind conditions at the orbits of both planets the solar wind sonic Mach number is taken to be equal to 10 and the Alfvén Mach number is equal to 8 for the MHD calculations. Several orientations of the IMF were considered, four are presented here as typical results. The calculation results are normalized to solar wind conditions. The solar wind parameters used in the MHD calculations, based on various spacecraft observations [*Joy et al.*, 2002; *Jackman & Arridge*, 2011; *Achilleos et al.*, 2006; *Jackman et al.*, 2008] are summarized in Table 3 and agree with basic scaling laws of the magnetic field and plasma density (see Table 1).

	V <sub>sw</sub>	n <sub>sw</sub>	P <sub>d</sub>	M <sub>A</sub>	M <sub>s</sub>	$ \mathbf{B}_{\mathrm{IMF}} $
Jupiter	400 km/s	0.168 cm <sup>-3</sup>	0.045 nPa	8	10	0.94 nT
Saturn	400 km/s	0.064 cm <sup>-3</sup>	0.017 nPa	8	10	0.58 nT

Table 3: Solar wind parameters for scaling results of MHD calculations. Parameters are based on observations from several spacecraft.



Figure 12: Plasma density in the jovian magnetosheath, normalized to the solar wind density. Two IMF clock angles, 85° (left column) and 95° (right column) are considered. Magnetopause shapes of  $(A/B)^2 = 1.25$  (top), 1.5 (middle), and 2 (bottom) are presented. The 3D paraboloid surface is projected into 2D, with X-JSO from -40 R<sub>J</sub> to ~90R<sub>J</sub> at the subsolar point. In the case of the least oblate magnetopause (top), the bulk of the plasma remains near the equatorial plane. As the asymmetry of the magnetopause increases, the stagnation line, where the plasma density is enhanced, moves out of the equatorial region.

Plotted in Figure 12 is the plasma density in the jovian magnetosheath from the *Erkaev et al.* [1996] calculations, normalized to the solar wind density. Three magnetopause shapes,  $(A/B)^2 = 1.25$  (top), 1.5 (middle), and 2 (bottom) are presented, along with two IMF clock angles, 85° (left column) and 95° (right column) with respect to the planetary axis of rotation. In all



Figure 13: Plasma density in Jupiter's magnetosheath, normalized to the solar wind density. Four IMF clock angles,  $85^{\circ}$  (top left),  $95^{\circ}$  (top right),  $-95^{\circ}$  (bottom left) and  $-85^{\circ}$  (bottom right) are considered. Only the most asymmetric magnetopause shape, with  $(A/B)^2 = 2$  is shown. The cases of  $85^{\circ}$  and  $-95^{\circ}$  have identical patterns of the plasma density and stagnation line, as well as the cases of  $95^{\circ}$  and  $-85^{\circ}$ .

cases there is a region of enhanced density at the subsolar point, where the flow is stagnated. As the asymmetry of the magnetopause boundary increases, the stagnation line along which the density is enhanced is rotated out of the equatorial plane. The width of the enhanced density region also appears to increase with increasing asymmetry. Changing the clock angle by 10°, so that it has a negative Z-component rather than a positive Z-component, rotates the orientation of the stagnation line with respect to the orbital plane.

In Figure 13 the plasma density in Jupiter's magnetosheath is plotted as in Figure 12 for four IMF clock angles, 85° (top left), 95° (top right), -95° (bottom left), and -85° (bottom right). The top row of Figure 13 is the same as the bottom row of Figure 12. Only the most asymmetric case of  $(A/B)^2 = 2$  is presented, which is the asymmetry closest to the magnetopause shape found for Jupiter in the (Stahara, Rachiele, Spreiter, & Slavin, 1989) calculations. The cases of 85° (95°) and -95° (-85°) have identical plasma density patterns, demonstrating that clock angles 180° apart result in similar plasma magnetosheath conditions.

In Figure 14 the plasma density in Saturn's magnetosheath from the Erkaev model is plotted. Two IMF clock angles,  $85^{\circ}$  (left) and  $95^{\circ}$  (right) are shown. The magnetopause is asymmetric, with an oblateness of  $(A/B)^2 = 1.5$ . The density is enhanced near the orbital plane, with a rotation from north to south on the flanks when the IMF clock angle rotates. For the most asymmetric jovian magnetopause the density is more enhanced near the orbital plane than at Jupiter (Figure 12, Figure 13).



Figure 14: Plasma density in Saturn's magnetosheath for two clock angles,  $85^{\circ}$  (left) and  $95^{\circ}$  (right), normalized to the solar wind density. The magnetopause asymmetry is  $(A/B)^2 = 1.5$ . The density is more concentrated near the orbital plane than at Jupiter (Figure 13)

The plasma flow speed and direction in Jupiter's magnetosheath as calculated in the Erkaev model, is plotted in Figure 15. The magnetopause shapes and IMF clock angles are the same as in Figure 12. The IMF orientations and magnetopause shapes are as in Figure 12. Flow is stagnated at the subsolar point for all IMF orientations. In all cases flow is symmetric outward from the stagnation point. Flow reaches solar wind values on the flanks in the case of the most oblate magnetopause shape (bottom), while in the case of the more symmetric magnetopause, the flow speed is increased above the poles. In all cases, the flow is symmetric about the stagnation line defined by the magnetic field orientation in the magnetosheath at the subsolar point. Due to the rotation of this line for increased asymmetry, the maximum flow speeds are rotated towards the magnetosphere flanks. It



Figure 15: Plasma flow in Jupiter's magnetosheath at the magnetopause, normalized to the solar wind flow. The IMF orientations and magnetopause shapes are as in Figure 12. Flow is stagnated at the subsolar point for all IMF orientations. In all cases flow is symmetric outward from the stagnation point. Flow reaches solar wind values ( $\sim$ 400 km/s) on the flanks in the orbital plane in the case of the most oblate magnetopause shape (bottom) while in the case of the more symmetric magnetopause, the flow speed is increased above the poles.

must be noted that the directional arrows are not organized along streamlines; the apparent spiraling is just an artifact of the points chosen to plot and not a real effect.

In Figure 16 the flow in the jovian magnetosheath is plotted for the cases originally presented in Figure 13 where again, the top row of Figure 16 is the same as the bottom row of Figure 15. The cases of 85° (top left) and -95° (bottom left) are indistinguishable, as are the cases of 95° (top right) and -85° (bottom right), a pattern also observed in the plasma density plots of Figure 13.



Figure 16: Plasma flow in Jupiter's magnetosheath, normalized to the solar wind speed. The IMF clock angles and magnetopause shape is as in Figure 13. The flow patterns, magnitude and direction, are indistinguishable between the cases of  $85^{\circ}$  and  $-95^{\circ}$ , and between the cases of  $95^{\circ}$  and  $-85^{\circ}$ , a symmetry that was also observed in the plasma density (Figure 13). The plasma speed returns to solar wind values (~400 km/s) on the flanks in the orbital plane tailward of the planet.

This is due to the identically oriented stagnation line in these cases.

In Figure 17 the plasma flow in Saturn's magnetosheath, normalized to the solar wind speed, is plotted. The magnetopause asymmetry is given by  $(A/B)^2 = 1.5$ , and two IMF clock angles, 85° (left) and 95° (right) are presented as in Figure 14. The plasma flow is more stagnated in the orbital plane than at Jupiter (Figure 16), only reaching speeds of ~200 km/s. Due to the smaller size of the magnetopause, the stagnation region relative to the total size of the magnetopause surface is larger than at Jupiter.



Figure 17: Plasma flow in Saturn's magnetosheath, normalized to the solar wind speed. The cases presented are the same as in Figure 14, with a magnetopause asymmetry of  $(A/B)^2 = 1.5$  and two IMF clock angles presented. The flow is more stagnated in the orbital plane than for the most asymmetric case at Jupiter. Flows only reach ~200 km/s, even far tailward of the planet.

In Figure 18 the magnetic field in Jupiter's magnetosheath at the magnetopause, normalized to the maximum magnetic field is plotted for the cases originally presented in Figure 12. The maximum magnetic field varies between 8.6 and 9.2 nT depending on magnetopause shape. The region of the stagnation line exhibits slightly weaker fields than the surrounding surface, due to the increased plasma



Figure 18: Magnetic field in Jupiter's magnetosheath at the magnetopause, normalized to the maximum magnetic field. The IMF orientations and magnetopause shapes are the same as in Figure 12. In all cases the magnetic field reaches a maximum near the subsolar point. Maximum values of the field are 9.2 nT (top), 8.8 nT (middle), and 8.6 nT (bottom). As the oblateness of the magnetopause increases, there is a rotation of the field towards alignment with the planetary rotation axis. This results in a field that is almost coplanar with the IMF for the least asymmetric case (top) but almost perpendicular to the IMF for the most asymmetric case (bottom).

density and pressure in this region, and the requirement of total pressure balance. The field is maximized near the subsolar point, where there is a compression of the field lines in the magnetosheath. As the magnetopause asymmetry increases, the magnetic field is rotated to the same degree as the stagnation line. The region of increased magnetic field strength is rotated further onto the flanks.

The influence of changing the sign of the Y-component (East-West) of the IMF is explored in Figure 19. The same cases as in Figure 12 are presented. Rotating the field 180°, such as from 85° (top



Figure 19: Magnetic field in Jupiter's magnetosheath at the magnetopause, normalized to the maximum magnetic field. Four IMF clock angles are shown, for the most asymmetric magnetopause shape. The top row of this figure is the same as the bottom row of Figure 18. When the field is rotated by 180° (85° to -95° and 95° to -85°), the pattern of the magnitude of the field stays the same, but the direction of the field on the flanks rotates by 180°, resulting in four distinctly different magnetic field configurations.

left) to -95° (bottom left) and 95° (top right) to -85° (bottom right), results in a field magnitude pattern that does not change, but this rotation does change the direction of the magnetic field. This results in four distinctly different magnetic field configurations in the magnetosheath, even though there are only two distinctly different plasma configurations (Figure 14 and Figure 17).

In Figure 20 the magnetic field in Saturn's magnetosheath at the magnetopause is plotted, normalized to the maximum magnetic field. The maximum magnetic field is 5.11 nT. As at Jupiter, the field is maximized near the subsolar point and minimized along the stagnation line where the density and plasma pressure is increased. The field points mostly East-West near the subsolar point, but rotates slightly more towards the Z-axis on the flanks. I do not consider here the effect of reversing the Y-component of the magnetic field, but note that the effect would be similar to Figure 19.



Figure 20: Magnetic field in Saturn's magnetosphere, normalized to the maximum magnetic field of 5.11 nT. The magnetopause asymmetry is  $(A/B)^2 = 1.5$ , and two IMF clock angles are presented, as in Figure 14. The field is maximized near the subsolar point, where the field is compressed in the magnetosheath.

The rotation of the magnetic field can be observed in Figure 21 where  $|B_z|$  (normalized to |B|) in the jovian magnetosheath is plotted. This rotation is not observed at the symmetric magnetopause of Earth, and results in a magnetic field in the magnetosheath that is quite unexpected based solely on solar wind IMF observations. This rotation results in an unexpected field geometry at the magnetopauses of Jupiter and Saturn, where the field can be rotated almost parallel/antiparallel to the planet's dipole field, creating conditions more favorable for large-scale reconnection and the KH instability.

In Figure 21 the same cases as in Figure 12 are presented, and the role of the magnetopause asymmetry on the field rotation can be clearly observed. As the asymmetry increases, the field is rotated towards perpendicular with the orbital plane, and the region of maximum rotation is shifted towards the orbital plane. In the case of the highly oblate magnetopause, with  $(A/B)^2 = 2$ , the field is completely antiparallel (left) or parallel (right) with the normal to the orbital plane, which is essentially parallel to the planet's dipole. This means as the solar wind flows from the subsolar point along the flanks of the magnetopause there is almost a 90° rotation of the field.

Figure 22 shows the Z-component of the magnetic field in Jupiter's magnetosheath for the cases originally presented in Figure 13, normalized to the total field. Cases with the same orientation of the stagnation line, 85° (top left) and -95° (bottom left) or 95° (top right) and -85° (bottom right) exhibit identical patterns in  $|B_Z|$ . However, the direction of the field reverses in these cases – the field will be northward on both flanks for 85° and -85° and southward on both flanks in the cases of 95° and -95°.

In Figure 23, the Z-component of the magnetic field in Saturn's magnetosheath is plotted for the cases presented in Figure 14. Since the magnetopause is not as asymmetric as the most asymmetric case at Jupiter, the field rotation on the flanks is not as significant. Furthermore the region of maximum rotation is not collocated with the orbital plane.



Figure 21: Z-component of the magnetic field in Jupiter's magnetosheath, normalized to the total field. The same magnetopause shapes and IMF clock angles as in Figure 12 are presented. In all cases there is a region of enhanced  $B_z$ . As the asymmetry of the magnetopause increases, this region rotates towards the equator and increases in magnitude. For the most asymmetric magnetopause shape, in the bottom row, the field on the flanks tailward of the planet are completely anti-parallel (left) or parallel (right) to the normal to the orbital plane; this direction is approximately parallel to the planet's dipole.



Figure 22: Z-component of the magnetic field in Jupiter's magnetosheath, normalized to the total field strength. The same cases as in Figure 13 are presented. Cases with the same orientation of the stagnation line (85° and -95°; 95° and -85°) exhibit identical patterns in the magnitude of  $B_z$ , however the direction of  $B_z$  is opposite in these cases.

Lepping et al. [1981] analyzed observations of Jupiter's magnetosheath by Voyager 1 and 2. They found that the magnetic field in the magnetosheath on the dawn flank was predominately northsouth, despite the east-west orientation of the IMF at Jupiter's orbit. This agrees with the rotation of the magnetic field in the magnetosheath in the Erkaev model. Additionally, *McAndrews et al.* [2008] looked at two magnetopause crossings by Cassini on Saturn's dawn magnetopause flank. They found that the field in the magnetosheath was predominately northward, suggesting again that the field is rotated from the IMF orientation in the magnetosheath.



Figure 23: Z-component of the magnetic field in Saturn's magnetosheath. The same cases as in Figure 14 are presented. The field never completely rotates towards perpendicular with the orbital plane as it does at Jupiter, and the regions of maximum rotation are at higher latitudes than at Jupiter.

### Jupiter's magnetosphere magnetic field model

In addition to the description of the plasma and magnetic field in the magnetosheath, a description of the plasma and magnetic field in the magnetosphere at the magnetopause boundary is needed to understand the interaction region between the plasmas on either side of the magnetopause. Due to limited observations of the plasma and magnetic fields in the outer magnetospheres of Jupiter and Saturn, I employ global empirical models to describe the magnetic fields and plasma in the jovian and kronian magnetospheres. In this and the following sections I describe the features and limitations of these models.

The basis for modeling Jupiter's magnetic field is the planet's internal field, but as a result of the corotating or subcorotating plasmasheet the magnetic field becomes more complicated farther from the planet. As the plasma rapidly rotates, it exerts a centrifugal stress on the magnetic field lines. The radial pressure gradient of the hot plasma provides an additional stress, resulting in field lines that are stretched out away from Jupiter. *Connerney et al.* [1981] accounted for these stresses by modeling the magnetic field as the internal field plus an azimuthally symmetric ring of current stretching from 5 to 50 R<sub>J</sub>. Radial currents that transfer momentum from the planet to the plasma in order to enforce corotation contribute an azimuthal component to the magnetic field in the magnetosphere. At large distances ( $\geq 40 \text{ R}_J$ ) from the planet, local time asymmetries also develop, and the *Connerney et al.* [1981] field model is no longer valid.

*Kburana* [1997] and *Kburana*  $\Leftrightarrow$  *Shwarzf* [2005] developed an empirical model of the jovian magnetic field out to ~100 R<sub>j</sub> based on magnetometer data from multiple Galileo orbits, which includes both the azimuthal and radial currents. The Khurana magnetic field model agrees with Galileo magnetometer data within ~150 R<sub>j</sub>. The model includes magnetopause currents in order to close the magnetic field within the magnetosphere. The field, as illustrated in Figure 24, exhibits a significant dawn-dusk asymmetry in addition to the stretching of the magnetic field lines. The field lines are significantly more bent back on the dawn flank than on the dusk flank. Although the stretching of the magnetic field is more pronounced in the tail, where the magnetopause does not confine the magnetic field, the field lines are stretched out from a dipolar configuration throughout the entire magnetosphere. The shape of the magnetopause surface in the Khurana field model is axisymmetric about the X-axis. The angle between the spin axis and the normal to the orbital plane (Z-axis in JSO coordinates) is ~3°. The angle between the spin axis and the magnetic axis is ~10°, causing the magnetic equator/plasmasheet to flap up and down as the planet spins. I consider in this thesis only the case where the dipole is tilted such that the center of the plasmasheet is collocated with the orbital plane on the dawn flank.



Figure 24: Schematic of the currents associated with the magnetosphere magnetic field, and field line tracings from the Khurana magnetic field model. Azimuthal and radial currents lead to magnetic field lines that are both stretched out and bent back. The noon-midnight asymmetry of the field due to the imposed magnetopause boundary is seen in (c), while the dawn-dusk asymmetry is observed in (d).

The Khurana magnetic field model for Jupiter's magnetosphere is written in FORTRAN. The model combines a spherical harmonic model of the planet's magnetic field with a Euler potential formulation of the external field due to the currents in the plasmasheet and along the magnetopause. A small penetration of the IMF is also included. Inputs to the model are position in right-handed spherical system III coordinates and date/time. System III is a commonly used coordinate system that rotates with the planet. Outputs are the three components of the magnetic field in Cartesian-SIII and the height of the current sheet at the input location.

In order to develop a grid of magnetic field values at the magnetopause, I stepped along the Xaxis from -40 R<sub>J</sub> to the maximum subsolar point in steps of 0.2 R<sub>J</sub>. At each point along the X-axis, I rotated through an angle  $\alpha$  where  $\alpha = \tan^{-1} (Z/Y)$ . Because the shape of the magnetopause is symmetric, I stepped out along the cylindrical radius,  $\rho = \sqrt{Y^2 + Z^2}$  until I reached the magnetopause surface. A transformation from the JSO coordinates to System III allows for input to the Khurana FORTRAN code in order to calculate the magnetophere magnetic field at the magnetopause.

In Figure 25, the magnetic field in Jupiter's magnetosphere for the three asymmetric magnetopause shapes is plotted. The color contour is the magnitude of the magnetic field; the arrows show the direction of the field. The different magnetopause shapes show only slight variations in the magnetic field at high latitudes, due to the projection of the symmetric (around  $\hat{x}$ ) magnetopause of the Khurana magnetic field model onto the asymmetric magnetopause shapes. For all three cases, the magnetic field is maximized on the dusk flank and subsolar region, with strengths of 5-10 nT. The field is dipolar in the equatorial plane in these regions, pointing southward along the subsolar region and dusk flank. On the dawn flank, the significant bend back of the field can be observed. North of the orbital plane the magnetic field is directed tailward, while south of the orbital plane the field points sunward. There is a significant rotation of the magnetic field direction across the orbital plane.



Figure 25: Magnetosphere magnetic field at Jupiter for the three magnetopause shapes originally presented in Figure There are only slight 12. differences between the magnetopause shapes, due to the projection of the field at the symmetric magnetopause onto the asymmetric magnetopause surfaces. The field is maximized along the dusk flank and subsolar region, with strengths of 5-10 nT. The arrows show the direction of the field. The field is dipolar, southward pointing, through the subsolar region and dusk flank. On the dawn flank, the bend back of the field is clearly observed. North of the orbital plane the field points tailward, while south of the orbital plane the field points sunward.





Figure 26: Comparison of magnetopause shapes at Jupiter (A) and Saturn (B). In (A), the blue dashed line shows the magnetopause boundary for the most asymmetric magnetopause  $([A/B]^2 = 2)$  in the dawn-dusk meridian plane for the asymmetric magnetopause model used in the (Erkaev, Farrugia, & Biernat, 1996; Farrugia, Biernat, & Erkaev, 1998) MHD simulations, the purple line shows the shape for  $[A/B]^2 = 1.5$ , and the red line shows the shape for  $[A/B]^2 = 1.25$ . In (B), the red dashed line shows the asymmetric magnetopause shape in the dawn-dusk meridian at Saturn. The black lines show the symmetric magnetopause shape employed in the Khurana magnetophere magnetic field models.

plane. Within  $\sim 50 \text{ R}_{\text{J}}$  of the equatorial plane, the deviation between the cylindrical magnetopause radii of the symmetric and asymmetric shapes is less than 10%. At higher latitudes, the error in projecting

the Khurana magnetic field model onto the asymmetric magnetopause boundary is large enough to limit the validity of our results in these regions. The Khurana magnetic field values are gridded using the IDL routine GRIDDATA as the Erkaev calculation results are.

An alternative jovian magnetic field model was developed by *Alexeev & Belenkaya* [2005]. The Alexeev model does not include an asymmetric magnetopause either, and unlike the Khurana field model is not based on spacecraft observation. This model is dynamic, in that a variation of the solar wind dynamic pressure can be included, changing the magnetopause standoff while still closing the magnetosphere magnetic field. The model does not, however, include the bend back of the field lines, which will be an important factor when considering the relative magnetic field orientations and stabilizing forces at the magnetopause. Eventually, including a variable magnetopause with a spacecraft observation based model such as the Khurana magnetic field model will improve these static models and our understanding of global magnetosphere dynamics.

## Saturn's magnetosphere magnetic field model

*Khurana et al.* [2006] developed an empirical model of Saturn's magnetic field based on magnetometer data from the Cassini spacecraft. The model includes magnetopause currents to close the magnetic field within the magnetosphere. *Carbary et al.* [2010] binned an updated set of Cassini observations and found that the magnetic field structure generally agrees with the magnetic field developed by *Khurana et al.* [2006]. The shape of the magnetopause surface in the Saturn Khurana field model is axisymmetric around the X-axis and is based on the model of *Arridge et al.* [2006]. The Arridge magnetopause model size varies with the solar wind dynamic pressure and is fit to magnetopause crossings from Cassini and Voyager, which are generally limited to regions close to the equator. The Saturn Khurana magnetic field model does not include a dynamic magnetopause and instead assumes a nominal solar wind dynamic pressure of 0.017 nPa to determine the size and shape of the magnetopause. The asymmetric magnetopause shape (Equation (12)) and the axisymmetric shape employed in the Khurana field model are compared in Figure 26B.

As with Khurana's magnetic field model at Jupiter, the Saturn magnetic field model is written in FORTRAN and combines a spherical harmonic model of the planet's field with a Euler potential model for the currents in the plasmasheet and magnetopause. Inputs to the model include location in kronian System III and date/time. The corresponding outputs are the three components of the magnetic field in Cartesian-SIII and the height of the current sheet at the input location. In order to develop a grid of magnetic field values at the magnetopause, I stepped along the X-axis from -40 R<sub>s</sub> to the maximum subsolar point. At each position along the X-axis, I rotated through an angle  $\alpha$  where  $\alpha$ = tan<sup>-1</sup> (Z/Y). Because the shape of the magnetopause is symmetric, I stepped out along the cylindrical radius until I reached the magnetopause surface, rotated from JSO to System III coordinates, and then used the Saturnian Khurana magnetic field model to calculate the magnetic field.

At Saturn, the spin axis is tilted  $\sim 23^{\circ}$  with respect to the normal to the orbital plane. The magnetic axis is approximately aligned with the spin axis. As the planet orbits the sun with a period of  $\sim 29.5$  terrestrial years, the angle between the planet's magnetic axis/spin axis and the sun-planet line changes, changing the seasons on the planet. This in turn changes the magnetic field at the magnetopause significantly. In this thesis I present four orientations of the planet's spin axis – with the north pole directed towards midnight (winter in the northern hemisphere), dawn, noon, and dusk to explore how the solar wind interaction will vary with season. Cassini entered orbit around Saturn shortly after the northern hemisphere's winter solstice in 2004 and has observed the shift through spring over the last 8 years.

The magnetospheric magnetic field at Saturn's magnetopause is plotted in Figure 27 for four orientations of the spin axis: pointed towards noon (top left), dawn (top right), midnight (bottom left),



Figure 27: Magnetic field in Saturn's magnetosphere at the magnetopause. Four spin axis/dipole orientations are considered – pointed to noon (top left), when the northern hemisphere of the planet is in summer, dawn (top right), midnight (bottom left), and dusk (bottom right). Due to the large angle between the Z-axis (normal to the orbital plane) and the dipole, rotating the orientation of the spin axis significantly changes the magnetic field topology at the magnetopause. The region of maximum field strength, which is generally a narrowband near the subsolar point, rotates both in angle and latitude with the spin axis.

and dusk (bottom right). Due to the large angle between the Z-axis (normal to the orbital plane) and the dipole, rotating the orientation of the spin axis significantly changes the magnetic field topology at the magnetopause. The region of maximum field strength, which is generally a narrow band near the subsolar point, rotates both in angle and latitude with the spin axis. The field on the flanks also changes significantly with spin axis orientation. The spiral pattern of the directional arrows is an artifact of the points chosen to plot and should be ignored.

#### Plasmasheet description at Jupiter

The description of the plasma density in the jovian plasmasheet in the magnetosphere derives from *Frank et al.* [2002] and *Bagenal & Delamere* [2011]. An average ion mass of 20 amu, corresponding to a mix of sulfur and oxygen ions with protons, has been assumed. The radial dependence of the density is a power law fit to Galileo PLS data on the G8 orbit [*Frank et al.*, 2002]. By looking at where there was an *e*-folding drop in density as the plasmasheet flapped over the spacecraft and combing measurements from Voyager and Galileo, *Bagenal & Delamere* [2011] created a description of the plasmasheet scale height. Their description is averaged over measurements in the late morning sector from Voyager and  $\pm 30^{\circ}$  in longitude at noon and midnight from Galileo. They found that in the outer magnetosphere the scale height asymptotes to ~4 R<sub>1</sub>.

Khurana  $\mathfrak{S}$  Shwarzl [2005] analyzed magnetic field measurements from several spacecraft and found that a large  $B_{\theta}$  component in the dusk region was suggestive of a thicker current sheet at that local time. I therefore incorporate a local time variation into the scale height, so that it is maximized on the dusk flank. The scale height is an indicator of the plasma temperature; for a simple dipole magnetic field and  $T_i \gg T_e$ , the scale height is related to the ion temperature by

$$H = \left[\frac{2}{3}kT_i/(m_p \operatorname{Ai}\Omega^2)\right]^{1/2} = H_0 \left[\frac{T_i(\mathrm{eV})}{\operatorname{Ai}(\mathrm{amu})}\right]^{1/2}$$
(14)

where  $H_0 = 0.64 R_J$  and 0.59  $R_s$  at Jupiter and Saturn and Ai is the average ion mass. The observed variation of the scale height by *Khurana & Shwarzl* [2005] is likely not due to a variation in the ion temperature with local time, but rather due to the deviation of the magnetic field from dipolar. Since the magnetic field is closer in structure to a dipole on the dusk Figure 25 we can use the scale height of  $10R_J$  to estimate the thermal ion temperature, in eV from Equation (14). This temperature is ~4 keV. I do not consider variation in scale height with ion species, or the possibility of temperature anisotropy. The full description of the plasmasheet density used in this thesis [cm<sup>-3</sup>] is given by

$$n = A \times R^{-1.28} \times exp\left[\frac{-(Z - Z_{CS})^2}{H^2}\right],$$

$$H = 7.0 + 3.0 \times \cos\left(\phi - \frac{\pi}{2.0}\right),$$

$$A = \frac{39.2}{H},$$
(15)

where  $R = \sqrt{X^2 + Y^2}$  is the cylindrical radius  $[R_j]$ ,  $\phi$  is the polar angle from noon, H is the scale height  $[R_j]$ , and  $Z_{CS}$  is the height of the current sheet with respect to the planet's equator  $[R_j]$ , as derived from the Khurana magnetic field model.

The plasma density in the magnetosphere is shown in Figure 28 for the three magnetopause asymmetries of  $[A/B]^2 = 1.25$ , 1.5, and 2. The variation in the plasmasheet scale height is clearly observed. Due to the orientation of the magnetic axis, the plasmasheet is centered close to the orbital plane on the dawn flank, but dips below the orbital plane on the tailward dusk flank. Changing the magnetopause asymmetry changes the relative size of the plasmasheet at the magnetopause and the total magnetopause size. A small background proton population, with a density of 0.01 cm<sup>-3</sup>, is also

included in the plasma description but is not included in Figure 28. Equation (15) describes only the thermal plasma population, and does not include an energetic population, which has been observed throughout the jovian magnetosphere [*Kane et al.*, 1995; *Krupp et al.*, 2001]. This population is expected to increase the plasma pressure in the middle magnetosphere, and possibly in the outer magnetosphere, increasing the plasma  $\beta$ . The influence of an energetic plasma population on the magnetosphere plasma conditions and interaction with the solar wind will be discussed further in Chapter 4.

The plasma flow is assumed to be tangential to the magnetopause and in the direction of corotation, with a magnitude of 200 km/s, based on Figure 3.23 in *Belcher* [1983] and Ulysses observations reported in *Cowley et al.*, [1996]. This is much lower than corotation at the magnetopause, which is ~1000 km/s at 100 R<sub>j</sub>. Though there are variations in the plasma flow speed at all radial distances, the Low-Energy Charged Particle instrument on Voyager 2 measured flows 0.3-0.7 times the corotation speed (~200 km/s at 100 R<sub>j</sub>) in the outer magnetophere [*Kane et al.*, 1995] and the Galileo Energetic Particles Detector measured flows 0.2 times the corotation speed in this region *Krupp et al.*, 2001]. Based on these measurements I believe that using a steady, sub-corotating flow at the magnetopause is a reasonable first-order assumption.



Figure 28: Plasmasheet density Jupiter's in magnetosphere. The description of the plasmasheet is given in Equation 2. The scale height ranges from 4  $R_J$  on the dawn flank to 10  $R_1$  on the dusk flank. The plasmasheet is thinnest on the dawn flank, and gets thicker on the dusk flank, where the magnetic field becomes more dipolar.

#### Plasmasheet description at Saturn

The description of the plasmasheet in Saturn's magnetosphere derives from *Thomsen et al.*, [2010] and *Bagenal & Delamere* [2011]. An average ion mass of 12 amu, a combination of water group ions and protons, has been assumed. *Thomsen et al.* [2010] took statistical moments for Cassini data to obtain the density in the center of the plasmasheet for different ion species and computed the plasmasheet scale heights. In the outer magnetosphere the density is ~0.07 cm<sup>-3</sup> in the center of the plasma sheet, and the plasma sheet has a scale height of ~5 R<sub>s</sub>, which agrees with energetic plasma measurements [*Krupp et al.*, 2005]. Using this scale height and Equation (14), the thermal ion temperature is ~850 eV. The full description of the plasmasheet density [cm<sup>-3</sup>] is given by

$$n = 0.07 \times exp\left[\frac{-(Z - Z_{CS})^2}{5.0^2}\right]$$
(16)

where  $Z_{CS}$  is the height of the current sheet with respect to the ecliptic plane [R<sub>s</sub>], as given by the Khurana magnetic field model.

The plasma density in the magnetosphere is shown in Figure 29 for four orientations of the planet's spin axis. When the spin axis is pointed towards the sun the plasma sheet is centered below the ecliptic plane, and above the plane when the spin axis is pointed away. When the spin axis is pointed toward dawn or dusk, the plasmasheet is close to aligned with the orbital plane. The plasmasheet becomes warped further from the orbital plane down the magnetosphere tail [*Carbary et al.*, 2008; *Arridge et al.*, 2008]. A background proton population with a density of 0.01 cm<sup>-3</sup>, not plotted, is assumed. As at Jupiter, a supra-thermal plasma population has been observed in the middle magnetosphere [*Sergis et al.*, 2010], which increases the plasma  $\beta$  in the middle and possibly outer magnetosphere. The plasma flow is assumed to be tangential to the magnetopause and in the direction

of co-rotation, with  $V_{\phi} = 0.6 V_{co}$  (150-200 km/s near the magnetopause) as derived by *Thomsen et al.* [2010].



Figure 29: Plasmasheet density in Saturn's magnetosphere. The description of the plasmasheet is given in Equation 16. The scale height throughout the magnetosphere is 5  $R_s$ . As the direction of the spin axis changes, the position of the plasmasheet relative to the orbital plane changes.

### Limitations of these models

Using static, steady-state models when describing an inherently dynamic system allows us to understand global, persistent features of the system. No realistic dynamic, 3-D global model of the jovian or kronian magnetospheres currently exists, due in part to our limited understanding of how plasma is heated in the magnetosphere, how the magnetosphere reacts to changes in the solar wind, and how the magnetosphere interacts with the solar wind. Using static models, however, does have some drawbacks. Due to the lack of high-latitude boundary measurements, the magnetopause shapes are not well constrained. Despite the highly variable stand-off distances at both planets, only one standoff distance at each planet is considered here, due to the static magnetosphere magnetic field models being employed. As the magnetopause standoff compresses at Jupiter, for example, the magnetic field in the magnetosphere will become stronger, it may become more dipolar, the plasmasheet may thicken, and the magnetosphere may become less oblate.

At Jupiter, only one tilt of the magnetic axis is presented. Changing the tilt of the magnetic axis with respect to the sun-planet line has the effect of moving the center of the plasmasheet up and down, as well as slightly changing the strength and direction of the magnetic field at the magnetopause. These changes were explored, however they were found to be relatively insignificant in terms of affecting the onset of large-scale reconnection and the Kelvin-Helmholtz instability.

Variations in the solar wind conditions and the IMF could have a marked affect on the results presented later in this text. Here a small solar wind dynamic pressure, corresponding to a low density, is considered at Jupiter, and an average value is considered at Saturn. It is expected that increasing the dynamic pressure would increase the density in the magnetosheath, which may affect my results. Additionally, variations in the IMF could affect the magnetosheath conditions. Increasing the angle of the IMF with respect to the orbital plane is not expected to affect our results significantly at Jupiter, because the field is rotated to align with the Z-axis, and increasing the angle of the IMF would not change this rotation. At Saturn, since the field does not completely rotate, the increased angle could slightly affect the magnetic field orientation in the magnetosheath at the dawn and dusk flanks. Additionally, changes in the IMF strength from the nominal values presented here could potentially have a small affect on our results – for example, increasing the magnetic field strength at Jupiter could result in a larger region of the magnetopause that is viable for reconnection. All of these effects are expected to be small, and general conclusions about the nature of the solar wind interaction at these planets can still be drawn from the results presented in the remainder of this text.

As mentioned in this chapter, a description of the energetic particle population in the magnetosphere is not included at either planet. This population is expected to increase the plasma  $\beta$  in the magnetosphere, but observations in the outer magnetosphere are too limited to create a global description. There is some evidence that at Saturn the magnetospheric energetic population may leak into the magnetosheath, also increasing the plasma  $\beta$  in this region [*Masters et al.*, 2012]. The influence of plasma  $\beta$  and the energetic magnetosphere population will be discussed further in Chapter 4.

Finally, boundary layers have been observed on the magnetospheric side of the magnetopause at both Saturn and Jupiter [*Staines et al.*, 1993; *Galvin et al.*, 1993] as well as at Earth. These boundary layers exhibit magnetic fields that are not well organized, stagnated or sub-corotational flows, and mixed plasma populations. The origin of the boundary layers are not well understood, but due to the mixed nature of the plasma, with both magnetospheric and magnetosheath plasma present, it is thought to be due in part to the interaction between the solar wind and the magnetosphere. A description of the boundary layers is left out of this study, which seeks to understand the nature of the solar wind-magnetosphere interaction. Additionally, at Jupiter there is evidence for a cushion region in the outer magnetosphere for 10's of  $R_1$  behind the magnetopause, which is not evident at Saturn [Went et al., 2011], through which the current sheet breaks down and the magnetic field has a more dipolar structure. This cushion region is thought to be due in part to the loss of mass down the tail due to the Vasyliunas cycle described in the Introduction [Went et al., 2011], and in part to the solar wind interaction. Since the structure of this region is not well understood or organized, it is not included in this study.

## Summary

In this chapter I detailed the models used to describe the plasma and magnetic field conditions at the magnetopause boundaries of Jupiter and Saturn. The magnetopause shape at both planets is assumed to be asymmetric; three degrees of asymmetry at Jupiter and one asymmetric shape at Saturn were analyzed. The description of the magnetic field and plasma in the magnetosheath, just outside of the magnetopause, is given by the results of MHD calculations for the solar wind flow past an asymmetric tangential discontinuity. Nominal solar wind conditions, based on various spacecraft observations, are used to scale the MHD simulation results. Four orientation of the IMF at Jupiter, and two at Saturn, were considered.

The plasma in the magnetospheres at both planets is modeled as a plasmasheet, the parameters of which are based on spacecraft observations of density and plasmasheet thickness. The magnetic field models in the magnetospheres are based on Galileo measurements at Jupiter and Cassini measurements at Saturn. Due to the large angle between the magnetic axis and the normal to the orbital plane at Saturn, four orientations of the spin axis (aligned with the magnetic axis) are considered, while at Jupiter, where the angle between the magnetic axis and normal to the orbital plane is smaller, only one orientation is considered. In the following three chapters I will use the models presented in this chapter to analyze whether the conditions allow for large-scale reconnection and the destabilization of the Kelvin-Helmholtz instability. In each case I will explore the affect of magnetopause asymmetry on the results by presenting the cases for Jupiter originally put forth in Figure 12. I will then consider the effect of reversing the sign of the Y-component of the IMF at Jupiter, as in Figure 13. Finally, I will consider how large-scale reconnection and the Kelvin-Helmholtz instability at Saturn are affected by the spin-axis orientation and change in season, as in Figure 14. In Chapter 6 I will use the values for the plasma parameters and magnetic field given by these models to constrain hybrid code simulations of the Kelvin-Helmholtz instability at Jupiter and Saturn's magnetopauses.

# CHAPTER 3 VELOCITY SHEAR EFFECT ON RECONNECTION

The influence of a shear in the plasma flow across a reconnection region on reconnection rate, shock formation, and reconnection suppression has been studied in depth [*Mitchell Jr. & Kan*, 1978; *La Belle-Hamer et al.*, 1994; *Cassak & Otto*, 2011]. It has been established that large shear flows parallel to the reconnecting magnetic field can suppress the onset of reconnection. The presence of a shear flow releases the tension in the reconnecting magnetic field, decreasing the outflow speed in one direction. Specifically, when the plasma shear flow parallel to the reconnecting magnetic field components exceeds the outflow speed from the reconnection region (nominally the Alfvén speed), outflow is suppressed, and the flow patterns needed to sustain reconnection cannot develop [*Cassak & Otto*, 2011].

At the dawn flank of the magnetopauses of Jupiter and Saturn, and tailward of the planets on the dusk flank, the shear flow across the boundary is large (100s km/s) due to the anti-sunward flow in the magnetosheath (Figure 15, Figure 16, Figure 17) and co-rotating plasma in the magnetosphere. Due to the complex geometry of the fields and flow patterns, as presented in Chapter 2, it is not trivial to determine how the shear flow parallel to the reconnecting magnetic fields compares to the reconnecting Alfvén speed. In this chapter I use the models of plasma flows, plasma densities and the magnetic fields on either side of the magnetopause discussed in Chapter 2 to calculate the reconnecting magnetic fields, the reconnecting Alfvén speed, and the shear flow parallel to the reconnecting fields. I then test whether the onset of reconnection will be suppressed due to the shear flow, and how conditions such as the IMF clock angle, magnetopause shape, and spin axis orientation affect the shear flow and reconnection viable region.

### Asymmetric reconnection

In order to determine the reconnecting magnetic field vectors, I assume that the X-line is the line bisecting the shear angle between the magnetosheath and magnetosphere magnetic fields [*Swisdak* & *Drake*, 2007]. This assumption is valid when the density ratio across the region is close to 1. More generally, *Swisdak* & *Drake* [2007] proposed that reconnection occurs in the plane in which the outflow from the X-line, and therefore the reconnection rate, is maximized. The unit vector in the direction of the X-line is calculated by:

$$m_{x (y,z)} = 0.5 \left( \frac{B_{1,x (y,z)}}{B_1} + \frac{B_{2,x(y,z)}}{B_2} \right)$$
$$|m| = \sqrt{m_x^2 + m_y^2 + m_z^2}$$
$$\widehat{m}_{x(y,z)} = \frac{m_{x(y,z)}}{|m|}$$
(17)

where the subscripts denote the sides of the boundary, and the magnetic field is the total field. The reconnecting fields are then the components of the total field perpendicular to the X-line direction defined by  $\hat{\mathbf{m}}$ . The Alfvén speed (V<sub>A</sub>), which is the outflow speed of the plasma from the reconnection region [*Swisdak & Drake*, 2007], is calculated taking into account both the asymmetry in the density and magnetic field [*Cassak*, 2007; *Birn et al.*, 2010].

$$V_A = \sqrt{\frac{B_1 B_2}{\mu_0 \bar{\rho}}} \tag{18}$$

$$\bar{\rho} = \frac{B_1 \rho_2 + B_2 \rho_1}{B_1 + B_2} \tag{19}$$
where the subscripts denote the side of the boundary, and the magnetic fields are only the reconnecting components. The components of the flows parallel to the reconnecting fields are then used to calculate the shear in the flow speed.

### Velocity shear effects at Jupiter

The shear speed parallel to the reconnecting fields across Jupiter's magnetopause, normalized to the maximum shear speed, is plotted in Figure 30. Three magnetopause asymmetries and two IMF clock angles are considered, as was presented initially in Figure 12. The shear speed is normalized to the maximum speed, which varies between 510 km/s and 526 km/s, depending on magnetopause shape. The shear is generally maximized on the dawn flank and minimized on the dusk flank, as expected, however the exact topology is sensitive to the magnetopause shape and IMF orientation. The shear is not maximized in the equatorial region, where the Alfvén speed is minimized, but at higher latitudes. This is due to the lower magnetosheath speeds near the equator (Figure 13). The shear is small near the sub-solar region because the flows on either side of the magnetopause are perpendicular – the magnetosheath flow is in the  $\hat{z}$  direction while the magnetosphere flow is parallel to the  $\hat{y}$  axis, in the direction of corotation.

For the cases with an IMF clock angle of 85° (left column), as the asymmetry of the magnetopause increases, the region of high shear flow on the dawn flank changes shape and location. The highly asymmetric magnetopause rotates the magnetic field in the magnetosheath towards the normal to the ecliptic plane. Since the direction of the X-line depends on the orientation of the magnetic fields, rotating the field in the magnetosheath rotates the X-line and the reconnecting magnetic field components as well. In addition, the stagnation line and flow patterns that develop



Figure 30: Shear flow parallel to the reconnecting magnetic fields across Jupiter's magnetopause, normalized to the maximum shear flow (510-526 km/s). Three shapes of the magnetopause and two IMF clock angles are considered. In all cases, shears are minimized on the dusk flank and maximized near the dawn flank. Shears are sensitive to the rotation of the stagnation line and magnetic field in the magnetosheath. Shears are higher when the IMF has a component parallel to the planet's dipole field, because the components that are antiparallel and available for reconnection are oriented in the direction of the plasma flows.

around this line rotate, changing the direction and magnitude of the shear flow. The sharp gradient in the shear flow on the dawn flank is due to the superposition of the effects of the change in magnetic field direction across the equatorial plane in the magnetosphere with the rotated magnetic field and stagnation line in the magnetosheath. When the IMF has a southward component (right column) the shears are higher on the flanks and increase with increasing asymmetry. This is also due to the rotation of the IMF and stagnation line in the magnetosheath, combined with the parallel orientation of the Z-components of the magnetic fields in the region of the equator.

In Figure 31, four IMF orientations are compared for the most asymmetric magnetopause shape, as in Figure 13. The two cases with an IMF component that is southward (95° and -95°) show a symmetry in the shear flow pattern across the equatorial plane, due to the rotation of the stagnation line in these two cases (Figure 19). This symmetry similarly exists in the two cases with a northward IMF component. Other than this north-south variation, reversing the sign of the Y-component of the IMF does not affect the velocity shear at the magnetopause.

The region where the shear flow is less than the reconnecting Alfvén speed, where the onset of steady-state reconnection is viable, based on the shear flow and the Alfvén speed for the six cases presented in Figure 30, is shown in Figure 32. For the cases of IMF clock angle of 85°, which include a component anti-parallel to the dipole component of the planet's dipole magnetic field, reconnection is generally not suppressed on the dusk flank, where shears are small (Figure 30). The region viable for reconnection on the dawn flank is primarily north of the equator, where the bent-back field in the magnetosphere is anti-parallel with the draped Y-component of the IMF and the Z-components of the fields are anti-parallel. As the magnetopause asymmetry increases and the field is rotated towards the perpendicular direction with respect to the equatorial plane, the reconnection viable region broadens into the southern hemisphere.

For the cases in the right column, with an IMF clock angle of 95°, reconnection is suppressed on the dawn flank, where the shears parallel to the reconnecting fields are large (Figure 30). As the asymmetry of the magnetopause increases and the field is rotated towards perpendicular with the ecliptic plane, the shear angle between the magnetic fields approaches 0° on both flanks, so that even on the dusk flank, where shears are generally low,



Figure 31: Shear flow parallel to the reconnecting magnetic fields across Jupiter's magnetopause, normalized to the maximum shear flow. The most asymmetric magnetopause shape is shown, with four IMF orientations. There is a North-South symmetry between cases with similar Z-components of the IMF (i.e. 95° and -95°).

reconnection begins to be suppressed. Reconnection is always viable between noon and three, local time.



Figure 32: Region of potential reconnection at Jupiter's magnetopause based on the influence of the plasma shear flow for the cases presented in Figure 30. The red region is the area where reconnection is viable. On the dusk flank, the region between noon and dusk is viable, with reconnection shut off on this flank tailward of the planet in the cases of a southward component of the IMF, due to the rotation of the magnetic field towards parallel with the dipole component of the planetary magnetic field. When the fields have antiparallel components (left column) reconnection is viable on the dawn flank.

In Figure 33, four IMF clock angles for the most asymmetric magnetopause shape are considered, as in Figure 31. As with the shear flow, there is symmetry across the equator as the sign of the Y-component is reversed and the Z-component is held constant. For a field with a component



Figure 33: Region of potential reconnection at Jupiter's magnetopause based on the influence of the plasma shear flow for the cases presented in Figure 31. The red region is the area where reconnection is viable. Reversing the sign of the Y-component of the magnetic field creates a mirror reflection across the equatorial plane of the region viable for reconnection.

parallel to the planet's dipole field (95° and -95°), reconnection is viable near the equator between noon and three, local time. Reversing the Y-component does not significantly change this, however it does change the region of the high latitude reconnection. As remarked in Chapter 2, my results in this

high latitude region are limited in validity due to the approximation of the magnetosphere magnetic field. Both flanks near the equator are viable for reconnection when the magnetosheath field is antiparallel to the planet's dipole.

Even in regions where reconnection is not suppressed, the reconnection rate may be reduced due to the shear flow. *Cassak & Otto* [2011] found that the shear-flow-dependent reconnection rate is

$$E = E_0 \left( 1 - \frac{v_s^2}{v_A^2} \right) \tag{20}$$

where  $E_0$  is the reconnection rate without a velocity shear,  $v_s$  is the shear speed, and  $v_A$  is the Alfvén speed of the reconnecting magnetic field. This will further reduce the ability of large-scale reconnection to mediate the solar wind interaction.

#### Velocity shear effects at Saturn

The shear flow parallel to the reconnecting magnetic field, normalized to the maximum shear speed, is plotted in Figure 34. Two IMF clock angles, 85° and 95°, and four spin axis orientations (north pole pointed towards noon, dusk, midnight, and dawn) are presented. The shear is generally maximized on the dawn flank and minimized on the dusk flank. The specific pattern of the shear flow on the magnetopause is highly sensitive to the orientation of the planet's spin axis and the IMF clock angle. The relative orientation of these two fields determines the direction of the reconnection X-line and reconnecting magnetic fields, which changes the shear flow that can affect reconnection; the shear flow is plotted in Figure 34. The maximum shear is south of the equator on the dawn flank when the spin axis is pointed towards midnight. As the spin axis rotates towards the dawn flank and then noon, the region of maximum shear moves north towards the equator. Shears are low (close to zero) on the dusk flank near the equator in all cases.



Figure 34: Velocity shear across Saturn's magnetopause. The shear is minimized on the dusk flank, where the co-rotational and magnetosheath flows are in the same direction, and maximized on the dusk flank where the flows are in opposite directions. The maximum shear region is not in the equator but above or below due to the direction of the stagnation line and the flow perpendicular to it.

These results are similar to the results found at Jupiter for this magnetopause shape,  $[A/B]^2 =$ 

1.5 (Figure 30). There does not appear to be quite as much variation with IMF clock angle at Saturn as

there was at Jupiter, where shears on the dawn flank were much higher when the IMF Z-component was southward than northward. In Figure 34, the shears are higher in the equatorial region of the dawn flank when there is a southward component of the IMF and the spin axis points to midnight or dusk, however shears do not change significantly with IMF clock angle when the spin axis is pointed toward noon and dawn.

In Figure 35 the region available for reconnection at Saturn's magnetopause, based on the shear flow parallel to the reconnecting magnetic fields, is plotted. The same cases as in Figure 34 are presented. First, I consider the variation with season (spin axis orientation) when the IMF clock angle is held constant. For the left column, IMF clock angle equal to 85°, there appears to be no symmetry or consistency between seasons. When the spin axis is pointed to noon, reconnection is not viable at all on the dawn flank, but is still possible on the dusk flank where shears are low, except in the region of the dense plasmasheet (see Figure 29). When the dipole is pointed to midnight, the entire magnetopause in the equatorial region is available for reconnection. The dawn flank is viable for reconnection is possible north and south of the subsolar point, and the dusk flank is viable except in a small strip centered on the plasma sheet. As the spin axis rotates toward dawn, reconnection is possible on the dusk flank, except in a strip collocated with the plasmasheet and deep on the tail where the shear is slightly higher. For the spin axis pointed towards dusk, the region available for reconnection increases on the dawn flank, possibly due to the increased field strength on this flank, and is reduced on the dusk flank.



Figure 35: Region of potential reconnection at Saturn's magnetopause based on the influence of the plasma shear flow. The red region is the area where reconnection is viable based on the plasma flows. The dawn flank of the magnetopause is generally shut-off due to the high shears. On the dusk flank, the region between noon and dusk is viable, with reconnection shut off on this flank tailward of the planet in the cases of a southward component of the IMF, due to the rotation of the magnetic field towards parallel with the dipole component of the planetary magnetic field.

For the right column, the IMF has a southward component, parallel to the planet's dipole field.

In all cases, reconnection is suppressed on the dawn flank, likely due to the parallel orientation of the

magnetic fields combined with the relatively high shear flows (Figure 34). As in the case of the other IMF orientation (left column) the reconnection viable region is variable on the dusk flank with spin axis orientation. The regions available for reconnection appear to have similar patterns as in the left column, suggesting that the spin axis orientation and magnetospheric magnetic field largely control the reconnection viable region on this flank. Much of the dusk flank is viable for reconnection when the spin axis is pointed to midnight and when it is pointed toward noon, however the reconnection viable region is thin and centered near the equator when the spin axis is pointed to noon. Where the plasma sheet is most dense, reconnection is not possible. This trend continues for the spin axis pointed to dawn and dusk – reconnection is suppressed in the region of the dusk flank where the plasma is most dense, however due to the low shears the rest of the dusk flank is reconnection viable, even though the IMF has a southward component.

## Conclusions

In this chapter I have explored how the velocity shear can affect reconnection at Jupiter and Saturn. When the shear flow parallel to the reconnecting magnetic field components is larger than the reconnecting Alfven speed, reconnection is suppressed. Due to the large tailward solar wind flows in the magnetosheath and the co-rotating flow in the magnetospheres at both planets, shears were expected to be large on the dawn flank and small on the dusk flank at both planets, inhibiting reconnection on the former while not affecting reconnection on the latter. Due to the complex geometries of the magnetic fields, however, and the fact that only the shear flow parallel to the reconnecting magnetic field components affects reconnection, my results are not so simply stated. I found that:

- Shear flows at Jupiter's magnetopause are generally higher on the dawn flank and lower on the dusk flank, however as the asymmetry of the magnetopause increases, the shear increases on both flanks when the IMF has a component parallel to the planet's dipole.
- At Jupiter along most of the magnetopause equator reconnection is viable when the IMF has a component anti-parallel to the planet's dipole field, regardless of magnetopause asymmetry. When the IMF has a component parallel to the planet's dipole, reconnection is viable on the dusk flank, however as the asymmetry of the magnetopause increases, the dusk flank becomes less viable for reconnection.
- At Jupiter, reversing the Y-component of the IMF causes a mirror reflection over the equatorial plane of the shear flow pattern ie when the IMF is 95° the shear is maximized south of the equator on the dawn flank, whereas when the IMF clock angle is -95°, the shear is maximized north of the equator.
- Reversing the Y-component of the IMF does not significantly effect where reconnection is viable in the equatorial region.
- At Saturn, shears are high on the dawn flank and low on the dusk flank, however the shear flow patterns are highly dependent on the planet's spin axis orientation.
- At Saturn, only when the IMF has a component anti-parallel to the planet's dipole field, and the dipole is pointed to midnight or dusk, small sections of the dawn flank can be reconnection viable. This differs significantly from reconnection at Jupiter, which is always viable on the dawn flank when the IMF Z-component is anti-parallel.
- On Saturn's dusk flank reconnection is viable for both IMF orientations except where the plasma density is high in the plasmasheet. Reversing the sign of the Z-component does not significantly change the region of reconnection on this flank. This also differs significantly

from Jupiter, where the dusk flank is entirely viable for reconnection when the IMF has a component anti-parallel to the planet's dipole and the dusk flank is only viable for reconnection between noon and dusk and the IMF has a component parallel to the planet's dipole.

# CHAPTER 4 DIAMAGNETIC DRIFT EFFECT ON RECONNECTION

The onset of steady-state large-scale reconnection can be affected by the presence of a pressure gradient across the reconnection region. *Swisdak et al.* [2003] and *Swisdak et al.* [2010] showed that when the diamagnetic drift caused by the pressure gradient exceeds a critical value, reconnection is suppressed. *Swisdak et al.* [2003] ran particle-in-cell simulations of collisionless magnetic reconnection to explore the effect on reconnection of a field parallel to the X-line (a guide field) combined with a density asymmetry across the current layer. They showed that the reconnection X-line is advected by the diamagnetic drift of the electrons and fast reconnection cannot develop when the relative drift between the electrons and ions exceeds a critical value. *Swisdak et al.* [2010] used MHD simulations of the heliosphere to show that at the heliopause large diamagnetic drifts may develop and suppress reconnection.

The diamagnetic drift is not a particle drift, but a fluid drift. To understand the origin of this drift, consider the fluid equation of motion for a single plasma population,

$$\rho \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = \rho (\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \nabla p.$$
<sup>(21)</sup>

This equation differs from Equation (6) because Equation (6) combined the equations of motion for ions and protons, while Equation (21) is the equation for a single plasma population. Taking the ratio of the first term to the fourth,

$$\frac{mni\omega\mathbf{v}_{\perp}}{qn\mathbf{v}_{\perp}B} \approx \frac{\omega}{\omega_c} \tag{22}$$

with  $\frac{\partial}{\partial t} = i\omega$  and assuming the fluctuations in v are on a much slower time scale than  $\omega_c$ , the cyclotron frequency, the first term can be taken to be small and ~0. The second term will also be

taken to be zero, an assumption explained *a posteriori*. With the left-hand side of Equation (21)  $\approx$  0., take the cross product of Equation (21) with **B**, and solve for **v**<sub>1</sub>, the velocity perpendicular to the magnetic field:

$$0 = qn(\mathbf{E} \times \mathbf{B} + (\mathbf{v} \times \mathbf{B}) \times \mathbf{B}) - \nabla p \times \mathbf{B}$$
$$0 = qn(\mathbf{E} \times \mathbf{B} + \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) - \mathbf{v}(\mathbf{B} \cdot \mathbf{B})) - \nabla p \times \mathbf{B}$$
$$\mathbf{v}_{\perp} = \frac{(\mathbf{E} \times \mathbf{B})}{B^2} - \frac{\nabla p \times \mathbf{B}}{qnB^2}.$$
(23)

The first term on the right hand side of (10) is the  $\mathbf{E} \times \mathbf{B}$  drift, and the second term is the diamagnetic drift,

$$\mathbf{v}_{\boldsymbol{D}} = -\frac{\boldsymbol{\nabla}p \times \mathbf{B}}{qnB^2}.$$
(24)

Since the drift is perpendicular to the gradient, when  $\mathbf{E} = 0$  our assumption that  $(\mathbf{v} \cdot \nabla)\mathbf{v} = \mathbf{0}$  is valid. In other cases, the expression for the drift may be complicated by the  $(\mathbf{v} \cdot \nabla)\mathbf{v}$  term. The diamagnetic drift can be understood by considering the individual particle motions, and is conceptualized in Figure 36. The pressure gradient is shown to be due to a density gradient, and is pointed towards the left. **B** is out of the plane. There are more particles that pass through the volume box represented in the center from the left than from the right, resulting in a net motion towards the bottom of the box, despite the fact that the individual particles are not drifting.

This net motion changes sign with charge, resulting in a current in the region of the pressure gradient, and motion of the electrons and ions in opposite directions. When a pressure gradient is present across the current layer at a potential reconnection site, the reconnection X-line is propagated by the electrons. Since the drift is perpendicular to both the gradient and **B**, a magnetic guide field in the plane parallel to the current sheet and perpendicular to the reconnecting magnetic field is required

in order to create a drift which is parallel to both the reconnecting magnetic field and the outflow from the reconnection region.



Figure 36: Schematic of the diamagnetic drift. The pressure gradient is to the left and the magnetic field is out of the page. More particles pass through the box from the left than from the right, resulting in a net motion toward the bottom of the box.

The ions do not advect the X-line, presumably because the frozen-in condition is broken in the reconnection region. It is therefore not obvious that the electrons would advect the magnetic X-line, as the electron fluid assumption may not be applicable in that region, yet simulations show that the X-line does drift at the electron diamagnetic drift speed [*Swisdak et al.*, 2003; *Pritchett*, 2008].

When the speed of the X-line in the ion rest frame is greater than a critical value, the flow patterns necessary to sustain large-scale reconnection cannot develop and reconnection is suppressed [*Swisdak et al.*, 2003]. Reconnection will be suppressed when the speed of the X-line is greater than the ion outflow speed, nominally the ion Alfven speed, such that

$$\left| -\frac{\nabla p_e \times \mathbf{B}_g}{q_e n B^2} \right| + \left| -\frac{\nabla p_i \times \mathbf{B}_g}{q_i n B^2} \right| > \frac{B_r}{\sqrt{\mu_0 m_i n}}$$
(25)

where the subscript g denotes the guide field parallel to the X-line and the subscript r denotes the reconnecting component. The left-hand side is the relative drift of the X-line with respect to the drifting ions, and the right-hand side is the Alfvén speed of the reconnecting fields. *Swisdak et al.* [2010] reformulated this limit on the diamagnetic drift for the onset of reconnection in terms of the difference in the plasma  $\beta$  across the reconnection region and the magnetic shear angle,  $\theta$ . For the case when the magnetic X-line is directed midway between the magnetic fields on either side of the reconnection region, which is a reasonable approximation if the magnetic field strengths on either side of the boundary are not too different [*Swisdak & Drake*, 2007], Equation (25) becomes

$$\frac{\nabla p_{e} * B \cos\left(\frac{\theta}{2}\right)}{|q|nB^{2}} + \frac{\nabla p_{i} * B \cos\left(\frac{\theta}{2}\right)}{|q|nB^{2}} > \frac{B \sin\left(\frac{\theta}{2}\right)}{\sqrt{\mu_{0}m_{i}n}}$$

$$\frac{2\mu_{0}\Delta(p_{e} + p_{i})}{B^{2}} > 2L \frac{\mu_{0}qn}{\sqrt{\mu_{0}mn}} \tan\left(\frac{\theta}{2}\right)$$

$$\Delta\beta > 2\left(\frac{L}{\lambda_{i}}\right) \tan\left(\frac{\theta}{2}\right)$$
(26)

where L represents a typical gradient scale length near the X-line, which is approximately the thickness of the magnetopause current layer,  $\lambda_i$  is the ion inertial length, and  $\theta$  is the shear angle between the magnetic fields. At Earth,  $\frac{L}{\lambda_i} \sim \mathcal{O}(1)$  [Berchem  $\Leftrightarrow$  Russell, 1982; Eastman  $\Leftrightarrow$  Hones, 1979]; due to the limited measurements of magnetopause thickness at Jupiter and Saturn we assume the ratio holds at the outer planets, though observations by Pioneer 10 and 11 [Sonnerup et al., 1981] suggest that this ratio might be larger at Jupiter ( $\frac{L}{\lambda_i} \sim \mathcal{O}(10)$ ). Due to the lack of confirmation of the magnetopause thickness, I will assume the thickness is approximately the ion inertial length. A thicker magnetopause would increase the  $\Delta\beta$  needed to suppress reconnection. This expression (Equation (26)) puts an upper limit on the  $\Delta\beta$  across the magnetopause boundary for which reconnection can occur. *Phan et al.* [2010] used solar wind observations to verify this formulation. I will use Equation (26) to test whether reconnection is suppressed by the diamagnetic drift at Jupiter and Saturn by combining estimates of the  $\Delta\beta$  with the magnetic field shear angle calculated using the models described in Chapter 2.

#### Diamagnetic drift effect at Jupiter

Based on the plasma properties and magnetic field from the *Erkaev et al.* [1996] simulations described in Chapter 2, I am able to calculate the plasma  $\beta$  in the jovian magnetosheath, which varies between 1 and 4. The plasma  $\beta$  in the magnetosphere is not as well constrained. Based on pressure balance, using the *Erkaev et al.* [1996] model solutions in the magnetosheath and the magnetic pressure from the Khurana magnetic field model, the plasma  $\beta$  should be around unity in the magnetosphere. Measurements by *Mauk et al.*, [2004], however, suggest that  $\beta$ ~100 at 40 R<sub>j</sub> in the equatorial plane. The large plasma pressure is attributed to the high-energy plasma, not included in the models described in Chapter 2.

Due to the ambiguity in the magnetospheric plasma pressure, I consider whether reconnection is suppressed for a magnetospheric plasma  $\beta = 1$  (Figure 37, Figure 38) and a calculated plasma  $\beta$ 



Figure 37: Effect of the diamagnetic drift on reconnection at Jupiter, and variability of this effect with magnetopause shape. The magnetosphere plasma  $\beta=1$ .  $\beta$  in the magnetosheath is based on the MHD simulations and is approximately unity. At this low  $\Delta\beta$ , the field geometry allows for the onset of reconnection along most of the magnetopause. The exceptions are the southern dawn flank, where in the cases of the more symmetric magnetopauses the highly bent-back field is parallel to the draped field in the magnetosheath, and the dusk flank in the case of an IMF with a component antiparallel to the planetary dipole field in the equatorial plane.

(Figure 40, Figure 41) assuming a plasma pressure due to the high energy plasma derived by *Mauk et al.* [2004] and magnetic pressure calculated from the Khurana magnetic field model employed in this study (Figure 18). I examine the influence of both the magnetopause shape and IMF direction on this effect. The model of the magnetospheric plasma pressure with plasma  $\beta = 1$  does not vary with magnetic pressure. Instead, the ratio of the plasma pressure and magnetic pressure is held constant. In the second model, the plasma pressure is held constant at 0.1 nPa and the magnetic pressure is allowed to vary. This is a more realistic model than the first because of the variation in magnetic pressure, based on observation, and the observationally constrained plasma pressure, however the plasma  $\beta = 1$  model provides a minimum constraint on the effect of the  $\Delta\beta$  across the magnetopause. An even more realistic model allow plasma pressure to vary with local time and latitude, however limited measurements of the energetic plasma in the outer magnetosphere prevent me from creating this type of detailed model of the plasma pressure.

First, the influence of the magnetopause asymmetry on the diamagnetic drift suppression of reconnection, for the plasma  $\beta = 1$  model, is considered in Figure 37. Three asymmetries are modeled, as discussed in Chapter 2 and originally presented in Figure 12. The plasma  $\beta$  in the magnetosphere is equal to 1 throughout the magnetosphere, and the plasma  $\beta$  in the magnetosheath is based on the MHD simulations. Due to the small  $\Delta\beta$ , reconnection is viable along most of the magnetopause in all cases. There is a region south of the equator on the dawn flank in all cases where reconnection is inhibited. This region shrinks in size as the asymmetry of the magnetopause increases, suggesting that it is the effect of the draping of the magnetic field in the magnetosheath, specifically the shear angle between the magnetic fields, inhibiting the reconnection. There is a region on the dusk flank where reconnection is not viable and increases in size with increasing magnetopause asymmetry for the case of a southward component to the IMF (right column). This can be understood by the

rotation of the field towards parallel with the magnetosphere dipole field component, which increases with asymmetry (Figure 18).

In Figure 38 the influence of the IMF Y-component (east-west) on the suppression of reconnection by the diamagnetic drift, with magnetospheric plasma  $\beta = 1$ , is examined. The top two images are the same as the bottom two images of Figure 37, the highly asymmetric magnetopause. Reversing the sign of the Y-component (85° to -85°, 95° to -95°) does not change which regions on the



Figure 38: Region at Jupiter's magnetopause that is viable for reconnection based on the influence of the diamagnetic drift. The magnetosphere plasma  $\beta = 1$ . The magnetopause shape is highly asymmetric, with  $(A/B)^2 = 2$ . The effect of reversing the Y-component of the IMF is considered. Due to the small  $\Delta\beta$  across the magnetopause, reconnection can occur except in cases of a southward IMF component (top right and bottom left) where the magnetic fields on either side are aligned on the flanks. Switching the Y-component of the IMF flips the regions which are/are not viable for reconnection across the equatorial plane, which can be seen by comparing the top left and bottom right figures and the top right and bottom left figures.

flanks are available for reconnection, however this rotation does cause a mirror reflection of the reconnection viable region across the equatorial plane— i.e. for the case of 85° the northern hemisphere is not viable for reconnection yet for the case of -85° the southern hemisphere is not viable, due to the reversal in the magnetic field shear angle in these regions.

In Figure 39 I consider a model of the plasma pressure where the plasma pressure in the magnetosphere is based on the energetic plasma pressure derived in *Mauk et al.* [2004] of 0.1 nPa, and the magnetic pressure varies with location and is based on the Khurana magnetic field model. This results in a plasma  $\beta \sim 10$  in the magnetosphere along much of the magnetopause. Again, I begin by considering the effect of changing the magnetopause shape on the diamagnetic drift suppression of reconnection. The magnetopause is generally susceptible to reconnection near the subsolar point and onto the dusk flank in the equatorial plane. This region grows as the magnetopause asymmetry increases when there is an IMF component anti-parallel to the planetary dipole field and decreases with increasing magnetopause asymmetry when there is an IMF component parallel to the planetary dipole field, due to the rotation of the magnetic field in the magnetosheath. The region that is susceptible to reconnection is very small relative to the size of the magnetopause in all cases, with a maximum size when the fields are anti-aligned on the dusk flank. In this area the magnetosphere plasma  $\beta$  is approximately unity, due to the increased magnetic field strength in this region, and can be compared to Figure 37.

The effect of reversing the east-west component of the IMF is considered in Figure 40, for the most asymmetric magnetopause shape. Reversing the sign of this component while not changing the Z-component appears to slightly alter the region that is viable for reconnection. In the case of a northward component of the IMF (85° and -85°), the region viable for reconnection stretches further



Figure 39: Effect of the diamagnetic drift on reconnection, and variability of this effect with magnetopause shape. The magnetosphere plasma pressure from (Mauk, et al., 2004) and magnetic pressure from the Khurana magnetic field model determine the magnetospheric plasma  $\beta$ . The plasma  $\beta$  in the magnetosheath is based on the MHD simulations and is approximately unity. Plasma  $\beta$  in the magnetosphere is close to unity between noon and three local time in the equatorial region, where the magnetic field is ~5 nT. Along the rest of the magnetopause the magnetic field is weaker, increasing the plasma  $\beta$ . The dusk flank is viable for reconnection when the shear angle between the magnetic fields is close to 180°, in the most asymmetric case, but otherwise the reconnection viable region is limited in extent.



Figure 40: Effect of the diamagnetic drift at Jupiter's magnetopause on large-scale reconnection, and influence of variation in the IMF direction. The magnetosphere plasma pressure from (Mauk, et al., 2004) and magnetic pressure from the Khurana magnetic field model determine the magnetospheric plasma  $\beta$ . The plasma  $\beta$  in the magnetosheath is based on the MHD simulations and is approximately unity. Reconnection is suppressed along most of the magnetopause except on the dusk flank when the magnetic fields are antialigned, when the IMF has a northward component. Reversing the Y-component of the IMF causes slight changes in the area viable for reconnection, however these changes do not appear to be very significant.

on to the dawn flank when the east-west component is reversed from 85° to -85°, however the region on the dusk flank is less extended in latitude.

In the cases of a southward component of the IMF, the region is small in both cases, and shifts slightly from the dusk side of the subsolar region to the dawn, with the rotation from 95° to -95°. The differences on the dusk flank, in the cases of a northward IMF component (top left and bottom

right), are due to the rotation of the magnetic field in the magnetosheath, changing the magnetic field shear angle.

The difference at the subsolar point, for the cases of a southward IMF component (top right and bottom left), may be attributed to the rotation of the shear angle, but may also be a result of the rotation of the stagnation line, along which the plasma  $\beta$  in the magnetosheath is maximized.

In Figure 41 I consider a third possibility for the plasma pressure at the magnetopause. Zhang et al. [1993] reported the diffusion of energetic electrons from the magnetosphere to the magnetosheath at Jupiter. Masters et al. [2012] reported plasma pressure in the Saturn's magnetosheath from an energetic population of the same magnitude as the energetic plasma pressure in the magnetosphere. The fly-by of Jupiter by the Cassini spacecraft on the dusk flank was analyzed by *Svenes et al.* [2004]. They found that there was a clear magnetopause boundary between the thermal electrons in the magnetosheath and magnetosphere, whereas there was no clear boundary in the energetic populations. The observations of energetic plasma in the magnetosphere by *Svenes et al.* [2004] and *Thomsen et al.* [2010] suggest that using a plasma pressure contribution from the energetics in analyzing the diamagnetic drift is a realistic approximation, and the analysis of *Svenes et al.* [2004] suggests that assuming a leaking of the energetics into the magnetosheath is a reasonable model.

These studies, along with a requirement of pressure balance at the magnetopause, suggest that there may be leakage of the energetic plasma population from the magnetosphere to the magnetosheath at both Jupiter and Saturn. With this in mind I add a pressure due to the energetic plasma population of 0.1 nPa to the thermal plasma pressure in the magnetosheath calculated from the *Erkaev et al.* [1996] simulations (Figure 41). For simplicity I consider only the cases



Figure 41: Effect of the diamagnetic drift at Jupiter's magnetopause on large-scale reconnection, and influence of variation in the IMF direction. The magnetosphere plasma pressure from *Mauk et al.* [2004] and magnetic pressure from the Khurana magnetic field model determine the magnetospheric plasma  $\beta$ . The magnetosheath plasma  $\beta$  is based on the Erkaev simulation results plus a plasma pressure due to an energetic population of 0.1 nPa. Reconnection is suppressed along most of the magnetopause except on the dusk flank and towards the dawn flank when the IMF has a northward component and the magnetic fields are anti-aligned. There are regions that appear to be susceptible to reconnection near the equator even when the IMF has a southward component, however this area is small, highly variable and likely inconsequential.

presented in Figure 40. When compared to Figure 40 this increased plasma pressure in the magnetosheath does not significantly change where reconnection is suppressed. When the IMF has a northward component slightly more of the equatorial region is available for reconnection, due to the decrease in the  $\Delta\beta$  with the addition of the hot plasma pressure in the magnetosheath. For the cases of southward IMF there are also spots near the equator that appear to be viable for reconnection.

This arises from the complicated geometry of the magnetic field and plasma density patterns in the magnetosheath and magnetosphere. These regions are small and variable, and are not likely to contribute significantly to the reconnection activity at Jupiter's magnetopause.

### Diamagnetic drift at Saturn

At Saturn, as at Jupiter, the magnetosheath plasma  $\beta$  is based on the Erkaev MHD simulations, with  $\beta$  varying between 1 and 10. The high  $\beta$  ( $\beta > 3$ ) region is constrained to the stagnation line where the plasma density is enhanced. This differs significantly from the magnetosheath beta reported in *Masters et al.* [2012]. Considering Figure 1 in *Masters et al.* [2012], this difference appears to be a result of the energetic electron and ion pressure in the magnetosheath that is not included in the Erkaev simulations and may be a result of "leakage" of this population from the magnetosphere to the magnetosheath.

Calculations based on Cassini data suggest that the plasma  $\beta$  in the equatorial region of the magnetosphere is ~2, varying between ~0.3 and ~10 [*Masters et al.*, 2012], and that the dominant contribution of the plasma pressure comes from the energetic plasma population. *Sergis et al.* [2009] presented energetic plasma pressures in the plasmasheet of Saturn's magnetosphere measured by Cassini and report a pressure of ~0.01 nPa at 20 R<sub>s</sub>, averaged over local time. This plasma pressure corresponds to a plasma  $\beta$  in the outer magnetosphere of ~5. *Kellet et al.* [2010] analyze two Cassini passes in the equatorial plane and report total plasma pressures (energetic plus thermal populations) of 0.01 - 0.1 nPa at 20 R<sub>s</sub>. In Figure 42 we assume the plasma pressure in the magnetosphere is 0.015 nPa, and calculate the magnetosphere plasma  $\beta$  based on this value and the magnetic field pressure

from the *Khurana et al.* [2006] magnetic field model. The magnetosheath plasma  $\beta$  in Figure 42 is based solely on the Erkaev simulations.

In Figure 42 I demonstrate that the effect of the diamagnetic drift is highly sensitive to both IMF and spin axis orientation. In most cases the diamagnetic drift does not restrict reconnection in the subsolar region. When the spin axis/magnetic axis is oriented towards noon, there is an increased magnetosphere magnetic field strength at the subsolar point in the southern hemisphere; when the magnetic axis is oriented towards midnight, there is an increased magnetosphere magnetic field strength in the northern hemisphere, resulting in lower magnetosphere plasma  $\beta$  and a region susceptible to large-scale reconnection. Tilting the spin axis to dawn or dusk tilts both the current sheet and region of enhanced magnetospheric magnetic field, thus changing the location of the reconnection viable region. The flanks, especially the dawn flank, are generally not viable for reconnection. The dusk flank is viable for reconnection when the IMF has a northward component that is antiparallel to the planetary dipole field.

In Figure 43, a plasma pressure contribution from the energetic population is added to the magnetosheath. As in Figure 42, the magnetopause near the subsolar region is viable for reconnection, however these regions are generally small. The increase in the magnetosheath plasma pressure reduces the  $\Delta\beta$  across the magnetopause, increasing the region viable for reconnection. Depending on the spin axis orientation, the flanks become viable for reconnection. Even in cases of a southward component of the IMF, which is aligned with the planet's dipole magnetic field, reconnection is viable on the flanks. This differs from Jupiter, where the onset of reconnection was inhibited on the flanks in the case of southward IMF, due to the antiparallel magnetic fields on the flanks. This difference can be attributed to the magnetic field orientation on the flanks at Saturn. The magnetic field in the magnetosheath is not completely aligned with the normal to the orbital plane because of the less-oblate



Figure 42: Region viable for reconnection at Saturn's magnetopause based on the effect of the diamagnetic drift. The plasma  $\beta$  in the magnetosphere is based on the energetic plasma pressure and magnetic pressure from the Khurana magnetic field model, while the plasma  $\beta$  in the magnetosheath is based on the Erkaev MHD simulation results. The region viable for reconnection is highly variable with both season (spin axis orientation) and IMF orientation. The regions near the equator that are viable for reconnection are generally small and near the subsolar region.



Figure 43: Region viable for reconnection at Saturn's magnetopause based on the effect of the diamagnetic drift. The plasma  $\beta$  in the magnetosphere is based on the energetic plasma pressure. The plasma  $\beta$  in the magnetosheath is based on the MHD simulation results plus a contribution equal to the energetic plasma pressure in the magnetosphere. The region viable for reconnection is highly variable with both season (spin axis orientation) and IMF orientation. The regions near the equator viable for reconnection are generally small and near to the subsolar region. The contribution of the energetics in the magnetosheath increases the region viable for reconnection, especially on the flanks, because of a reduction in the  $\Delta\beta$  across the magnetopause.

shape. Additionally, the orientation of the spin axis significantly changes the magnetosphere magnetic field at the flanks, so that it is not necessarily normal to the orbital plane near the equator.

These results appear to differ slightly from the findings of *Masters et al.* [2012] who combined plasma pressure and magnetic field pressure measurements from instruments on the Cassini spacecraft to calculate the  $\Delta\beta$  across Saturn's magnetopause. They considered magnetopause crossings between June 2004 and August 2007 that vary between magnetic latitudes of -38° and 52° between Saturn local times of 03:25 and 17:37 [*Masters et al.*, 2011]. At this time, the northern hemisphere was in winter/carly spring, corresponding to the spin axis pointing between midnight and dawn, as in the second row of Figure 43. They found that large  $\Delta\beta$  measurements and low magnetic shears lead to suppressed reconnection for most of their crossings. Based on Figure 43, we would expect that near the magnetic equator reconnection would be viable, however the large range of magnetic latitude considered in *Masters et al.* [2012] covers a significant area that is at higher latitude and is not reconnection viable. It is therefore possible that the magnetopause crossings analyzed in *Masters et al.* [2012] were predominately at locations where our model predicts reconnection is not viable, which could explain the discrepancy seen in the results.

The results presented here are sensitive to the IMF strength and solar wind plasma  $\beta$ , which can vary substantially. *Jackman et al.* [2004] found that three types of interplanetary intervals were observed with the Cassini magnetometer instrument – weak IMF intervals where the IMF had an average value of ~0.06 nT, intermediate IMF intervals where the average was ~0.6 nT, and strongfield compression regions where the field strength averaged ~1.1 nT. Here I have considered only an intermediate field strength. Weaker field strengths would increase the plasma  $\beta$  in the magnetosheath, reducing the region viable for reconnection, while an increased field should increase the magnetic field strength in the magnetosheath, decreasing the plasma  $\beta$ .

## Conclusions

In this chapter I have explored how the diamagnetic drift may restrict the viability of largescale reconnection at Jupiter and Saturn's magnetopauses. The diamagnetic drift, a fluid drift that develops from a pressure gradient, can inhibit the ability of reconnection flow patterns to form. A criterion based on the change in the plasma  $\beta$  across the magnetopause and the magnetic field shear angle has been developed to test for the suppression of reconnection by the diamagnetic drift. I test this criterion at Jupiter and Saturn, and examine how changing the magnetopause shape and interplanetary magnetic field direction, as well as the spin axis orientation at Saturn, affect the suppression of reconnection by the diamagnetic drift. I use realistic plasma  $\beta$  values based on energetic plasma pressure measurements by spacecraft in both magnetospheres and the magnetic field models described in Chapter 2. I consider how the  $\Delta\beta$  is affected by leakage of the energetics from the magnetosphere to the magnetosheath.

My findings are summarized as:

- At Jupiter, the plasma β due to the energetic populations in the magnetosphere is high, resulting in a large Δβ, so that reconnection is suppressed except when the magnetic field shear angle is ~180°.
- Including leakage of the energetic plasma from the magnetosphere to the magnetopause at Jupiter increases the plasma  $\beta$  in the magnetosheath, and does not reduce the  $\Delta\beta$  significantly. Leakage of the energetics does not increase the viability of reconnection at Jupiter.
- The region viable for large-scale reconnection at Saturn is a larger area relative to the magnetopause size than at Jupiter and is highly sensitive to the orientation of the planet's spin axis. The results presented here appear to agree qualitatively with the conclusions of *Masters et al.* [2012] when the spin axis orientation is taken into account.

• Leakage of the energetic plasma, from the magnetosphere to the magnetosheath, increases the plasma  $\beta$  in the magnetosheath at Saturn, and decreases  $\Delta\beta$  so there is a slightly larger region of the magnetosphere viable for reconnection.

# CHAPTER 5 THE KELVIN-HELMHOLTZ INSTABILITY

As discussed in the Introduction, the Kelvin-Helmholtz (KH) instability is a flow-shear driven instability. It has been observed at Earth's magnetopause flank as a means to transfer plasma and momentum across the magnetopause boundary, especially when a northward IMF is present and the Dungey-cycle (large-scale reconnection) is not active. The non-linear vortices that develop twist the magnetic field and compress the magnetopause current sheet layer, leading to transport of mass, energy, and momentum across the boundary. This results in a viscous boundary across which the solar wind can interact with the magnetophere. The KH instability is stabilized by the magnetic tension force from magnetic field components in the plane of the velocity shear; the instability criterion is given in Equation (11).

At Earth's magnetopause, the KH instability has been studied extensively. 2-D MHD simulations have been used to show that the KH instability is an effective means of transporting mass across the shear boundary [*Nykyri & Otto*, 2001]. *Foullon et al.* [2010] used multi-spacecraft observations to confirm the presence of KH waves at the terrestrial magnetopause; their analysis suggests that the instability may be affected by the 3D geometry inherent in this environment. *Hasegawa et al.* [2004] also reported spacecraft observations of KH vortices on the flank of the magnetopause, tailward of the planet on the dusk flank.

Due to the weak magnetic fields and fast plasma flows on either side of the magnetopauses of Jupiter and Saturn, it has been hypothesized that the KH instability will be active at these planets. *Delamere & Bagenal* [2010] presented a model of the interaction of the solar wind with Jupiter's magnetosphere that include a significant contribution from the KH instability. *Masters et al.* [2009] showed evidence of surface waves at Saturn's magnetopause that were driven by the KH instability. Masters et al. [2010] showed evidence of a KH vortex on the dawn flank of Saturn's magnetopause. Delamere et al. [2011] used spacecraft measurements to constrain hybrid code simulations (discussed in more detail in Chapter 6) of the Saturnian KH unstable magnetopause boundary and found that the instability would lead to significant transport of mass and momentum between the solar wind and magnetosphere. Wilson et al. [2012] analyzed data from the Cassini spacecraft to identify two KH vortices at Saturn's magnetopause on the dawn flank.

The models of plasma flow and the magnetic field in the magnetosheaths and magnetospheres of Jupiter and Saturn, described in Chapter 2, are used to analyze the instability criterion. In order to determine if the instability is destabilized, I have rotated the direction of the wave vector  $\mathbf{k}$  at each grid point in the plane of the magnetopause until the ratio of the left hand side of Equation (11) to the right hand side is maximized. Generally, the wave vector direction will be close to parallel with the direction of the shear in the flow across the magnetopause. However, when there is a significant component of the magnetic field parallel to the shear flow the wave vector may point in a different direction.

### Kelvin-Helmholtz instability at Jupiter

At Jupiter there are high shear flows on the dawn flank, and down the tail flank, as shown in Figure 44 and Figure 45. In Figure 44 the total velocity shear, the magnitude of the difference in the velocity vectors across the magnetopause, is plotted for the three asymmetric magnetopause shapes and two IMF orientations originally presented in Figure 12. As expected, the shear is generally maximized on the dawn flank and minimized on the dusk flank. However, due to the presence of the stagnation line in the magnetosheath the shear is not maximized in the equatorial region. As the asymmetry of the magnetopause increases, the rotation of the stagnation



Figure 44: Total shear flow across the jovian magnetopause for the three magnetopause asymmetries presented in Chapter 2. The shear is generally maximized on the dawn flank and minimized on the dusk flank. For the least symmetric magnetopause shape (top) the shear is highest at high latitudes, and lower in the equatorial plane due to the presence of the stagnation line. As the asymmetry of the magnetopause increases, the stagnation line rotates out of the equator and the region of maximum shear is rotated towards the equatorial plane. The shear tailward of the planet on the dusk flank is also increased with the increased asymmetry.
line causes the region of maximum shear to move closer to the equatorial region. In addition, the shear flow increases on the dusk flank tailward of the planet.

In Figure 45 the shear flow is plotted for four IMF orientations. The shear flow pattern is identical when the IMF is rotated by 180° (top left to bottom left; top right to bottom right). For all



Figure 45: Shear flow across Jupiter's magnetopause for four orientations of the IMF. Rotating the IMF by 180<sup>o</sup> (top left to bottom left; top right to bottom right) results in identical shear flow patterns. The shears in all cases are maximized on the dawn flank near the equator and tailward of the planet on the dusk flank.

four cases the shear is almost identical in the equatorial plane. In all cases the shear is maximized on the dawn flank near the equator and tailward of the dusk flank.

In Figure 46 the region of Jupiter's magnetopause that exhibits Kelvin-Helmholtz instability behaviors is plotted. For each of the three magnetopause shapes as well as the two IMF orientations the dawn flank near the equator is unstable. The region of instability on the dawn flank is very thin in latitudinal extent, suggesting that is highly dependent on the position of the dense plasmasheet (Figure 28). In addition the bent-back field on the dawn flank above and below the equator may act as a stabilizing force. As the asymmetry of the magnetopause increases, the shear flow on the dusk flank tailward of the planet increases (Figure 44) and becomes unstable to the KH instability. This region is thicker than the unstable region on the dawn flank, due to a combination of the thicker plasmasheet and more dipolar magnetic field. The variation with IMF direction is small; there is a reflection across the equator with the rotation of the IMF from 85° to 95°, and the unstable region on the dusk flank develops further with increasing asymmetry.

The Kelvin-Helmholtz unstable region at Jupiter's magnetopause for the cases presented in Figure 45 is shown in Figure 47. Four IMF orientations are presented for the most asymmetric magnetopause shape. Rotating the IMF orientation by 180° (top left to bottom left; top right to bottom right) results in identical regions of instability. In all cases the equatorial region is stable to the KH instability between noon and three local time, where shears are minimized (Figure 45).

The results presented in Figure 46 and Figure 47 suggest that the KH instability on the dawn flank may be less sensitive to changing conditions at the magnetopause than large-scale reconnection was found to be in Chapters 3 and 4. KH vortices on the dawn flank may be difficult to observe due to the thin extent of the KH unstable region; they may be easier to observe on the dusk flank tailward of the planet where the unstable area is thicker.



Figure 46: Region at the jovian magnetopause that is Kelvin-Helmholtz unstable for the cases presented in Figure 44. For the least asymmetric case (top) the magnetopause is only unstable near the equatorial plane, where the plasma sheet is dense but thin. As the asymmetry increases, the dawn flank becomes more unstable, but the region of instability remains thin . The increasing asymmetry also causes the dusk flank tailward of the planet to become unstable, due to the increased shears on that flank (Figure 44). There is only a small variation in the unstable region with IMF orientation.



Figure 47: Region at Jupiter's magnetopause that is Kelvin-Helmholtz unstable for the cases presented in Figure 45. As with the shear flow pattern, the region of KH instability is identical for an IMF rotation of 180°. The magnetopause is generally KH stable between noon and three local time.

## Kelvin-Helmholtz instability at Saturn

At Saturn, as at Jupiter, shear flows are high at the magnetopause. In Figure 48 the shear flow at Saturn's magnetopause is plotted for two IMF clock angles. The shear is greatest tailward of the planet on the dawn flank and minimized on the dusk flank in the equatorial region. The shear flows on the dawn flank are even greater than what was seen at Jupiter, possibly due to the variation in plasma rotation with radial distance from the planet, as discussed in Chapter 2. Because of the shape of the magnetopause, the shear does not increase tailward of the planet on the dusk flank as much as it does at Jupiter (Figure 44 and Figure 45).



Figure 48: Shear flow across Saturn's magnetopause. As at Jupiter, the shear is maximized on the dawn flank and minimized on the dusk flank. The region of minimum shear is located close to the equatorial region.

In Figure 49 the Kelvin-Helmholtz unstable region of Saturn's magnetopause is plotted. Four orientations of the planet's spin axis and two IMF orientations are presented. The thick dense plasmasheet and weak magnetic fields cause KH to be destabilized in the region of the plasmasheet regardless of the IMF orientation on the dawn flank. This unstable region varies significantly with latitude due to the varying location of the plasmasheet. The KH unstable region at the subsolar point and onto the dusk flank varies with both spin axis orientation and IMF clock angle. The region between noon



Figure 49: Kelvin-Helmholtz unstable region of Saturn's magnetopause for four spin axis orientations and two IMF orientations. The dawn flank is always unstable in the region collocated with the thick plasmasheet. This region varies in latitude significantly with spin axis orientation (season), as shown in Figure 29. The KH unstable region near the subsolar point and on the dawn flank varies significantly with both IMF orientation and spin axis, due to the variation in the stabilizing component of the magnetic field parallel to the shear flow.

and three local time is generally stable, due to the minimized shear (Figure 48), as at Jupiter, except when the spin axis/magnetic axis is pointed toward dusk and dawn. This variation associated with spin axis pointing is likely due to changes in the portion of the magnetospheric magnetic field that is parallel to the shear flow.

### Conclusions

In this chapter I have analyzed the onset criterion of the KH instability at the magnetopauses of Jupiter and Saturn for nominal solar wind conditions. The KH instability has been hypothesized to be a significant mediator of the solar wind interaction at the outer planets, due to the high shear flows and weak magnetic fields. My findings can be summarized as follows:

- At Jupiter, there is a region near the equator of the dawn flank where the magnetopause is KH unstable regardless of magnetopause shape or IMF orientation. This area is thin and collocated with the magnetosphere plasmasheet.
- At Jupiter, as the asymmetry of the magnetopause increases toward the shape found in the gas-dynamic modeling of *Stahara et al.* [1989], the dusk flank of the magnetopause tailward of the planet becomes unstable.
- The Saturn magnetopause is also KH unstable on the dawn flank in the plasmasheet region. The location of the plasmasheet and the KH unstable region will change with season (spin axis pointing) due to the significant angle between the spin axis and the normal to the ecliptic.
- The region between the subsolar point and the dusk flank can be KH unstable. However, this result is highly dependent on the direction of the spin axis pointing.

Changing the direction that the spin axis is pointed changes the magnetic field direction and strength at the magnetopause.

These findings generally support observation of KH at Jupiter and Saturn to date. Due to the small latitudinal extent of the KH unstable region at Jupiter, particularly on the dawn flank, direct observation of the vortical structures in the plane of the plasmasheet may be difficult, explaining why there have been few measurements of KH at Jupiter. On the other hand, the region of KH instability at Saturn is very large when compared to the overall size of the magnetopause. KH vortices and surface waves due to the KH instability have been observed at Saturn's magnetopause, as expected from my results. Additionally, the findings of *Delamere et al.* [2012], who examined Cassini data for magnetic field signatures of the KH instability, suggest that the instability may be active in the prenoon and subsolar regions of the magnetopause. This conclusion is also supported by my findings.

# CHAPTER 6 HYBRID CODE SIMULATIONS OF THE KELVIN-HELMHOLTZ INSTABILITY

In the previous chapters I used models of the plasma conditions and magnetic field on either side of the magnetopause at Jupiter and Saturn to analyze whether the onset of large-scale reconnection and the Kelvin-Helmholtz (KH) instability were viable. I found that while the onset of large-scale reconnection was highly sensitive to changes in solar wind and magnetosphere conditions, the boundary was KH unstable on the dawn flanks at both planets independent of these changes. Additionally, regions of the dusk flanks of Jupiter and Saturn's magnetopauses were KH unstable; however this region of instability was sensitive to changing magnetosheath and magnetosphere conditions. In this chapter I will use the model conditions at the KH unstable regions of these magnetopauses as input parameters to a hybrid (fluid electrons, kinetic ions) simulation. I will examine how the unique magnetic field geometries and plasma conditions affect the evolution of the KH instability as well as transport across the magnetopause boundary.

Hybrid simulations have often been used to model the KH instability. In these simulations, a boundary separates two distinct plasma environments. The boundary represents the magnetopause. The plasma flows on either side of the boundary are in opposite directions. Input parameters include bulk flow speed, plasma density and temperature, and magnetic field strength and orientation. A comprehensive review of hybrid simulations of the KH instability can be found in *Filippychev* [2002]. Recent studies of the KH instability have explored how asymmetries in the density and temperature [Cowee et al., 2009] as well as a magnetic shear across the boundary between the two environments affect the development of the KH instability [*Cowee et al.*, 2010]. The instability has been analyzed with both two- and three-dimensional codes [*Filippychev*, 2002].

*Convee et al.* [2009] and *Convee et al.* [2010] used input parameters based on the terrestrial magnetosheath and magnetosphere to model the KH instability in two-dimensions. The magnetic field normal to the boundary was taken to be zero. *Convee et al.* [2009] found that as the asymmetry in the plasma density across the boundary increases, the growth of large-scale vortices is suppressed and transport across the boundary decreases. *Convee et al.* [2010] added a shear in the magnetic field to their simulations. The magnetosphere magnetic field was oriented perpendicular to the shear flow, while the magnetosheath magnetic field was rotated so that it was allowed to have a component parallel to the shear flow. They considered shear angles of 0°, 15°, and 30° and found that as the shear angle increased, the increasing magnetic field component parallel to the shear flow stabilized the KH instability, decreasing growth.

The hybrid simulation used in this thesis was written by P. Delamere. The algorithms of the code were developed in *Swift* [1996]. The code has been applied to the solar wind interaction with Comet 19P/Borrelly, Pluto, and Saturn [*Delamere*, 2006; *Delamere*, 2009; *Delamere et al.*, 2011; *Delamere et al.*, 2012]. The simulation domain is two-dimensional, assumes quasi-neutrality (the density of electrons and ions is approximately equal), and is non-radiative. The simulation is in the x-z plane with the velocity shear initialized in the x direction. The shear boundary separates two distinct regions, which is a model for the magnetopause boundary between the magnetosheath and magnetosphere.

In the hybrid code model, the electrons are modeled as a fluid and the electric field is related to the electron flow by the electron fluid momentum equation,

$$\mathbf{E} = -\mathbf{u}_{e} \times \mathbf{B}, \tag{27}$$

where for computational ease **E** is the electric field in units of proton acceleration,  $\mathbf{u}_{e}$  is the electron flow velocity, **B** is the magnetic field in units of the proton gyro-frequency, and  $\mathbf{B} = \mathbf{B}_{0} + \mathbf{B}_{1}$ .  $\mathbf{B}_{0}$  is the curl-free ambient magnetic field and  $\mathbf{B}_{1}$  is the variable magnetic field. The electron flow speed is evaluated from Ampère's law, and Faraday's law is used to update the first order magnetic fields, so that

$$\frac{\partial \mathbf{B}_{1}}{\partial t} = -\nabla \times \left[ \left( \frac{\nabla \times \mathbf{B}_{1}}{\alpha n} - \mathbf{u}_{i} \right) \times \mathbf{B} \right]$$
(28)

where  $\alpha = (\mu_0 e^2)/m_p$ , *n* is the plasma density, and **u**<sub>i</sub> is the ion bulk flow. The ambient magnetic field strength,  $B_0$ , is held constant across the shear boundary, but the initial direction may be rotated so that there is a variable in-plane magnetic field component. The in-plane component is given by  $B_{0x} = B_0 \sin \phi$ ;  $\phi$  is the angle that the magnetic field makes with the normal to the simulation plane. Note that, by necessity, **B** in the Z-direction (normal to the shear boundary) is zero.

The velocity shear has a hyperbolic tangent profile of the form

$$v_{sh}(z) = \frac{v_0}{2} \tanh(z/L_0).$$
 (29)

The total velocity jump across the boundary is  $v_0$  and the scale length of the jump is  $L_0$ . This profile is often used [*Filippychev*, 2002] because it ensures a smooth transition across the boundary and takes into account the finite thickness of the transition region. The finite thickness of the transition region suppresses the growth of small wavelength modes of the KH instability [*Miura & Pritchett*, 1982]. The plasma density and temperature across the boundary are allowed to vary. The ion population on the magnetosphere side contains both heavy ions from the internal plasma sources and protons, while the ion population on the magnetosheath side, due to the solar wind, is only protons. The heavy ions result in an increased mass density in the magnetosphere, increasing the plasma momentum from a purely proton population. The inclusion of the heavy ions is unique to the outer planets, and is not usually considered in modeling the KH instability at the terrestrial magnetopause.

#### Properties at the KH active magnetopauses of Jupiter and Saturn

In order to simulate the KH instability at Jupiter and Saturn, realistic values for the plasma parameters and magnetic field at the KH active region are needed. I analyzed the regions of KH activity determined in Chapter 5. I compiled average values of the parameters in the equatorial region of the dawn flank and KH active dusk flank tail at Jupiter, as well as the dawn flank of Saturn's magnetopause. These average parameter values are reported in Table 4 and Table 5.

At Jupiter I consider two cases of IMF orientation for the most asymmetric magnetopause shape, since the KH unstable region was shown to not vary significantly with the east-west component of the IMF or the magnetopause shape. The magnetosheath plasma density in the dawn KH active region is approximately ten to fifty times the magnetosphere plasma density; the heavy ions in the magnetosphere can reduce the ratio between the mass densities. For a density ratio between the magnetosheath and magnetosphere plasmas of 10, and taking the fraction of heavy ions (mass 16) in the magnetosphere as 0.25, the mass density ratio between magnetosheath and magnetosphere is 2. The thermal speed in the magnetosheath at both flanks is ~200 km/s. The magnetic field angle ( $\phi$ ) relative to the shear boundary normal varies on both sides of the boundary. The magnetic field strengths in the magnetosheath and magnetosphere are generally comparable at ~5 nT.

At Saturn, I compiled average values for the plasma and magnetic field parameters for two IMF orientations and the four spin axis orientations considered in this thesis. Due to the variability in the KH active region on the dusk flank, I considered only points on the dawn flank. The magnetosheath plasma density is  $\sim 0.1$  cm<sup>-3</sup>, whereas the magnetosphere plasma density varies between 0.01 and 0.05 cm<sup>-3</sup>. As at Jupiter the thermal speed in the magnetosheath is  $\sim 200$  km/s. The magnetic fields are weaker than at Jupiter,  $\sim 2-3$  nT on either side of the boundary. Additionally, the variation in the magnetic field angle relative to the shear boundary normal is larger, varying between 0 and 80

degrees. At both planets, the components of the magnetic field in the plane of the plasma shear flow and perpendicular to it are either parallel or anti-parallel depending on IMF orientation and spin axis pointing. Except for the magnetic field strengths and orientations, the values of the parameters at both planets are comparable, with similar plasma densities, thermal speed, and shear speeds.

IMF angle	MP flank	Sheath density [cm <sup>-3</sup> ]	Msp. density [cm <sup>-3</sup> ]	Sheath thermal speed [km/s]	Sheath B field [nT]	Msp. B field [nT]	Sheath B field angle	Msp. B field angle	Shear speed [km/s]
85°	dawn	0.2	0.005-0.02	200	4-7	4	0°-10°	5°-35°	450
85°	dusk	0.14	0.0025-0.01	175	5	4-7	10°-25°	5°-45°	200
95°	dawn	0.2	0.005-0.02	210	4-7	4	0°-5°	0°-10°	420
95°	dusk	0.15	0.0025	180	5	4	20°	20°-30°	240

Table 4: Parameters in the Kelvin-Helmholtz active region of Jupiter's magnetopause based on models described in Chapter 2 and results presented in Chapter 5. Magnetosphere properties are indicated by Msp. The magnetosheath and magnetosphere magnetic field angles are relative to the normal to the plasma shear.

IMF angle	Spin axis orientation	Sheath density [cm <sup>-3</sup> ]	Msp. density [cm <sup>-3</sup> ]	Sheath thermal speed [km/s]	Sheath B field [nT]	Msp. B field [nT]	Sheath B field angle	Msp. B field angle	Shear speed [km/s]
85°	dawn	0.1	0.05	200	3	0.5-1.5	10°-30°	0°-60°	420
85°	dusk	0.1	0.02	220	3	2-3	20°-30°	20°-50°	360
85°	midnight	0.1	0.02	200	3-4	1.5-3	10°-30°	10°-70°	400
85°	noon	0.1-0.15	0.02	220	3	1-3	20°-80°	10°-70°	360
95°	dawn	0.1-0.15	0.05	190-230	2.5-5	0.5-1.5	20°-50°	0°-80°	375
95°	dusk	0.1	0.01	190-210	2.5-5	1.5-3.5	10°-30°	20°-30°	400
95°	midnight	0.1-0.15	0.01	200-230	2-3	1.5-2.5	20°-80°	20°-60°	365
95°	noon	0.075	0.01	190	3-5	2	20°	45°	400

Table 5: Parameters in the KH active region of Saturn's magnetopause based on models described in Chapter 2 and results presented in Chapter 5. Msp. indicates magnetosphere properties. The magnetosheath and magnetosphere magnetic field angles are relative to the normal to the plasma shear.

Based on these findings I created a set of baseline parameters for modeling the KH instability

with the hybrid code at Jupiter and Saturn. These parameters are outlined in Table 6. The mass

density and number density vary across the boundary. The thermal speed in the magnetosphere is adjusted to enforce an initial balance in the plasma pressure across the shear boundary. Based on the range of conditions in Table 4 and Table 5, I used the hybrid code to examine how variations in the plasma density across the magnetopause affect the instability growth rate and plasma mixing. I also discuss how the orientation of the magnetic field affects the growth of the instability.

Parameter	Value
Magnetosheath density, [cm <sup>-3</sup> ]	0.2
Magnetosphere density. [cm <sup>-3</sup> ]	0.1
Magnetosheath thermal speed [km/s]	200
Fraction of heavies in magnetosphere	0.25
Mass of heavies [amu]	16
Magnetic field [nT]	3
Magnetosheath magnetic field angle	5°
Magnetosphere magnetic field angle	5°
Velocity shear jump [km/s]	350
Scale Length of velocity jump [km]	1200
Magnetosheath ion inertial length, $\lambda_i = c/\omega_{ni}$ [km]	720

Table 6: Baseline parameters for hybrid code simulations of the Kelvin-Helmholtz instability at the magnetopauses of Jupiter and Saturn.

The simulations were conducted on a 279 × 399 grid, spanning 116 × 166  $\lambda_i$  or 1.4 × 2 R<sub>s</sub> (1.2 × 1.7 R<sub>j</sub>). Boundary conditions are periodic in the x-direction, along the plasma flow, and reflective in the z-direction. The simulations were allowed to run for  $\omega_c t = 500 - 750$ , where  $\omega_c$  is the ion

cyclotron frequency. The number of particles in the magnetosphere varies between 80 and 200 particles per cell.

#### Effect of density asymmetry on the KH instability

In this section I consider the effect of an asymmetry in the plasma density across the magnetopause boundary. As indicated in Table 4 and Table 5, the asymmetry in the plasma density can be quite large, a factor of up to 100 at Jupiter and a factor of 2-5 at Saturn. When modeling the unstable boundary using the hybrid simulations, numerical stability of the code needs to be considered. The Courant condition requires that

$$\Delta t \le \Delta_{min}/|v| \tag{30}$$

(20)

where  $\Delta_{min}$  is the minimum grid spacing and v is the fastest propagation velocity. For the hybrid simulations this is the fastest Whistler mode, which determines the smallest wavelength supported on the grid. As the density decreases, the Alfvèn speed increases; therefore due to computational constraints I cannot consider an arbitrarily small magnetosphere plasma density. The asymmetric density cases considered are presented in Table 7.

Here I consider cases where the ratio of the magnetosheath (bottom) plasma density to the magnetosphere (top) plasma density  $(n_b/n_t)$  is 2 (baseline), 4, 6, and 8. It is important to note that the mass density ratios for the baseline case and Case 2 are less than one – the mass density is higher in the magnetosphere than in the magnetosheath. The thermal speed of the magnetosphere protons is varied to ensure pressure balance at the boundary. All other parameters are as for the baseline case.

	Number density ratio: $n_b/n_t$	Mass density ratio: $\rho_b \setminus \rho_t$
Case 1 (baseline)	2	8/19
Case 2	4	16/19
Case 3	6	24/19
Case 4	8	32/19

Table 7: Cases of asymmetric plasma density considered. The ratios of the magnetosheath (bottom) parameters to the magnetosphere (top) parameters are given. The asymmetry in density and mass density are not the same, due to the presence of the heavy ions. Note that in Cases 1 (baseline) and 2 the mass density in the magnetosphere is greater than the mass density in the magnetosheath. Additionally, the mass density of the heavies in Case 2 is equal to the mass density of the magnetosheath plasma.

The vortex evolution for the baseline parameters is shown in Figure 50. The magnetosphere is in the top half of the domain; the magnetosheath is modeled in the bottom half. The magnetopause boundary is at Z=0, indicated by the solid white line, and the dimensions are given in terms of Saturn radii for context. This simulation ran for  $\omega_{et} \sim 575$ . The small-scale vortices that initially develop coalesce into large-scale vortices through an inverse cascade. The size of the vortices is constrained by the size of the grid and the periodic boundary conditions: the largest mode that can be supported is the m=1 mode. There is coalescence to the m=2 mode, with two vortices in the simulation box, at t = 1500s, however the m=1 mode is not observed; this mode is expected to be observed for longer simulation run times. The color contours show the fraction of particles in each cell that were initialized in the top half of the box. The vortices initially develop on the magnetosheath side of the boundary, likely due to the high mass density in the magnetosheath. As the vortices are close to centered on the magnetopause. A profile along the dashed line in the t=1500s panel will be analyzed later in this chapter.



Figure 50: Evolution of the KH vortices for the baseline parameters outlined in Table 6. The magnetosphere is represented in the top half of the domain, the magnetosheath in the bottom half. The color indicates the fraction of particles in each cell that were initialized in the top half of the simulation domain. The vectors show the plasma flow velocity. There is development towards the m=2 mode, with two vortices filling the width of the box. The vertical dashed line in the third panel will be used to develop a profile of the plasma mixing with distance across the magnetopause.

In Figure 51 the evolution of Case 2 is shown. Again there is coalescence to the m=2 mode. Unlike in the baseline case, the vortical, wrapped-up structure is retained at t=2000s. This may be due to the mass density ratio across the boundary, which is close to one. The vortices are close to centered on the magnetopause, though the mixed cells are shifted slightly onto the magnetospheric side.



Case 3 is shown in Figure 52. There is evolution to the m=2 mode. At t=2000s, there is a breakdown of the vortical structures. This breakdown in the presence of a density asymmetry was also

Figure 51: Evolution of the KH vortices for the case based on the baseline parameters and with an increased density asymmetry of  $n_b/n_t = 4$  (Case 2). The magnetosphere is represented in the top half of the domain, the magnetosheath in the bottom half. The color indicates the fraction of particles in each cell that were initialized in the top half of the simulation domain. The vectors show the plasma flow velocity. The evolution reaches the m = 2 mode by t = 2000s. At this time the vortices are well formed, coherent, and round. The coherent structure may be due to the ratio of the mass density across the boundary, which is close to unity.

observed in the simulations of *Cowee et al.* [2009] and is attributed to the growth of secondary KH and Rayleigh-Taylor instabilities within the primary vortex [*Matsumoto and Hoshino*, 2004]. The penetration of magnetosheath plasma into the magnetosphere is much deeper than the penetration of magnetosphere into magnetosheath. Interpreted in the context of Jupiter and Saturn, where the



Figure 52: Evolution of the KH vortices for the case based on the baseline parameters and with an increased density asymmetry of  $n_b/n_t = 6$  (Case 3). The magnetosphere is represented in the top half of the domain, the magnetosheath in the bottom half. The color indicates the fraction of particles in each cell that were initialized in the top half of the simulation domain. The vectors show the plasma flow velocity. The evolution reaches the m = 2 mode by t = 1000s. At this time the vortices are well formed and coherent, with a wave-like shape – the magnetosheath plasma is penetrating further into the magnetosphere than the magnetosphere plasma into the magnetosheath. The vortices appear to form preferentially on the magnetosphere side of the boundary, with the center of the vortices on that low-density side. At t=2000s, the vortices begin to break down, as discussed in the text.

density asymmetries can be even greater, this suggests that most of the plasma mixing occurs on the magnetosphere side of the magnetopause; this could be a source of the boundary layers observed at the outer planets. This asymmetry in the position of the mixing has been attributed to the RaleighTaylor instability, which moves plasma from high-density to low-density regions [Matsumoto, 2004; Cowee et al., 2009].

The evolution of the KH instability for Case 4,  $n_b/n_t = 8$ , is presented in Figure 53. The



Figure 53: Evolution of the KH vortices for the case based on the baseline parameters and with an increased density asymmetry of  $n_b/n_t = 8$  (Case 4). The magnetosphere is represented in the top half of the domain, the magnetosheath in the bottom half. The color indicates the fraction of particles in each cell that were initialized in the top half of the simulation domain. There is small-scale breakdown of the vortices; most of the mixing occurs on the magnetosphere side of the boundary.

vortices still evolve to the m=2 state by t = 1500s, however their structure deteriorates by t = 2000s.

The features observed in Case 3 - centering of the vortices in the magnetosphere as well as

penetration of the magnetosheath plasma into the magnetosphere – persist and are even more significant.

The amount of mixing that occurs in each of these cases is quantified in Figure 54. The total number of mixed cells ( $Mix_{in}$ ), defined as cells that contain between 25% and 75% of the particles initialized in the top half, normalized to the area of the velocity shear ( $A_0$ ), is plotted as a function of time [*Cowee et al.*, 2009; *Delamere et al.*, 2011]. The mixing increases with time as the vortices develop. *Cowee et al.* [2009] found that, without the inclusion of heavy ions, increasing the asymmetry in the plasma density (and mass density) across the boundary decreased the mixing. *Delamere et al.* [2011] found that increasing the mass of the heavies decreases plasma mixing due to the increased inertia of the heavy ions, however an asymmetry in the mass density across the boundary was not considered. Based on these studies, I would expect Case 1 to have the smallest amount of mixing, since the mass ratio across the boundary is the largest. Cases 2, 3, and 4 should have decreasing amounts of mixing. Instead, there is less mixing in Case 2, shown in Figure 53, than in Cases 3 and 4. This is likely related to the cohesive vortical structure which is retained in Case 2 (Figure 51).

Following *Delamere et al.* [2011], a diffusion coeffecient, which describes how mixed cells spread across the boundary, can be calculated using the time derivative of the width of the mixing region,

$$D(t) = \frac{dL_{mix}(t)^2}{dt}$$
(31)

where  $L_{mix} = L_0 \left(\frac{mix_{tot}}{A_0}\right)$ . The diffusion coefficient in these cases ranges from 2.7 × 10<sup>9</sup> to 5.9 × 10<sup>9</sup> m<sup>2</sup>/s.



Figure 54: Number of mixed cells normalized to the number of cells in the initial velocity shear region as a function of time. The mixing increases in all cases with time. Mixing decreases with increasing mass density asymmetry across the boundary; this is consistent with the findings of *Cowee et al.* [2009]. The case of  $n_b/n_t = 4$  appears to be an outlier, with less mixing than expected. This case also exhibits more cohesive instability vortices; this may be related to the mass density ratio across the boundary being close to 1.

The in-plane magnetic fields at t=1500s for these asymmetric density cases are shown in Figure 55. The development of magnetic filaments, thin regions of enhanced magnetic field strength that border the vortices, can be observed in all cases. The field strength in these filaments is ~3 nT, the field strength of the unperturbed background field. The energy density in these filaments is of the order of the plasma flow energy density. Once again Case 2,  $n_b/n_t = 4$ , shows features which differ significantly from the other cases. The vortices are less rounded, and the magnetic filaments do not completely surrounded the vortices.



Figure 55: In-plane magnetic field at t=1500 s for the baseline case (top left), and cases of increasing density asymmetry. In the baseline case, the magnetic field filaments that border the vortices are fairly symmetric in the magnetosphere (top) and magnetosheath (bottom) regions. For Cases 3 and 4 the filaments become thicker in the low-density region on top, while becoming less pronounced in the higher density region at the bottom. The case of  $n_b/n_t = 4$  clearly deviates from the pattern of the other cases.

Hybrid code simulations can be used to understand spacecraft observations. Figure 56 is an example of observations at Saturn's magnetopause by the Cassini spacecraft. Magnetic field components as well as electron density and temperature are measured. *Masters et al.* [2010] analyzed the data presented in Figure 56 and found evidence of a vortex (indicated by the dashed lines). This evidence included a twisted in-plane magnetic field, with large variations of the in-plane components, B<sub>x</sub> and B<sub>y</sub> as well as deflection of the plasma bulk flow. *Wilson et al.* [2012] re-examined this data along with ion data from the same time period and also found evidence of vortices in this region.



Figure 56: An example of observations from the Cassini spacecraft. From *Masters et al.* [2010]. (a) KSM components of the magnetic field. (b) Magnetic field magnitude. (c) Magnetic field elevation angle, defined as the angle between the field vector and the KSM x-y plane, with 90° and -90° corresponding to field vectors in the positive and negative z directions, respectively. (d) Electron number density (red) and temperature (blue). The dashed vertical lines indicate the start and end of an encounter with a KH vortex.

For comparison with Figure 56, I took profiles of the plasma mixing, plasma density, and magnetic field along the dashed lines in Figures 50-54. These profiles are presented in Figures 57-60. The mixing shows where the vortices are centered. For the baseline case, Figure 57, the oscillation between magnetosheath composition on the left to magnetosphere plasma, back to magnetosheath, and finally completely into the magnetosphere is seen in both the mixing ratio and the total plasma density. The magnetic field similarly shows a structure due to the KH vortex. A bipolar signature in  $B_x$ , parallel to the shear flow and  $B_z$  perpendicular to the shear flow, in the plane of the shear is evidence of the enhanced magnetic field (Figure 55) filaments bordering the vortex.



Figure 57: Profile of plasma mixing, density, and magnetic field through a vortex for the baseline case presented in Figure 50. The profile traverses the vortex from the magnetosheath (left) to the magnetosphere (right). Oscillations in the plasma composition (mixing) and plasma density are indicative of the center of the vortex at  $Z\sim 0$  R<sub>s</sub>. Bipolar signatures of the in-plane magnetic field due to the magnetic filaments border the vortex region.

In Case 2, with a density asymmetry  $n_b/b_t = 4$ , there are signatures of the edge of the vortex at -0.25 R<sub>s</sub> and ~0.3 R<sub>s</sub>. There are enhancements of the in-plane magnetic field bordering the vortex region. The vortex region is broader than in the previous case. There are signatures on either side of the vortex where there are significant density and composition changes, which may be an observable signature in data.



Figure 58: Profile of plasma mixing, density, and magnetic field through a vortex for the  $n_b/n_t = 4$  case presented in Figure 51. The profile traverses the vortex from the magnetosheath (left) to the magnetosphere (right). Bipolar signatures of the in-plane magnetic field due to the magnetic filaments border the vortex region. These signatures are shifted slightly off center toward the magnetosphere side due to the preferred location of the vortex center on this side of the boundary. The mixing region is broad and fairly uniform. There are signatures of reduced and enhanced plasma density bordering the vortex.

In Figure 59 the simulated data along the dashed white line in Figure 52 is presented. The density asymmetry across the magnetopause boundary is now a factor of 6, while the mass density ratio between the magnetosheath and magnetosphere is ~1.25. The vortex region is between -0.15  $R_s$  and 0.3  $R_s$ , as indicated by the bipolar signatures in the in-plane magnetic field. Rather than the sharp changes in density at the boundaries of the vortex, there is a gradual increase in the mixing (plasma composition) and a gradual decrease in the plasma density as the vortex is traversed from magnetosheath to magnetosphere. The vortex intrudes further into the magnetosphere than in the previous cases.



Figure 59: Profile of plasma mixing, density, and magnetic field through a vortex for the  $n_b/n_t = 6$  case presented in Figure 52. The profile traverses the vortex from the magnetosheath (left) to the magnetosphere (right). Bipolar signatures of the in-plane magnetic field due to the magnetic filaments border the vortex region. These signatures are shifted off center toward the magnetosphere side due to the preferred location of the vortex center on this side of the boundary. Rather than sharp changes in the plasma density at the boundaries of the vortex, as was observed in the previous cases, there is a slow transition between the magnetosheath and magnetosphere plasma composition.

In Figure 60 the simulated observations of the most asymmetric density case is presented. The vortex spans the region between  $\sim$ -0.125 and 0.375 R<sub>s.</sub> The bipolar magnetic field signatures are not as large in magnitude as the previous cases. There are oscillations between the magnetosheath and magnetosphere plasma composition as the vortex is traversed.



Figure 60: Profile of plasma mixing, density, and magnetic field through a vortex for the  $n_b/n_t = 8$  case presented in Figure 53. The profile traverses the vortex from the magnetosheath (left) to the magnetosphere (right). Slight bipolar signatures of the in-plane magnetic field ( $B_x$ ,  $B_z$ ) due to the magnetic filaments border the vortex region. The mixing region is broad and fairly uniform.

These examples of simulated observations show that there are specific signatures of KH activity in the plasma density measurements and magnetic field measurements. These signatures include the bipolar in-plane magnetic field, which bounds the vortex region and oscillations between magnetosheath and magnetosphere plasma compositions. A global survey of Cassini data for signatures such as these has been undertaken by *Delamere et al.* [2012]. They found that there are magnetic signatures consistent with KH vortices at Saturn's magnetopause, particularly in the sub-solar region.

## Effect of magnetic field shear angle on the KH instability

As was noted in the discussion of Table 4 and Table 5, there is significant variation in the magnetic shear angle with respect to the normal to the plasma flow plane. The effect of a magnetic shear on the KH instability was examined by *Cowee et al.* [2010]. They simulated the instability with a

two-dimensional hybrid code, using parameters typical for the terrestrial magnetopause. They held the magnetosphere magnetic field constant and purely northward, varying the direction of the magnetosheath magnetic field to create a shear between the fields. They found that cohesive vortices could develop with a small magnetic shear, and that, due to the stabilizing magnetic tension force (Equation 11), these vortices were sometimes more coherent than in the case of no magnetic shear when a density asymmetry was present. As was noted in the previous section, coherent vortices are more effective at transporting plasma across the boundary; a small magnetic shear could therefore counter the effect of a significant density asymmetry and lead to increased transport across the magnetopause. Magnetic shear angles up to 30° were simulated in *Cowee et al.* [2010]; it was found that these large shear angles resulted in fields parallel to the flow that were strong enough to decrease the KH growth.

These previous findings suggest that there may be a complicated interplay between the density asymmetries and magnetic field shear angles at the magnetopauses of Jupiter and Saturn. However, two-dimensional hybrid simulations artificially constrain the KH wave-vector to the plane of the plasma flow. When there is a component of the magnetic field parallel to the shear flow, the wave vector may be directed anywhere in the plane parallel to the boundary, so that it satisfies Equation (11). In order to accurately model a magnetopause boundary where there is a large magnetic shear angle, a three-dimensional hybrid code should be employed [*Filippychev*, 2002].

The effect of anti-parallel in-plane magnetic fields was not considered in *Cowee et al.* [2010]. I consider here a variation of the baseline case with the magnetosheath magnetic field angle equal to -5°. This creates a small magnetic field in the plane of the shear flow anti-parallel to the magnetosphere magnetic field. The evolution of the vortices with anti-parallel in-plane magnetic field components is plotted in Figure 61. When compared to Figure 50, it is apparent that the vortical structures remain

more cohesive at t=1500s. There is not as much small-scale breakdown of the vortices as in the baseline case.



Figure 61: Development of vortices for a case with baseline conditions and the addition of anti-parallel in-plane magnetic field components. The magnetosphere is represented in the top half of the domain, the magnetosheath in the bottom half. The color indicates the fraction of particles in each cell that were initialized in the top half of the simulation domain. The vectors show the plasma flow velocity. There is development towards the m=2 mode, with two vortices filling the width of the box. The vertical dashed line in the third panel will be used to develop a profile of the plasma mixing with distance across the magnetopause. Comparing with Figure 50, the vortices are more coherent at t=1500s, however by t=2000s they have begun to break down. There is not as much small-scale structure as in the baseline case.

In Figure 62 the evolution of the in-plane magnetic field for this case is presented. Initially, the

in-plane components on either side of the boundary are anti-parallel. As the vortices develop, the

fields bounding the vortices are still stronger than the background in-plane field, however the field strengths do not reach the strength of the baseline case (3 nT). This is likely due to the nulling effect of the in-plane fields in the vortical structures.



Figure 62: Evolution of the in-plane magnetic field for the baseline case with initial antiparallel in-plane magnetic field components. The white vectors show the in-plane magnetic field direction. Magnetic filaments bordering the vortices develop as in the baseline case, however the field strength in these filaments is much weaker, due to annihilation of the antiparallel magnetic fields.

Finally, we can consider how mixing is effected by anti-parallel in-plane magnetic field components (Figure 63). The mixing ratio for the baseline case (parallel in-plane fields) and this case are compared. Mixing is increased slightly with the anti-parallel in-plane fields. This can be attributed to the weaker magnetic filaments that form in the vortices. These filaments act as barriers for the plasma transport. Simulated observations along the dashed line in Figure 61 show weaker bipolar magnetic field signatures and a broader mixing region.



Figure 63: Comparison of plasma mixing for the baseline case and an altered baseline case with anti-parallel in-plane magnetic field components. There is more mixing in the anti-parallel case, possibly due to the development of weaker magnetic field filaments bordering the vortices that allow for greater plasma transport across the vortices.

## Conclusions

In this chapter, I used a hybrid code simulation to model environments at Jupiter and Saturn in which the Kelvin-Helmholtz instability may be active. The models described in Chapter 2 and analyzed in Chapter 5 exhibit an environment where the ratio of the plasma densities on either side of the magnetopause is highly variable. Additionally, the magnetic field shear angles can vary by as much as 90° in the KH active region. I used a two-dimensional hybrid code simulation to examine the effect of a density asymmetry on the development of the instability and mixing of the plasma. This is an example of how the large-scale models presented in this thesis can be used to constrain smaller-scale simulations. My findings in this chapter are summarized below.

- Mixing in the KH vortices is reduced by an increasing mass density ratio across the magnetopause. The mass density asymmetry, rather than the number density asymmetry, affects the mixing of the plasmas.
- Due to the density asymmetry, the KH vortices tend to develop on the magnetosphere (lowdensity) side of the boundary. This agrees with previous simulations as well as observations of KH vortices at Saturn. I propose that this enhanced plasma mixing in the magnetosphere may contribute to the development of boundary layers that have been observed at both Saturn and Jupiter.
- The magnetic shear configurations in the KH active regions at Saturn and Jupiter's magnetopauses will affect the growth and evolution of the instability. Anti-parallel in-plane magnetic field components increase the amount if mixing in the KH vortices. Three-dimensional hybrid code simulations should be used to explore the effect of the magnetic shear in more detail, in order to allow the wave vector to point out of the shear flow plane for larger in-plane magnetic field components.
- Cuts through the simulation domain can be used to create magnetic field and plasma density profiles with distance; these profiles can be compared to observation by spacecraft such as Cassini or Galileo. Hybrid simulations suggest there are signatures of KH vortices, such as bipolar in-plane magnetic field components bordering the vortices and oscillations in the plasma composition, which may manifest in spacecraft measurements.

# CHAPTER 7 CONCLUSIONS AND FURTHER STUDIES

In this thesis I have used models of the plasma conditions and magnetic field at the magnetopauses of Jupiter and Saturn to explore how conditions at the outer planet magnetopauses affect the onset of large-scale reconnection and the Kelvin-Helmholtz instability. I considered the effect of the large velocity shears on reconnection. I also considered the suppression of reconnection due to the diamagnetic drift created by a pressure gradient across the magnetopause boundary. Additionally, I used a hybrid code simulation to analyze how the evolution of the KH instability is affected by varying plasma conditions at the outer planet environments. I found the following:

- Although shear flows across Jupiter's magnetopause are high, due to the rotation of the
  magnetic field in the magnetosheath toward perpendicular with the shear flow, reconnection is
  viable along much of the magnetopause when the IMF has a component antiparallel to the
  planet's magnetic dipole. Reversing the Y-component of the IMF does not significantly effect
  where reconnection is viable in the equatorial region.
- At Saturn, shears are high on the dawn flank and low on the dusk flank, however the shear flow patterns are highly dependent on the planet's spin axis orientation. Due to less rotation of the magnetic field in the magnetosheath than at Jupiter, shear flows parallel to the reconnecting fields are generally higher, and reconnection is suppressed on the dawn flank. This differs significantly from Jupiter, where reconnection is always viable on the dawn flank when the IMF has a component anti-parallel to the planet's dipole. Similarly, reconnection is suppressed along more of Saturn's dusk flank than at Jupiter.

- At Jupiter, the plasma  $\beta$  due to the energetic populations in the magnetosphere is high, resulting in a large  $\Delta\beta$  across the magnetopause. This leads to suppression of large-scale reconnection by the diamagnetic drift along most of the magnetopause, except when the magnetic field shear angle is ~180°.
- At Saturn, the diamagnetic drift suppresses reconnection along part of the magnetopause, however the region viable for large-scale reconnection is a larger area relative to the magnetopause size than at Jupiter. These results are highly sensitive to the spin axis/magnetic axis orientation.
- At Jupiter, there is a region near the equator of the dawn flank where the magnetopause is Kelvin-Helmholtz (KH) unstable regardless of magnetopause shape or IMF orientation. This area is thin and collocated with the magnetosphere plasmasheet. For a highly asymmetric magnetopause, the dusk flank tailward of the planet is KH unstable.
- The Saturn magnetopause is also KH unstable on the dawn flank in the region of the plasmasheet. Due to the significant angle between the spin axis and the normal to the ecliptic, the location of the plasmasheet and the KH unstable region will change with season (spin axis pointing).
- Hybrid code simulations of the KH unstable regions at these planets suggest that the asymmetric density across the magnetopause promotes the evolution of the KH vortices in the magnetosphere. This may contribute to the development of the boundary layers in the magnetospheres observed at the outer planets.
- There are significant variations in the magnetic field shear angles across the magnetopauses of both Jupiter and Saturn. Previous two-dimensional studies suggest that the magnetic shear and density asymmetry may have countering affects on the evolution of the instability and the

amount of plasma mixing or diffusion. High magnetic shear angles are expected to suppress the development of the KH vortices. Consideration of anti-parallel in-plane magnetic field components show that this field orientation increases plasma mixing in the KH vortex region. Three-dimensional hybrid code simulations should be used to model the instability under these conditions, so that wave vector orientations out of the plane of the shear flow are not suppressed.

Generally, these findings suggest that at both planets the diamagnetic drift is the primary method by which large-scale reconnection can be suppressed. The high shear flows do not suppress reconnection as much as might be expected at Jupiter, due to the relative orientations of the shear flow and magnetic field. At Saturn, the shear flows can suppress reconnection, however this suppression is highly sensitive to spin axis orientation. It is possible that for a given spin axis orientation (9 year season), a large-scale reconnection pattern could develop. For example, the diamagnetic drift and the shear flow north of the subsolar point do not suppress reconnection when the spin axis is pointed towards midnight.

At both planets conditions are ripe for the Kelvin-Helmholtz instability. My analysis at Jupiter suggests that this instability is not sensitive to changes in IMF orientation. While there are variations in the KH active region at the subsolar point and on the dusk flank at Saturn, the dawn flank is continuously KH active. The KH instability appears to be a reliable means of mediating the solar wind interaction at both Jupiter and Saturn. Hybrid code simulations show that plasma mixing occurs preferentially on the low-density side of the velocity shear boundary (magnetosphere side). Three-dimensional hybrid simulations can be used to analyze the effect of the magnetic shear, which may result in a KH wave vector oriented out of the plane of the plasma shear flow.
## **Implications for Future Observations**

Few spacecraft have observed the magnetopause region and outer magnetospheres of Jupiter and Saturn. Pioneer 10 and 11 and Voyager 1 and 2 flew by the Jovian system in the 1970s; the Galileo spacecraft spent 8 years in the Jovian system beginning in 1995. Ulysses and Cassini also completed flybys of the outer jovian magnetosphere and magnetosheath. Pioneer 11 and the Voyager spacecraft also encountered Saturn. The Cassini spacecraft has been orbiting Saturn since 2004. The observations that have been analyzed and published are presented throughout this thesis. Unfortunately most other reported observations of the plasma and magnetic field at both planets either do not extend to the outer magnetosphere or are not well enough time-resolved to determine conditions at the magnetopause boundary.

There is a great deal of interest in the scientific community in the solar wind interaction at the giant outer planets. To this end, spacecraft observations have been examined for signatures of reconnection and the Kelvin-Helmholtz instability. *Walker & Russell* [1985] searched observations of Pioneers 10 and 11 and Voyagers 1 and 2 and found evidence for reconnection events between 0900 and 1400 local time (near the subsolar point) in the equatorial plane. These events were small scale both spatially and temporally. All events corresponded to a northward magnetosheath magnetic field. This agrees with my results that showed that neither a diamagnetic drift or velocity shear will suppress the onset of reconnection in this region, and that the KH instability is not active at the subsolar point.

*McAndrews et al.* [2008] analyzed two Cassini magnetopause crossings at Saturn's dawn flank, near the magnetic equator, that showed evidence of reconnection. A magnetic field component normal to the magnetopause was observed in the first crossing, evidence that the reconnection event was happening at the location of the spacecraft. The second crossing showed indirect evidence of reconnection; the authors concluded that reconnection was probably occurring at higher latitudes. These crossings are north of the equator in the KSO coordinate system used in this thesis, due to the dipole orientation towards midnight. While large-scale reconnection is not suppressed in this region due to the diamagnetic drift or velocity shear, the highly active Kelvin-Helmholtz instability in this region could also be responsible for the reconnection events observed.

Lai et al. [2012] used Cassini 1s resolution magnetometer data to search for evidence of reconnection between 1000 and 1400 local time. They found no evidence of large-scale reconnection in the approximately four-hundred magnetopause crossings they analyzed. The conclusions in this paper suggest that the suppression of reconnection in this region is highly sensitive to latitude and spin axis tilting. It is surprising that they found no evidence for large-scale reconnection, however they did observe brief periods during which there was a magnetic field component normal to the magnetopause. It is possible that merging of the magnetic fields occurred, but that because of the dynamic environment steady-state reconnection could not develop.

Evidence for the Kelvin-Helmholtz instability at Saturn is plentiful. *Masters et al.* [2009] and *Cutler et al.* [2011] found evidence of Kelvin-Helmholtz waves on the dawn and dusk flanks. They analyzed the variation in the normal to the magnetopause boundary that they attributed to surface waves likely due to the KH instability. *Masters et al.* [2010] reported an observation of a KH vortex on Saturn's dawn flank. They cited a twisted magnetic field structure and oscillating plasma properties as evidence of the vortex. *Wilson et al.* [2012] re-examined the data set originally analyzed by *Masters et al.* [2010]. With the inclusion of thermal ion data (plasma velocity, density, and temperatures), they found evidence of not one but two vortices in that one data set. This evidence included a rotation of the ion velocity vectors, with a drop off in the ion count in the center of the rotation region. *Delamere et al.* [2012] combined signatures of KH vortices from hybrid code simulations with a thorough survey of magnetic field data from Cassini and found signatures of KH vortices may have developed predominately in

the pre-noon sector and then been convected towards the subsolar point by the magnetospheric plasma flow.

It is this sort of observational evidence that will support the models presented in this thesis. The Juno spacecraft will hopefully return valuable data as it crosses Jupiter's magnetopause that will allow us to search for signatures of reconnection and the KH instability. In addition, Juno's extensive observation of Jupiter's poles will provide information about the polar magnetosphere and how open it is to the solar wind. Further analysis of the plasma measurements and magnetometer measurements from Cassini and Galileo will provide a deeper understanding of the environment at the outer planet magnetopauses and signatures of reconnection and the KH instability. It may also be prudent to return to previously analyzed data sets from Pioneers 10 and 11 and Voyagers 1 and 2 with fresh eyes, to search for the signatures of the KH instability and vortices described in *Masters et al.* [2009] and *Delamere et al.* [2012].

## Extension of this work

In this thesis, I have used idealized models of the conditions at the jovian and kronian magnetopauses to investigate the solar wind interaction. These models are steady state and ideal. With a more robust data set of plasma and magnetic field measurements, these models can be checked for accuracy. Due to the lack of high-latitude boundary measurements, the magnetopause shapes are not well constrained. Despite the highly variable stand-off distances at both planets, only one standoff distance at each planet was considered, due to the static magnetosphere magnetic field models being employed. The development of magnetospheric magnetic field models that vary with solar wind dynamic pressure will also lead to greater accuracy in modeling the solar wind interaction.

A description of the energetic particle population in the magnetosphere is not included at either planet. This population is expected to increase the plasma  $\beta$  in the magnetosphere, but observations in the outer magnetosphere are too limited to create a global description. There is some evidence that at Saturn and Jupiter the magnetospheric energetic population may leak into the magnetosheath, as discussed in Chapter 4. While the effect of an energetic population on the diamagnetic drift was considered, the energetics were not included in modeling the Kelvin-Helmholtz instability. It is unclear what the influence of an energetic population on the development of the instability would be, however this would be a natural extension of the hybrid code simulations presented in this thesis.

Boundary layers have been observed on the magnetospheric side of the magnetopause at both Saturn and Jupiter [*Staines et al.*, 1993; *Galvin et al.*, 1993] as well as at Earth. The origins of the boundary layers are not well understood, but, due to the mixed nature of the plasma, with both magnetospheric and magnetosheath plasma present, it is thought to be due in part to the interaction between the solar wind and the magnetosphere. A description of the boundary layers was left out of this study, which seeks to understand the nature of the solar wind-magnetosphere interaction. Additionally, at Jupiter there is evidence for a cushion region in the outer magnetosphere for 10's of R<sub>J</sub> behind the magnetopause, which is not evident at Saturn [*Went et al.*, 2011], through which the current sheet breaks down and the magnetic field has a more dipolar structure. This cushion region is thought to be due in part to the loss of mass down the tail due to the Vasyliunas cycle (Figure 8) and in part to the solar wind interaction. Including a description of the cushion region at Jupiter would change both the velocity shear (generally reducing the shear across the boundary) and the diamagnetic drift across the magnetopause. The KH instability might develop on either side of the cushion region boundary; a parameter study using the hybrid code that includes variations in velocity shear and plasma composition could be used to explore this effect.

Additional modeling with the hybrid code should be done to explore how the combination of an asymmetric density with an asymmetric magnetic field across the magnetopause boundary can affect the KH instability. Furthermore the hybrid code model should be extended to three-dimensions so that the wave vector is not artificially constrained to the plane of the plasma flow. Threedimensional modeling will provide the most realistic simulation when a magnetic shear is present across the magnetopause boundary. Improved simulations can be a tool for interpreting spacecraft observations and will lead to a more robust understanding of how conditions at space plasma boundaries can influence the development of instabilities.

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