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PLASMA OUTFLOW AND SUPERROTATION IN THE JOVIAN MAGNETOSPHERE DEDUCED FROM VOYAGER OBSERVATIONS

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PLASMA OUTFLOW AND SUPERROTATION IN THE JOVIAN MAGNETOSPHERE DEDUCED FROM VOYAGER OBSERVATIONS

by

MARC ROTAN HAIRSTON

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF PHILOSOPHY

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May, 1986
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Marc Rotan Hairston

ABSTRACT

Magnetometer and plasma science data from the Voyager 1 and Voyager 2 encounters of Jupiter are combined with earlier theoretical analysis by T. W. Hill and V. M. Vasyliunas to determine the total mass outflow rate and radial bulk velocity of the magnetospheric plasma in the Jovian plasma sheet, as well as the height integrated Pedersen conductivity of the Jovian ionosphere. The analysis requires accurate determination of the orientation of the plasma sheet using magnetometer data surrounding the plasma sheet crossing points. This analysis has been applied to fifteen crossings of the Jovian plasma sheet on both the day side and the night side. Results obtained from this analysis are believed to be accurate within a factor of two, and confirm previous order-of-magnitude estimates. Evidence of an enhanced outflow of plasma in the "active hemisphere" of System III longitude is observed on the dayside. On the night side, evidence of plasma inflow and superrotation is seen in the "inactive hemisphere." These two observations lend support to the corotating-convection model of plasma transport in the Jovian magnetosphere.
O Star (the fairest one in sight),
We grant your loftiness the right
To some obscurity of cloud--
It will not do to say of night,
Since dark is what brings out your light.
Some mystery becomes the proud.
But to be wholly taciturn
In your reserve is not allowed.
Say something to us we can learn
By heart and when alone repeat.
Say something! And it says, 'I burn,'
But say with what degree of heat.
Talk Fahrenheit, talk Centigrade.
Use language we can comprehend.
Tell us what elements you blend.
It gives us strangely little aid,
But does tell something in the end.

from "Choose Something Like A Star"
by Robert Frost
The other scene is a nocturne. I see myself bathing with Hyoï in the warm lake. He laughs at my clumsy swimming, accustomed to a heavier world, I can hardly get enough of me under the water to make any headway. And then I see the night sky. The greater part of it is very like ours, though the depths are blacker and the stars brighter; but something no terrestrial analogy will enable you fully to picture is happening in the east. Imagine the Milky Way magnified—the Milky Way seen through our largest telescope on the clearest night. And then imagine this, not painted across the zenith, but rising like a constellation behind the mountain-tops—a dazzling necklace of lights brilliant as planets slowly heaving itself up till it fills a fifth of the sky and leaves a belt of blackness between itself and the horizon. It is too bright to look at for long, but it is only a preparation. Something else is coming. There is a glow like moonrise on the harandra. Ahíhra! cries Hyoï, and the other baying voices answer him from the darkness all around us. And now the true king of night is set up, and now he is threading his way through that strange eastern galaxy and making its lights dim by comparison with his own. I turn my eyes away, for the little disk is far brighter than the Moon in her greatest splendour. The whole handramit is bathed in colourless light. And now I guess what it is I have seen—Jupiter rising beyond the Asteroids and forty million miles nearer than he has ever been to earthly eyes. But the Malacandrians would say 'within the Asteroids,' for they have an odd habit, sometimes, of turning the solar system inside out. They call the Asteroids the 'dancers before the threshold of the Great Worlds.' The Great Worlds are the planets, as we should say, 'beyond' or 'outside' the Asteroids. Glundandra (Jupiter) is the greatest of these and has some importance in Malacandrian thought which I cannot fathom.

—Out of the Silent Planet

C. S. Lewis
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"The time has come," the Walrus said,
"To talk of many things.
Of friends, of thanks, of gratitude,
And certainly of funding."

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... and last, but certainly not least, thanks go to my advisor at Duke, Dr. Horst Meyer, for his long-standing (albeit unwitting) encouragement that I go into Space Physics.

The Unicorn spoke quietly to him. "You are a true wizard now, as you always wished. Does it make you happy?"

"Well," Schmendrick said slowly, "Men don't always know when they're happy, but I...I think so."

—The Last Unicorn
Peter S. Beagle

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I. INTRODUCTION

Despite the fact that only four spacecraft have been sent to it, and that all four have been only fly-bys, Jupiter and its magnetosphere have been the objects of intense study and scrutiny for over thirteen years now. With such a small data set compared to the huge data set that has been amassed about the Earth's magnetosphere in the past twenty-eight years, it is impressive how much understanding about the Jovian magnetosphere has been achieved. Still, the researchers in this field currently find themselves in the precarious (or perhaps ideal) situation where they have just enough data to give a broad outline of the nature of the Jovian magnetosphere, but not enough to definitely prove or disprove many of the intriguing ideas and implications that have arisen. Until the Galileo spacecraft arrives in Jovian orbit sometime in the late 80's or early 90's all Jovian magnetospheric work, such as this thesis, must consist of a detailed and careful examination of data sets provided by the two Voyager encounters and the two Pioneer encounters augmented by ground-based radio and optical observations.

By almost every measure Jupiter is the "champion" of the planets. Over a thousand times the volume of the Earth, it is larger than all the other planets combined. Despite its large size it spins very rapidly, turning once every nine hours, fifty-eight minutes, and thirty seconds. Since 1955 when radio signals were first detected emanating from Jupiter by Burke and Franklin (1955), it has been known that Jupiter possessed a magnetic field similar to the Earth's. That magnetic field was first measured directly when Pioneer 10 flew past Jupiter in 1973. It found
Jupiter possessed a dipole magnetic moment of about 4.0 Gauss-R\(_J\) (again, the largest of the planets) and tilted about 10 degrees relative to the Jovian spin axis. Pioneer also found a huge magnetosphere surrounding the planet, a magnetosphere so large that, if it were a visible object, its face-on orientation would appear on Earth to be four times the size of the full moon. The magnetosphere was found to be greatly distorted from a simple dipole shape to a "puffed-out" shape by the internal pressure and currents carried from the trapped plasma. Pioneer 11 confirmed these findings when it passed Jupiter in 1974. The more sophisticated Voyagers 1 and 2 swung past Jupiter in March and July (respectively) of 1979 and further enhanced and complicated our understanding of the Jovian magnetosphere. Figure I.1 shows a currently popular picture of the general morphology of the Jovian magnetosphere.

The differences between Jupiter's magnetosphere and the Earth's magnetosphere are so great as to place them in two separate categories. Earth's magnetosphere is directly affected by the solar wind. Much of the trapped plasma in the Earth's magnetosphere comes from the solar wind plasma that "leaks in" near the polar cusps. The solar wind's interaction with the Earth's magnetic field is the primary driver (both directly and indirectly) of most of the magnetospheric phenomena we observe. On the other hand, the large amount of trapped plasma in the Jovian magnetosphere comes almost entirely from an internal source: the satellite Io. Although there is still much controversy surrounding the exact mechanism for transporting material off of Io, it is generally accepted that Io emits something on the order of 10\(^{30}\) amu/s of material (mostly sulfur, oxygen, and sodium) into the magnetosphere. Also, owing
Figure I.1 Cartoon giving a three dimensional view of the currently accepted general model of the Jovian magnetosphere morphology. Jupiter is seen surrounded by a relatively thin sheet of plasma that roughly corotates with the planet at nearby distances, and streams away from the planet out in the distant tail (creating the magnetospheric wind).

Reprinted from Krimigis and Roelof (1983)
to the fast spin rate of Jupiter and the coupling of the ionosphere to the magnetosphere by means of field aligned (Birkeland) currents, most of the Jovian magnetospheric phenomena are driven by Jupiter's rotational energy (Hill et al., 1983).

This trapped plasma around Jupiter is kept in partial corotation with the planet by the currents flowing between the ionosphere and magnetosphere (Hill, 1979). The centrifugal force acting on this rotating plasma stretches the plasma out into a relatively thin disk called the plasma sheet. Eventually the centrifugal force overcomes the weak magnetic field in the magnetotail region and causes the plasma to escape out the tail. This results in a "planetary wind" of plasma in the far tail (Hill, Dessler, and Michel, 1974; Michel and Sturrock, 1974). As the loss of plasma through the "planetary wind" is balanced by the continuous introduction of plasma from Io and the Io torus, the result is a persistent outward transport of plasma through the plasma sheet.

The exact mechanism and description of this plasma transport has been a subject of much theoretical work and speculation for several years (see review article by Vasyliunas, 1983). One of the more intriguing possibilities was suggested by Vasyliunas (1978) and developed by Hill, Dessler, and Maher (1981). Owing to an asymmetry in the Jovian magnetosphere there is a region of enhanced Birkeland currents and increased plasma density in the plasma sheet known as the "active sector." The enhanced currents within this active sector set up a convection pattern in the plasma sheet, and this flow pattern corotates with Jupiter. Within this pattern, the denser plasma in the
active sector lags behind corotation while the less dense plasma on the opposite side of Jupiter may rotate faster than the corotation speed (superrotation). The apparent lack of evidence for superrotation in the Voyager spacecraft data led to modification of this model (Hill, Goertz, and Thompson, 1982) in the form of a "hybrid" model in which the average plasma transport is outward at all longitudes, but is enhanced in the active sector.

Although there has been much theoretical work on the question of plasma transport and related phenomena, there have been only rough order-of-magnitude estimates of many of the pertinent physical variables. This thesis presents the first detailed analysis of magnetometer and plasma data from the two Voyager encounters in order to determine the mass outflow rate and average radial velocity of the plasma in the plasma sheet, as well as the ionospheric height integrated Pedersen conductivity. Owing to the tilt of the Jovian magnetic dipole axis relative to the spin axis, the plasma sheet is not a simple flat disk, but a warped and twisted surface. Thus this analysis requires modelling of the plasma sheet in order to determine its local orientation and overall geometry. The results were analyzed to find if there were any variations of mass outflow rate, radial bulk velocity, and/or height integrated Pedersen conductivity with respect to the active sector. The results are consistent with enhanced outflow and increased conductivity in the active longitude sector when it is on the dayside. This work also revealed the first evidence of possible superrotation of plasma in the nightside plasma sheet.
II. BACKGROUND

In March 1979, and again in July of that same year, the giant planet Jupiter was host to two small robot spacecraft from the Earth. Swinging past the planet on their way to Saturn each of these spacecraft covered a large section of the Jovian magnetosphere. Approaching the planet in the dayside dawn to noon quadrant, both spacecraft passed within four and nine Jovian radii (respectively) of the surface, then passed down the magnetotail in the midnight to dawn quadrant and on out of the magnetosphere (Figure II.1). While these two encounters form a limited data set about the global nature of the Jovian magnetosphere, much work and analysis by researchers has succeeded in developing a broad outline of the nature and dynamics of the Jovian magnetosphere.

Several major discoveries about the Jovian magnetosphere were made by the experiments on board the Voyagers. Results from the magnetometer confirmed the Pioneer discovery of an internal magnetic field at Jupiter which is dominated by a dipole field with a magnetic moment of about 4 Gauss-$R_J^3$ tilted about ten degrees towards the System III longitude of 200 degrees. Most investigators consider the 04 dipole model developed at Goddard Space Flight Center to be the best fit to the data and thus it will be the model used throughout this thesis. The 04 model dipole has a magnetic moment of 4.28 Gauss-$R_J^3$ tilted 9.6 degrees towards System III longitude 201.7 degrees (Connerney et al., 1982).
Figure II.1 The flightpaths of Voyagers 1 and 2 relative to Jupiter and its magnetosphere. Tic marks occur every 24 hours.

Reprinted from Scarf et al., 1981
The Voyager plasma science instruments discovered the planet to be girded by a relatively thin (~2 R_J thick) sheet of plasma residing at or near the magnetic equator. Magnetometer data showed the magnetic field to be greatly distended radially from a dipole configuration (Figure II.2). This "puffing out" of the dipole field implies the existence of large azimuthal currents flowing in the plasma sheet. Magnetometer data also showed a small azimuthal magnetic-field component which implies currents flowing radially within the plasma sheet.

Prior to the Voyager encounters, it was generally assumed that (like the Earth) the trapped plasma in the Jovian magnetosphere came primarily from the Jovian ionosphere and the solar wind. In such a case the composition of the plasma would be mostly hydrogen with a few percent helium, and only traces of heavier ions. Instead, the Voyager plasma science instruments revealed a plasma comprised mainly of sulfur and oxygen with traces of sodium, hydrogen, and possibly other elements. The question of the source for these ions was quickly answered when the imaging experiment on Voyager 1 found the Galilean moon Io to be covered with active volcanoes spewing sulfur oxides and sodium compounds hundreds of kilometers above its surface. These volcanoes appear to be continually resurfacing the moon, creating plains of sulfur, sulfur dioxide, and sodium. The exact mechanism by which material and gas are removed from Io is still a subject of controversy (see Hill et al., 1983, for a discussion of the proposed mechanisms). However, it is generally agreed that through some combination of ejection, sputtering, and ionospheric diffusion about 10^{30} amu/s is continually being loaded into a belt of plasma and neutral particles along the orbit of Io which
Figure II.2  Computed model of the Jovian magnetosphere with contributions from the azimuthal current in the plasma sheet and the solar wind taken into account.

Reprinted from Engle and Beard (1980)
is called the Io torus. The neutral particles travel along Keplerian orbits, but are soon ionized through collisions or charge exchange with ions moving at near-corotational speeds. The newly created ions are then sped up to near-corotational velocities by the local magnetic and electric fields. At such speeds the centrifugal force starts to dominate, pulling the plasma outward along the plasma sheet. The plasma generally tends to spiral outward until it eventually is flung down the magnetotail, creating a "planetary wind" that streams out into interplanetary space.

This description of the plasma sheet clearly shows the two basic differences between the Jovian magnetosphere and the more familiar terrestrial magnetosphere. The first difference is the internal source of the Jovian plasma. Unlike the Earth, where much of the trapped plasma comes from solar wind plasma that leaks through at the polar cusps, the majority of the Jovian plasma comes from Io with only a small percentage believed to come from the solar wind. The second major difference lies in the energy source that drives the two magnetospheres. The coupling of the interplanetary magnetic field (IMF) of the solar wind with the Earth's magnetic field induces the currents that drive much of the terrestrial magnetospheric phenomena. The energy that drives Jovian magnetospheric phenomena comes from the rotational energy of Jupiter. This energy is transferred by means of currents that couple the Jovian ionosphere to the magnetosphere. This transfer of rotational energy by coupled currents was first outlined by Hill (1979).

In order to transfer a planet's rotational energy to the magnetosphere it is necessary to possess a medium that will couple the physical
motion of the planet with the electric and magnetic fields of the magnetospheric plasma. In Jupiter's case the ionosphere serves as the connecting medium. Ionospheric ions and electrons rotate at roughly the same speed as Jupiter (ignoring winds). As these particles pass through the planetary magnetic field, they see an induced electric field which sets up an equatorially directed current. The polarizing electric field is given by

\[ E = -(\Omega \times r) \times B \]  

where \( \Omega \) is the planetary rotation frequency, \( r \) is the radius vector (in cylindrical coordinates) from the spin axis, and \( B \) is the magnetic field at the ionosphere. The meridional current produces a \( J \times B \) force that acts to slow the ionospheric plasma to less than corotational velocity. However, collisions with the neutrals counteract the \( J \times B \) force and maintains the plasma near corotational velocity. The meridional current closes along the field lines by Birkeland currents to and from the magnetosphere. Figure II.3 shows a cartoon of this situation.

Out in the magnetosphere, the plasma sheet serves as a medium to close the circuit (Figure II.4). The \( J \times B \) force from this radial current drives the plasma sheet plasma in the direction of Jupiter's rotation, thus the closed current transfers the lost angular momentum from the ionosphere to the increased angular momentum of the magnetospheric plasma. The degree to which the magnetospheric plasma corotates with the planet is limited by two factors here: the ionospheric Pedersen conductivity (arising from the ion-neutral collision frequency and the
Figure II.3 As the charged particles in the ionosphere rotate at near-corotational speed, an equatorially directed current ($j_\theta$) is set up. The $j_\theta \times B$ force on the charged particles acts towards the west to slow them down. However, the $j_\theta \times B$ force is balanced by the collisional force of the corotating neutrals which acts towards the east to speed up the charged particles. This is the mechanism by which the rotational energy of Jupiter is transferred from the planet and its atmosphere to the ionospheric plasma and (by means of field-aligned currents) out to the magnetosphere.
Figure II.4  Cartoon of the radial current system associated with the azimuthal magnetic field. The size of Jupiter and its ionosphere are exaggerated for clarity.

Reprinted from Vasyliunas  1983
magnetic field intensity in the ionosphere) and the inertial drag arising from any local production of plasma and/or the outward transport of the magnetospheric plasma. If the conductivity were infinite, any deviation from corotation by the plasma would be instantaneously counteracted by the system, thus keeping the plasma rigidly rotating with the planet. If the amount of plasma in the magnetosphere were constant with neither losses nor loads introduced, then eventually the plasma sheet plasma would be spun up to corotational velocity and would rigidly rotate with the planet. The principle result of Hill's work was to show that, for the case where new plasma is constantly being introduced near the planet and old plasma being lost at the outer boundary of the plasma sheet (as is the case at Jupiter), there is a continual transfer of angular momentum from the planet out to the plasma sheet. As the plasma moves outward from the Io torus it begins to lag behind corotation owing to conservation of angular momentum. The radial current provides a torque in an attempt to enforce corotation, but the necessary torque for rigid corotation increases as the plasma moves farther out. Figure II.5 shows a cartoon of all the forces ($\vec{J} \times \vec{B}$ and inertial) acting on a unit block of plasma in the magnetosphere. Thus, in the case of Jupiter where there is a continual introduction of new plasma into the plasma sheet, the plasma lags behind corotation and this lag increases with increasing distance. Hill showed that this lag behind corotation becomes significant at a characteristic distance $r_o$ given by

$$r_o = \left( \frac{\pi \Sigma B^2 \mathcal{R}^6}{S} \right)^{1/4}$$

II.2
Figure II.5  Cartoon showing the orientation of the forces acting on a unit volume of plasma in a section of the plasma sheet.
where $\Sigma$ is the height integrated Pedersen conductivity, $B_J$ is the surface equatorial magnetic field strength, $R_J$ is the Jovian radius, and $S$ is the total mass outflow rate of plasma in the plasma sheet. Observations by the plasma science experiment of the azimuthal velocity component of the plasma sheet during Voyager 1's inbound path showed that $r_o = 20 \ R_J$ with a ratio $\Sigma/S = -(0.1 \ \text{mho})/(10^{20} \ \text{amu/s})$ (Hill, 1980).

Voyager magnetometer data also showed the existence of a magnetic anomaly in the surface magnetic intensity at Jupiter. This anomaly arises from higher order multipoles of the internal Jovian magnetic field. This anomaly is centered at about $\lambda_{III} = 260$ degrees (Acuña et al., 1983, Figure 1.5). Dessler and Hill (1975) proposed that such a surface magnetic anomaly would cause a longitudinal asymmetry of the plasma sheet mass density. The cartoon in Figure 11.6 shows how such an anomaly would, by lowering the surface magnetic field intensity on one side relative to the opposite side, increase the size of the foot of the flux tube, which in turn would increase the flux of ionospheric plasma out to the equatorial plasma sheet. The portion of the magnetosphere connected to this anomaly is known as the active sector. Evidence for an active sector can be seen in several different observations. For example, decametric radio emissions generated by current driven instabilities appear to originate primarily in the active sector (Carr et al., 1983). As the Birkeland currents are expected to be more intense in the active sector (Dessler and Hill, 1979), this is the appropriate sense. Optical observations of the Io torus by Pilcher and Morgan (1980) show enhanced emissions (and hence presumably enhanced mass
Figure II.6  Illustration of the enhanced plasma flow into the Io torus and Jovian magnetosphere due to a surface magnetic anomaly. Since the magnetic field anomaly has a weaker field strength at the ionosphere, the flux tube foot at the anomaly is larger than the equivalent foot for flux tube A which has the same equatorial cross-sectional area as B. Thus, for a given ionospheric escape flux, more ionospheric plasma will be transported to the equatorial plane by flux tube B.

Reprinted from Hill, Dessler, and Goertz (1983)
densities) and greater radial extension in the active sector region.

Following the suggestion of Vasyliunas (1978), Hill, Dessler, and Maher (1981) showed how the azimuthal asymmetry of mass density gives rise to a convection pattern of the plasma in the corotating frame. In this model the active sector, with its enhanced currents and mass densities, has a larger radial outflow rate of plasma, while the opposite side with its less dense plasma would see a net inflow of plasma. Figure II.7 shows a qualitative flow pattern in a corotating frame. First the plasma flows outward in the active sector, lagging behind corotation as it moves outward. This causes the flow lines to spiral backwards until the sink region is reached. It should be noted that plasma is actually lost only when the sink region is in the tail region so that the plasma can break away and flow out the tail. After the plasma loss, the remaining hot and less dense plasma then spirals inward towards Jupiter. As the plasma flows inward conservation of angular momentum causes it to speed up to velocities in excess of corotation. Such superrotational velocities are associated with inward radial currents in the plasma sheet that attempt to reduce the plasma's azimuthal velocity. Here the roles of plasma sheet and ionosphere have switched, with the superrotating magnetospheric plasma now generating the current and the ionosphere providing the load. This coupled ionosphere-magnetosphere current system produces a negative feedback such that any deviation (faster or slower) from rigid corotation produces a force in the plasma sheet that attempts to restore rigid corotation.
Figure II.7  Qualitative cartoon of the plasma flow in the plasma sheet shown in a corotating frame of reference. Note the plasma source is the Io torus with an enhanced outflow on one side (active sector). Corotational lag in the outflowing region causes a retrograde spiral in the flow pattern. The plasma sink is the region where plasma is lost when this region is in the magnetotail. The inflowing region covers a larger section of longitude and the compression of the plasma causes a prograde spiral in the flow pattern.

When no evidence for superrotation in the plasma sheet appeared to be forthcoming from either Voyager encounter (McNutt et al., 1981), the corotating convection model was modified by Hill, Goertz, and Thomsen (1981). Instead of distinct outflow and inflow regions in the plasma sheet, they proposed a hybrid model where the convection pattern was superimposed on a conventional "radial diffusion" model with plasma outflow being, on the average, outward at all longitudes. This resulted in a model with a net plasma outflow at all longitudes, but with a greater outflow in the active sector than on the opposite side.

In his review of plasma dynamics in the Jovian magnetosphere, Vasyliunas (1983) presents much of the mathematics to describe the preceding theory. The following section reviews Vasyliunas' derivation of the equations necessary for the analysis in this thesis. The necessary equations relate the unknown values of radial bulk plasma velocity, height integrated Pedersen conductivity, and total mass outflow rate, to the known values of magnetic field, azimuthal bulk velocity, etc. The magnetohydrodynamic (MHD) equation relating the electric field $E$, magnetic field $B$, and the bulk plasma flow velocity $V$, is used as a starting point

$$E + V \times B = 0$$

II.3
Transforming this into a frame of reference rigidly corotating with Jupiter gives

\[ \mathbf{E}^* + \mathbf{V}^* \times \mathbf{B} = [\mathbf{E} + (\Omega_J \times \mathbf{r}) \times \mathbf{B}] + \]

\[ [\mathbf{V} - (\Omega_J \times \mathbf{r})] \times \mathbf{B} = 0 \]

where quantities in the corotating frame are designated by a \(^*\), \(\mathbf{r}\) is the radius vector from the spin axis in a cylindrical coordinate system, and \(\Omega_J\) is the spin vector of Jupiter. The ionospheric conductivity is assumed to be high enough so that \(\mathbf{E}^* = 0\), thus leaving

\[ [\mathbf{V} - (\Omega_J \times \mathbf{r})] \times \mathbf{B} = 0 \]

II.5

Expanding equation II.5 into cylindrical components gives

\[ [(V_\phi - \Omega_J r)B_z - V_z B_\phi] \hat{r} + [V_z B_r - V_r B_z] \hat{\phi} \]

\[ + [V_r B_\phi - (V_\phi - \Omega_J r)B_\phi] \hat{z} = 0 \]

(II.6)

Since each term in brackets must equal zero, the \(\hat{z}\) component can be isolated as

\[ V_r B_\phi = (V_\phi - \Omega_J r) B_\phi \]

(II.7)
This can be rewritten as

\[ \frac{B_\phi}{rB_r} = \frac{V_\phi}{V_r} - \frac{\Omega_J}{V_r} = \frac{\omega_p - \Omega_J}{V_r} \]

where \( \omega_p = \frac{V_\phi}{r} \) is the angular frequency of the plasma in the magnetosphere and \( V_r \) is the radial bulk plasma velocity in the plasma sheet.

Equation II.8 gives the radial bulk plasma velocity of the magnetospheric plasma as a function of the known magnetic components near the plasma sheet, the radial distance, and the measured azimuthal bulk velocity of the plasma. However, the equation assumes that the Jovian ionospheric conductivity is high enough to enforce corotation in the ionosphere which, as explained above, is not true for Jupiter. This can be rectified by simply replacing \( \Omega_J \) in equation II.8 with \( \Omega_i \), the angular frequency of the ionosphere averaged around the planet at a constant latitude. This can be visualized as the angular velocity of the foot of a flux tube in the ionosphere. Thus equation II.8 becomes

\[ \frac{B_\phi}{rB_r} = \frac{(\omega_p - \Omega_i)}{V_r} \]

Unfortunately, while \( \Omega_J \) is a known quantity, \( \Omega_i \) is not. In the corotating frame the azimuthal bulk velocity of the ionosphere is given by

\[ V_{i\phi} = -R_J \sin \theta (\Omega_J - \Omega_i) \]

where \( R_J \) is the Jovian radius and \( \Theta \) is the colatitude of the ionospheric
plasma. Figure II.8 gives a cartoon showing this relationship. The height-integrated meridional current is given by

\[ j_\theta = \Sigma I_\theta = -\Sigma (V_i \times B)_\theta = 2\Sigma B_J R_J \sin \theta (\Omega_J - \Omega_i) \quad \text{(II.11)} \]

where \( B_J \) is the surface equatorial magnetic field strength on Jupiter. Since these currents flow from the ionosphere out to the plasma sheet, and then close back into the ionosphere at higher latitudes (Figure II.4), conservation of current requires that

\[ (r_j) \text{ plasma sheet} = (R_j \sin \theta j_\theta) \text{ ionosphere} \quad \text{(II.12)} \]

Combining II.11 and II.12 gives

\[ 2 \Sigma B_J R_J \sin \theta (\Omega_J - \Omega_i) = \frac{r_j}{R_j \sin \theta} \quad \text{(II.13)} \]

The radial currents in the plasma sheet set up an azimuthal magnetic field that is described by

\[ j_r = \frac{-2B_\phi}{\mu_0} \quad \text{(II.14)} \]

Substituting II.14 into II.13 gives an equation for

\[ \Omega_i - \Omega_j = \frac{r B_\phi}{2 \Sigma \mu_0 B_J (R_j \sin \theta)^2} \quad \text{(II.15)} \]

Replacing \( \Omega_i \) in equation II.9 and doing some algebra gives
Figure II.8  Illustration of how $V_i$ is defined in the Jovian ionosphere.
\[
\frac{B_\phi}{rB_r} = \frac{\omega_p - \Omega_j}{r^2 B_r \left( \frac{2 \mu_0 \Sigma J}{r \sin \theta} \right)^2}
\]

Substituting the dimensionless term

\[
\chi = \frac{2 B_j (R_j \sin \theta)^2}{r^2 B_r}
\]

reduces equation II.16 to

\[
\frac{B_\phi}{rB_r} = \frac{\omega_p - \Omega_j}{V_r + \frac{1}{\mu_0 \Sigma \chi}}
\]

In the low conductivity case

\[
V_r << \frac{1}{\mu_0 \Sigma \chi}
\]

and subsequent data analysis showed this to be true for Jupiter. Thus equation II.18 is further simplified to

\[
\frac{B_\phi}{rB_r} = \left( \omega_p - \Omega_j \right) \mu_0 \Sigma \chi
\]

Thus equation II.20 serves to relate known quantities to the unknown height integrated Pedersen conductivity, \( \Sigma \).

Next, the steady state force balance equation for the magnetospheric plasma in the plasma sheet is used to derive an equation which explicitly gives the mass outflow rate and the radial bulk velocity of the plasma (Hill et al., 1981; Vasyliunas 1983). In the plasma sheet a
unit block of plasma is acted upon by \( \mathbf{J} \times \mathbf{B} \) forces and inertial forces (both centrifugal and coriolis) as shown in Figure II.5. Summing these forces up gives the steady state force balance equation

\[
(\sigma \Omega_J r^2) - (2\sigma \Omega_J \times \mathbf{v}) + (\mathbf{J} \times \mathbf{B}) = \sigma (\mathbf{v} \cdot \nabla) \mathbf{v}
\]

II.21

In equation II.21 the first term gives the centrifugal force, the second term gives the coriolis force, and the third term gives the \( \mathbf{J} \times \mathbf{B} \) force. The right hand side of equation II.21 gives the acceleration term multiplied by the mass density. The term \( \sigma \) is the mass density of the plasma sheet integrated over \( z \), i.e.

\[
\sigma = \int \rho \, dz
\]

II.22

Breaking equation II.21 into its cylindrical components, and assuming there is no net motion in the \( z \) direction results in

\[
\sigma \Omega_J^2 \begin{pmatrix} r \\ 0 \\ 0 \end{pmatrix} - 2\sigma \begin{pmatrix} -V_\phi \Omega_J \\ V_r \Omega_J \\ 0 \end{pmatrix} + \begin{pmatrix} j_\phi B_z \\ j_r B_z \\ 0 \end{pmatrix} = \sigma \left( V_r \frac{\partial}{\partial r} + \frac{V_\phi}{r} \frac{\partial}{\partial \phi} + V_z \frac{\partial}{\partial z} \right) \mathbf{v}
\]

II.23

Of the three terms in parenthesis on the right hand side of equation II.23 only the first is non-zero (the average of \( \frac{\partial}{\partial \phi} \mathbf{v} \) over a complete circuit of Jupiter is zero and \( V_z = 0 \)). Expanding the remainder of the
right hand side of equation II.23 gives

\[
\frac{\sigma v_r}{\phi} \frac{\partial}{\partial r} v_r = \sigma v_r \left[ \frac{\partial}{\partial r} (v_r \hat{r} + v_\phi \hat{\phi}) \right]
\]

\[
= \sigma v_r \left[ \frac{3v_r}{r} \hat{r} + \frac{\partial}{\partial r} \left( (\omega_p - \Omega_J) r \hat{\phi} \right) \right]
\]

\[
= \sigma v_r \left[ \frac{3v_r}{r} \hat{r} (\omega_p - \Omega_J + r \frac{\partial}{\partial r} \phi) \right] \tag{II.24}
\]

Looking at only the \( \hat{\phi} \) components in equations II.23 and II.24 shows

\[
-2\sigma v_r \Omega_J - j_r B_z = \sigma v_r \left[ \omega_p - \Omega_J + r \frac{\partial}{\partial r} \phi \right] \tag{II.25}
\]

Defining \( \delta \omega \) as the difference between the Jovian angular frequency and the plasma angular frequency, i.e.,

\[
\delta \omega = \Omega_J - \omega_p \tag{II.26}
\]

and rearranging equation II.25 gives

\[
j_r B_z = \sigma v_r \left[ -2\Omega_J + \delta \omega + r \frac{\partial}{\partial r} (\delta \omega) \right] \tag{II.27}
\]

The total mass outflow rate of the plasma in the plasma sheet is \( S \), where

\[
S = (2\pi r) \sigma v_r \tag{II.28}
\]
Combining equations II.28 and II.14 with equation II.27 results in a relationship for the mass outflow rate in terms of known quantities

\[ S = \frac{2\pi r B_B B_z}{\mu_0 [\eta_j - \frac{5}{2} - \frac{r}{2} \frac{\partial}{\partial r}(\delta \omega)]} \]  \hspace{1cm} \text{II.29} \\

Once the value for the mass outflow rate is known, equation II.28 can be rewritten

\[ V_r = \frac{S}{2\pi r \sigma} \]  \hspace{1cm} \text{II.30} \\

so that the radial bulk plasma velocity can be calculated.

Using the above analysis and equations it is possible to take Voyager data values for magnetic fields, plasma densities, and azimuthal bulk plasma velocities to find values for the mass outflow rate and the radial bulk plasma velocity in the plasma sheet along with the height integrated Pedersen conductivity. Prior to the analysis done for this thesis, there had been no direct calculations of values for these variables. However, there were some rough calculations, order-of-magnitude estimates, and boundary conditions placed on these variables. Theoretical arguments and calculations of the Pedersen conductivity by Strobel and Atreya (1983) suggest that \( \Sigma \) ranges from 0.2 to 0.3 mho with the possibility of going as high as 10 mho in auroral regions due to intense particle precipitation. Vasyliunas (1983) estimated a value of \( \Sigma \geq 0.3 \) mho for the midnight to dawn quadrant. Various theoretical works and observational inferences all agree on a rough value of \( 10^{30} \text{ amu/s} \) for the mass outflow rate (Dessler, 1980; Evitar and Siscoe, 1980; Hill, 1980; Brown et al., 1983). McNutt et al. (1981) did a rough calculation
using order of magnitude estimates to arrive at an estimate of 13 km/s for the radial bulk velocity of the plasma. In their theoretical work on convection in the plasma sheet, Hill, Dessler, and Maher (1981) calculate a rough upper limit for the radial bulk velocity of

$$V_r = (2.8 \text{ km/s}) (L/6)^4$$

where $L$ is the equatorial crossing distance of the undistorted dipole field line. At 20 $R_J$ ($L=11$ using the model of Connerney et al., 1981) this corresponds to about 32 km/s.
III. ANALYSIS

From the preceding section it would appear the analysis of this project should be a fairly straightforward procedure. Simply determining the values for the magnetic field components, the plasma density, and the plasma azimuthal velocity, then plugging them into the appropriate equations for the results would seem to be all that is required. Unfortunately, Nature is rarely so accommodating to scientific endeavors. The complexity of the actual magnetosphere as opposed to the theoretical models made the determination of accurate values for the magnetic field and the plasma data into complicated analytic projects in themselves.

The first complication arises from the fact that Jupiter's magnetic dipole axis is tilted with respect to the Jovian spin axis. As the trajectories of both Voyager spacecraft lie close to and almost parallel to the spin equatorial plane this means that, in the frame of the magnetic equator, the spacecraft appeared to rock back and forth between the two magnetic hemispheres. This can be seen schematically in Figure III.1 where the spacecraft is first in the southern magnetic hemisphere then, as Jupiter rotates, it passes through the magnetic equator into the northern magnetic hemisphere and then back through the magnetic equator. With such a configuration it can be seen that the spacecraft crosses the magnetic equator twice each Jovian rotation. The question then arises: where is the plasma sheet?

In a simple case where both spin axis and magnetic dipole axis are aligned, the plasma sheet would obviously lie in their common equatorial
Figure III.1 Cartoon showing the rocking of the magnetic equator past a spacecraft during one Jovian rotation.

Reprinted from Hill, Dessler, and Goertz (1983)

Figure III.2 Illustration of the location of the plasma sheet's equilibrium plane two-thirds of the way between the rotational equatorial plane and the magnetic equatorial plane. The distension of the dipole field is also shown.

plane. In the case where the magnetic dipole axis is tilted with respect to the spin axis the plasma sheet would be somewhere in between the two equators. Assuming the particles are confined to move only along magnetic field lines, they would move toward an equilibrium point where the magnetic mirror force pulling them toward the magnetic equator is balanced by the centrifugal forces pulling them toward the spin equator. Hill, Dessler, and Michel (1974) examined this case and concluded that the plasma sheet would lie in a plane tilted two-thirds of the way from the spin equator towards the magnetic equator (Figure III.2). Later work by Kivelson et al., (1978) further complicated the picture by introducing the factor of a time delay into the magnetic field configuration. As the magnetic dipole changes its orientation by rotating, that information is transmitted out to the plasma sheet by means of Alfvén waves. Since the Alfvén wave has a finite propagation velocity, there is a time delay between the change in the orientation of the dipole at Jupiter and the change in the field line orientation out in the magnetosphere. This delay causes a warping of the plasma sheet (Figure III.3). Goertz (1981) took this model and added the effect of the plasma lag in the plasma sheet, which produced a twisting of the warped plasma sheet (Figure III.4).

As the above discussion shows, analyzing the shape and orientation of the plasma sheet is not a simple matter. Determining this orientation and shape is important because the radial and azimuthal components of the magnetic field must lie in a plane parallel to the plasma sheet in order for the analysis to be correct. This determination is also important because of the relatively small magnitude of the $B_\phi$ component.
Figure III.3  Cartoon of the "warped" configuration of the plasma sheet from the work of Kivelson et al., (1978).

Figure reprinted from Carbary (1980)

Figure III.4  Cartoon of the "warped and twisted" configuration of the plasma sheet.

Reprinted from Goertz (1981)
In most cases the $B_\phi$ component is one to two orders of magnitude smaller than either of the other two components. Thus any change in the orientation of the coordinate system can cause a large change in the magnitude of the $B_\phi$ component.

It is assumed that the magnetic field measured by the Voyager magnetometer is the sum of the Jovian dipole field and the magnetic field arising from the currents in the plasma sheet (Connerney et al., 1981). Figure III.5a shows that an undisturbed dipole field would contribute only to the radial and $z$ components of the total field. Figure III.5b shows that the currents in the plasma sheet set up a magnetic field that contributes only to the radial and azimuthal components. Thus Figure III.5c shows the combination of the dipole and current-sheet fields which results in the radial distortion of the field lines and the retrograde spiral of the field lines. Note that in this case the $B_r$ and $B_\phi$ components are always of opposite sign. If superrotation were present, with its associated inward current, the field lines would appear to be swept forward in the direction of Jovian rotation. In this case the $B_r$ and $B_\phi$ components would always have the same sign.

In a coordinate system correctly oriented with respect to the plasma sheet the positive $z$-axis would be perpendicular to the plasma sheet, the negative $r$-axis would be parallel to the plasma sheet and pointed towards the spin axis of Jupiter, and the positive $\phi$-axis would also lie parallel to the plasma sheet and would be pointed eastward. If the magnetic data were transformed into such a coordinate system then the $B_r$ and $B_\phi$ components would both go to zero at the center of the
Figure III.5a Cartoon showing the radial and z components of the dipole magnetic field in a cylindrical coordinate system.

Figure III.5b Cartoon showing the magnetic-field configuration above the plasma sheet that arises from the currents in the plasma sheet. This is also in a cylindrical coordinate system.

Figure III.5c Superimposing the dipole magnetic field with the magnetic field from the plasma sheet currents gives the configuration shown above where the dipole field is distented radially and has a retrograde spiral. Note that the radial and azimuthal components are always opposite in sign except at the crossing point where both are equal to zero. The above cartoon has been exaggerated for clarity.
plasma sheet. The plane perpendicular to the z-axis at this point is defined as the "crossing plane." As the spacecraft moved along the z-axis away from the crossing plane, the magnitudes of the $B_r$ and $B_\phi$ components would increase. Once the spacecraft was above (or below) the majority of the current carrying region, the $B_\phi$ component would level off to a constant value while the magnitude of the $B_r$ component would continue to increase due to the dipole contribution (Figure III.6). In reality, the spacecraft moves in longitude as well as in the z direction, thus causing the $B_\phi$ component to vary outside of the current carrying region due to time and spatial variations.

Initially I thought that a simple transformation of the data into a cylindrical coordinate system with the z-axis parallel to the 04 dipole would produce $B_r$ and $B_\phi$ components sufficiently accurate for the analysis. Unfortunately this transformation does not succeed in producing $B_r$ and $B_\phi$ curves that are out of phase with both going to zero at the same point. Subsequent attempts to fit the data to the more complicated models mentioned above showed that none of them were of sufficient accuracy to fit all of the crossing points. Instead of attempting to force a global model to fit all the crossing points, the data were used to determine a unique orientation of the plasma sheet for each of the crossing points individually.

But this procedure creates a dilemma. The analysis requires accurate values of the $B_r$ and $B_\phi$ components taken in a coordinate system properly aligned relative to the plasma sheet. However, the only place where the orientation of the plasma sheet normal can be uniquely determined is at the plasma sheet crossing, and by definition that is where
Figure III.6 Top panel shows the geometry of the spacecraft’s trajectory through the plasma sheet. The middle panel shows the response of the azimuthal magnetic-field component as the spacecraft crosses the plasma sheet. The bottom panel is the same for the radial magnetic-field component. Note that both curves go to zero at the center of the plasma sheet and that elsewhere they are opposite in sign. Also note that the azimuthal component "levels off" once the spacecraft is outside of the plasma sheet.
the $B_r$ and $B_\phi$ components go to zero. Given only a single spacecraft and the previously described geometry, there is no way to measure simultaneously both the plasma sheet orientation and the radial and azimuthal components of the magnetic field away from the plasma sheet. This "catch-22" was resolved by the following compromise. The normal to the plasma sheet was determined for each of the plasma sheet crossings the spacecraft made. Then data for a range of sixty to ninety degrees longitude on either side of the crossing point were transformed into this new coordinate system. Once the data were plotted, the sections outside of the current carrying region were identified and the values of $B_r$ and $B_\phi$ were averaged over these sections. These averages were used in the analysis equations as if they were the true values of $B_r$ and $B_\phi$ above or below the plasma sheet at the crossing point. While this compromise does not solve the problem of the warping and twisting of the plasma sheet, it was hoped that averaging over this range would still give reasonably accurate values. Subsequent analysis proved this to be correct. Once these values were obtained, they were combined with the values for mass density, azimuthal bulk plasma velocity, etc. calculated from published data in order to compute the conductivity, the radial bulk plasma velocity, and the mass outflow rate.

Analysis of the magnetometer data began by borrowing computer tapes of the Voyagers' Jovian encounters from the National Space Science Data Center at Goddard Space Flight Center. These tapes contained averages of the magnetic field components with resolutions of 1.96 seconds, 9.6 seconds, and 48 seconds. As the 48 second resolution was sufficient for the purpose of this analysis, those values were read from the tape and
loaded into data sets along with data about the spacecraft's longitude and latitude in System III Jovian coordinates, the spacecraft's distance from the center of Jupiter in Jovian radii, and the time. The magnetic field components were given in a spherical coordinate system with the origin at the center of Jupiter and the polar axis aligned with the Jovian spin axis.

The next step was to locate the plasma sheet crossing points. This was done by determining the local minima of the total magnetic field intensity. It can be seen from symmetry arguments that when the spacecraft lies in the central plane of the plasma sheet, the magnetic field contribution from the plasma sheet currents is zero. As the measured field is a combination of the internal Jovian dipole field and the field from the plasma sheet currents, the total field strength is minimum at the plasma sheet crossing points. The total magnetic field intensity plotted against the spacecraft's Jovicentric distance for part of the Voyager 1 inbound path is shown in Figure III.7. The local minima can be seen clearly and are indicated. However, it can also be seen that, due to the increasing magnitude of the overall field as the spacecraft approaches the planet, the actual location of the local minimum at a crossing may be difficult to ascertain (note crossing A in particular). In order to account for this uncertainty and find the true local minimum, each crossing region was individually detrended. This was accomplished by measuring the magnetic field intensity and spacecraft distance for two peaks on either side of the minimum. These values were substituted into the equation.
Figure III.7  Plot of the magnetic field intensity graphed against distance for Voyager 1 inbound. The three crossing points used in this thesis are located by arrows.
\[ B = \frac{M}{R^n} \]  

III.1

where \( B \) is the total magnetic field intensity, \( R \) is the spacecraft's distance in Jovian radii, and \( M \) and \( n \) are constants for a given crossing. From the known values of \( B \) and \( R \) at the two peaks, values for \( M \) and \( n \) were calculated. Once these values are found, the data are detrended by finding the difference between the measured field strength as the spacecraft passed through the plasma sheet and the inferred value of the local magnetic field strength outside the plasma sheet:

\[ \Delta B(R) = B_{\text{data}}(R) - \frac{M}{R^n} \]  

III.2

The data set of \( \Delta B \) versus distance was plotted and fitted to a second order polynomial curve. Figure III.8 shows the \( \Delta B \) curve for Voyager 1 inbound crossing A. From the coefficients of this curve, the location of the detrended minimum is located. This detrending operation was conducted only on the Voyager 1 inbound crossings because the minima determined by this method confirmed the fact that crossings occurred at the points where the \( B_r \) component changes sign. All the crossing points for the rest of the data sets were located by finding the \( B_r \) sign change locations. This proved to be effective since, in spherical coordinates, the radial component remains unchanged regardless of the orientation of the polar axis. Thus, to first order in spherical coordinates, the sign change of the radial component of the B-field marks the location of the plasma sheet crossing point regardless of the orientation of the sheet at that point.
Figure III.8  Diagram of ΔB as a function of distance with a second order polynomial curve fitted to it.
It should be noted here that in much of the literature the terms "plasma sheet" (the thin disk of maximum plasma density) and "current sheet" (the thin disk of maximum current density) are used interchangeably. In reality, the location of the maximum plasma density does not necessarily coincide with the location of the maximum current density (Belcher, 1983; Vasyliunas, 1983). Because of the definition that the plasma sheet crossing point occurs at the sign change of the $B_n$ component, the "plasma sheet crossing point" in this analysis refers to the current sheet crossing regardless of whether the plasma density maximum occurs there or not. As the analysis later integrates the plasma density over $z$, the exact location of the plasma density maximum is not critical.

Once the crossing points were determined, the next step was to calculate the orientation of the plasma sheet. This was accomplished by calculating the plasma sheet normal using a minimum-variance analysis from Lepping and Argentiero (1971):

$$\mathbf{n} = \frac{(B_2 - B_1) \times (B_1 \times B_2)}{|(B_2 - B_1) \times (B_1 \times B_2)|}$$  \hspace{1cm} \text{III.3}

where $\mathbf{n}$ is the unit normal vector and $B_1$ and $B_2$ are the magnetic field vectors on either side of the crossing point. Essentially, this equation takes two vectors with any two orientations and finds the direction in which they have a common component. Both B-field vectors are normalized first to correct for any skewing caused by the inner B-field vector being larger in magnitude. For Voyager 1 inbound crossings the normals were calculated using B-field vectors from $\pm 0.1^\circ$ to $\pm 10.0^\circ$ longitude on
either side of the crossing point. The normals were defined to point northward and their orientations were given by their tilt and the System III longitude toward which they were tilted. Examination of the range of normals for each crossing showed they were remarkably consistent. The tilts did not vary by more than 0.5° and the longitudes did not vary by more than 2.0°. Because of this consistency, the final values of tilt and longitude used for the analysis were the values from the ±0.1° longitude calculation. For the remainder of the data sets, the normal for each crossing was determined by a more sophisticated method. A set of normals was generated for intervals of 0.5° from ±0.5° to ±10.0°, then an average and standard deviation for both tilt and longitude were calculated (Bevington, 1969).

Determination of the normals provided the first selection criterion for crossing data sets that are suitable for further analysis. At distances larger than 20-25 R_J the relative noise level becomes so high that the normal can no longer be reliably calculated (e.g., tilts > 50°). One Voyager 1 inbound crossing at ~8 R_J also had to be discarded because calculations resulted in a normal at the crossing point that was oriented ~100° away from the dipole axis. In light of the relative uniformity of the orientations of the other normals, this was rejected as unreasonable. This criterion resulted in three useful crossing data sets for Voyager 1 inbound and two for Voyager 1 outbound. Voyager 2 passed by on a slower trajectory, thus providing more useful crossings: five for the inbound portion and six for the outbound portion.

Once the normal for each crossing had been determined, the magnetic field data for ninety degrees longitude on either side of the crossing
point were transformed into the current-sheet coordinate system. This coordinate system is a cylindrical system with the positive z-axis parallel to the current-sheet normal, the negative r-axis pointed toward the spin axis, and the positive φ-axis pointed eastward perpendicular to the other two axes. As the spin axis was tilted with respect to the z-axis, the condition that the negative r-axis point toward the spin axis at all points required a slight correction in the radial and azimuthal components for each individual data point. Figure III.9 shows how the r-axis for the normal coordinate system and the r-axis for the spin-aligned coordinate system track differently as the spacecraft moves around 90° of its track. Thus the final magnetic field data set was not cast exactly into a cylindrical coordinate system centered on a z-axis running through the center of Jupiter, but into an approximately cylindrical coordinate system. Owing to the large distance from the planet, the angle between the two r-axes never exceeded 3° in the closest data sets, and this maximum shrank to less than 0.5° in the distant data sets.

The data were then smoothed using a standard five channel smoothing technique from Bevington (1969):

\[
\begin{align*}
X(n)_{\text{smoothed}} &= \frac{1}{16} X(n-2) + \frac{1}{4} X(n-1) + \frac{3}{8} X(n) + \\
&\quad \frac{1}{4} X(n+1) + \frac{1}{16} X(n+2)
\end{align*}
\]

III.4

for each field component. The distance z of the spacecraft from the crossing plane was calculated and the data set from each crossing was
Figure III.9  Diagram showing how the $r$-axis oriented toward the spin axis varies from the $r$-axis oriented toward the $z$-axis as the spacecraft moves in longitude about the planet.
trimmed so that only the portion between the extremes of the z-distance remained. This accounts for the fact that some of the data sets cover less than 90° longitude on either side of the crossing point. Since the crossing points do not line up exactly in longitude, there is also some slight overlap of data sets (see Figures V.1 and VII.3). A full listing of this program is given in the Appendix.

Figures III.10a and 10b show the radial and azimuthal components of the Voyager 1 inbound A crossing in the original spin axis oriented spherical components. Figures III.11a and 11b show the same data after the transformation into the normal coordinate system. Note that in the spherical system the zero point of the azimuthal component is about 90° out of phase with the zero point of the radial component. In the normal system the two components go to zero at the crossing point and are opposite in sign throughout the rest of the data set. The crucial nature of finding the exact orientation of the normal is shown by the fact that variations of as little as a couple of degrees can produce a $B_\phi$ curve with the zero point offset by 20°-30°.

Once the magnetic data had been recast the average values for $B_r$ and $B_\phi$ were calculated. As explained above, the $B_\phi$ component should level off once the spacecraft is above or below the current carrying region of the plasma sheet. As the scale height of the plasma sheet is ~1 $R_J$ (Vasyliunas, 1983) the $B_\phi$ curve should generally level off at distances of $|z| \gtrsim 1 R_J$. However, the large amount of noise in the $B_\phi$ component makes the location of this boundary very ambiguous. Figure III.11b shows this problem for the A crossing of Voyager 1 inbound. Rather than settle on one average for the crossing, a range of averages
Figure III.10a Graph of the radial magnetic-field component in spherical coordinates centered on the Jovian spin axis. The region of the A crossing for Voyager 1 inbound is indicated.

Figure III.10b Same as figure III.10a for the azimuthal magnetic-field component in spherical coordinates centered on the Jovian spin axis. Note that the azimuthal curve is approximately 90° out of phase with the radial curve.
Figure III.11a  The curve of the radial component in cylindrical coordinates of the Voyager 1 inbound A crossing data set after being transformed into the new coordinate system based on the plasma sheet normal.

Figure III.11b  Same as figure III.11a for the phi component. Note that the two curves are now 180° out of phase.
was computed for each crossing to cover the possible variations. Here average 1 is the average of the absolute values of $B_r$ and $B_\phi$ for the entire set outside of the arrows labelled "1." The same goes for average 2. The preferred average is average 3 which includes only the $B_r$ and $B_\phi$ data within the "levelled off" region marked "3." The value for $B_z$ was simply its value at the crossing point.

The plasma data for this work were taken from the published data of the Plasma Science (PLS) experiment onboard the Voyagers. A detailed explanation of the experimental apparatus and analysis procedures can be found in Bridge et al. (1977) and McNutt et al. (1981). Briefly, the PLS consists of four Faraday cups that measure the electric currents from positive ions flowing into the detectors. Three of the cups are arranged symmetrically about the spacecraft's S-axis and each tilted 20° from this axis. The S-axis is parallel to the look direction of the main antenna which is always pointed toward the Earth. The fourth cup (the D cup) is at right angles to the S-axis. Both spacecraft were fixed in inertial space during the inbound portion of their encounters with both the S- and D-axes lying almost in the Jovian equatorial plane. The Faraday cups measure the flux at different energy to charge ratios, thus creating data curves such as shown in Figure III.12. From these data both the plasma flow velocity into the cup and the mass density of the plasma can be calculated.

Bagenal and Sullivan (1981) showed the middle magnetosphere plasma to be dominated by $O^{2+}$, $S^{3+}$, $O^+$, $S^{2+}$, and possibly $S^+$ ions, along with small background of $H^+$ ions. Setting the mass to charge ratio of the $H^+$ ions equal to one, then the mass to charge ratio of $O^{2+}$ is 8, $S^{3+}$ is 10
Figure III.12  Typical graph of particle flux measured by the Faraday cup detector D on the Voyager 1 Plasma Science (PLS) experiment. Peaks in the data represent different ionic species.

Reprinted from McNutt et al. (1981)

Figure III.13  Data plot of mass and charge density as a function of distance measured by the Plasma Science (PLS) experiment during Voyager 1 inbound.

Reprinted from McNutt et al. (1981)
2/3, O+ and S2+ are 16, and S+ is 32. The 1, 8, 10 2/3 and 16 peaks are clearly visible in Figure III.12. Using the flux intensities McNutt et al. (1981) estimated the mass density profile of the plasma sheet for the inbound middle magnetosphere of both encounters. Figure III.13 shows the resulting mass density in amu/cm³ for the Voyager 1 inbound section (bottom panel), along with the spacecraft's z-distance from the magnetic equator (top panel). It is apparent that the mass density peaks at or near the magnetic equator crossings. In order to calculate σ for this analysis the values of the mass density over each crossing region were read from the graph and correlated with the z-distance in the normal coordinate system. Using a simple step function these densities were then integrated over z for the total length of the plasma crossing data set which gives a value of σ for that crossing. As can be seen in Figure III.13 the mass density curve forms a rough Gaussian distribution for each of the plasma sheet crossing data sets. Calculation of a truly exact value for σ would require the spacecraft to have sampled the mass density at even larger z-distances from the plasma sheet. However, since the values of mass density in the "wings" of the distribution of the available data were usually an order of magnitude less than the peak value, the values of σ calculated by this method are believed to be within 90% of the true value.

During the inbound approaches of both spacecraft the D cup was pointed almost directly into the azimuthal flow of the plasma sheet. Using a least squares fit to each of the peaks of the various ions, McNutt et al. (1981) calculate the azimuthal velocity of plasma. The PLS operated in two modes: a high resolution mode (M mode) of 128
voltage windows and a low resolution mode (L mode) of 16 voltage windows. The M mode gives better resolution of the heavier ions, but tends to lose the $H^+$ ion peak in the noise. The L mode gives a better resolution of the $H^+$ peak, but a poorer resolution of the heavier ions. Figures III.14 shows the resulting azimuthal velocity of the plasma versus distance for part of Voyager 1 inbound. Two things should be noted about the graphs: first, the azimuthal velocity is always less than corotation, and second, the velocity peaks at the plasma sheet crossings. This increase in velocity at the crossings can be explained by the following: as the spacecraft moves toward the plasma sheet, because of the distended magnetic field it is also moving onto lower L shells. The azimuthal velocities of the lower L shells are closer to corotation and thus the crossing points should show relatively higher velocities. Hill (1980) fit his inertial loading curve to these data and found the characteristic distance $r_o = 20 R_J$. This fit is used in this analysis of the Voyager 1 inbound portion to calculate values for $\delta \omega = R_J - \omega_p$ and $\frac{3}{2} \frac{\delta \omega}{r}$. 

The final parameter required for the analysis is $\theta$, the colatitude in the ionosphere at the foot of the field line which passes through the crossing point. Owing to the distention of the field lines from the currents in the plasma sheet, this is not a simple calculation. Connerney, Acuña, and Ness (1981) modelled the field line configuration, taking into account the plasma sheet currents. The values for $\theta$ at the crossing point distances were derived from their schematic diagrams to within $\pm 0.1^\circ$. 
Figure III.14 Data plot of azimuthal velocities of the plasma in the plasma sheet as a function of distance and time for Voyager 1 inbound. A curve showing corotation velocities is also given.

Reprinted from McNutt et al. (1981)
Once all these values were ascertained, it was a direct matter to substitute them into the analytic equations. First equation II.20

\[ \frac{B_\phi}{r B_r} = (\omega_p - \Omega_J) \mu_o \xi \chi \]

is evaluated to find the range of values for ξ, the height integrated Pedersen conductivity. Then equation II.29

\[ S = \frac{2\pi r B_\phi B_z}{\mu_o \left[ \Omega_J - \frac{\delta \omega}{2} - \frac{r}{2} \frac{\partial}{\partial r}(\delta \omega) \right]} \]

is evaluated to find the total mass outflow rate, S. Finally, the radial bulk velocity of the plasma is calculated using equation II.30

\[ v_r = \frac{S}{2\pi r \sigma} \]

It should be noted here that the values obtained for the total mass outflow assume that the outflow is uniform over all longitudes, whereas the analysis only covers about one hemispehre of longitude. Thus a more accurate value for the global total mass outflow rate would be obtained by averaging together the values for S from two adjacent crossings.

The results for these analyses are presented in the next three sections.
IV. RESULTS OF VOYAGER 1 INBOUND

Results of the analysis of the Voyager 1 inbound data have been reported previously (Hairston and Hill, 1985). Following the procedures outlined in the previous section, the total magnetic field strength was calculated as a function of distance. The total field magnitudes were detrended to locate the exact local minima in order to find the plasma sheet crossing points. The normal to the plasma sheet for each crossing point was calculated using separations of $B_1$ and $B_2$ of up to ±10° in longitude. The final orientation of the normal was taken from the ±0.1° longitude calculation. Of the seven crossings observed only three were sufficiently free of noise for analytic purposes. Figure IV.1 shows a spiral plot of the spacecraft's path in the $r^{-\lambda}_{III}$ coordinate system which corotates with Jupiter. The regions of the crossing data sets are indicated on the curve. The magnetic data set for each crossing was then transformed into a new cylindrical coordinate system based on the plasma sheet normal.

The values for the mass density used to calculate $\sigma$ were taken from the data published in McNutt et al. (1981) which are reproduced in Figure IV.2. Values for $\omega_p$ were taken from the data for azimuthal plasma velocities also given in McNutt et al. (1981). This data curve is reproduced in Figure IV.3. Values for $\frac{2}{\delta r}(\delta \omega)$ were calculated using the analytic expression of Hill (1979) for the corotation lag as a function of distance, using a characteristic distance $r_o = 20R_J$ (Hill, 1980).

The data curves for the radial and azimuthal components of the transformed magnetic field for each crossing are presented in Figures
Figure IV.1  Plot of part of the inbound trajectory of Voyager I shown in the $r-\lambda_{III}$ plane. The crossing points are indicated by circles and the accompanying letter, while the range of the spacecraft during each data set is shown by the solid line.
Figure IV.2 Estimates of the total elementary-mass and elementary-charge concentrations of positive ions in units of amu per cm$^3$ and elementary charges per cm$^3$, respectively, for the Voyager 1 inbound encounter. The top panel shows the distance of the spacecraft from the magnetic dipole equatorial plane and arrows in the bottom panel indicate the crossing of this plane. The regions for each plasma sheet crossing data set are marked and labelled. Dates are given at 1200 UT.

Reprinted from McNutt et al. (1981)
Figure IV.3. Value of the azimuthal velocity component into the D sensor for Voyager 1 as determined from fits to low resolution (L-mode) and high resolution (H-mode) ion spectra. The regions for each plasma sheet crossing data set are marked and labelled.

Reprinted from McNutt et al. (1981)
IV.4 through IV.6. The arrows on the $B_\phi$ curves indicate the regions over which the data were averaged. The arrows labelled "1" show the averaging region for which the least amount of data in the center is excluded, while the arrows labelled "2" show the same for a more conservative estimate of where the spacecraft leaves the current-carrying region. The regions labelled "3" are the regions where the $B_\phi$ value appears to have levelled off, and these averages are preferred. The relevant data and results for each crossing are given in Tables IV.1 through IV.3. Where three values are given the first is the preferred value while those inside the parenthesis give the range of possible values.

Please note that all the magnetic data are presented as a function of both $z$-distance from the crossing plane and System III longitude. By convention, the $z$-axis always goes from negative to positive; this means the longitude can go either way depending on the spacecraft's trajectory. Thus increasing time always follows increasing longitude.
### TABLE IV.1

**Voyager 1 Inbound Crossing A**

Data set covers:

| distance: | 14.7483 RJ | 11.1718 RJ |
| z distance: | $1.7928 \times 10^8$ m | $-1.7924 \times 10^8$ m |
| $\lambda_{III}$ longitude | 208.09° | 354.11° |
| time: | 63d 21h 54m | 64d 2h 13m |

Crossing point occurs at:

| distance: | 12.94 RJ |
| $\lambda_{III}$ longitude: | 282.3° |
| time: | 64d 0h 5m |

Orientation of the normal:

| tilt: | 11.4° |
| $\lambda_{III}$ longitude: | 204.2° |

Data:

- $\langle B_r \rangle$: 83.0 nT (75.8-90.6)
- $\langle B_\phi \rangle$: 3.0 nT (2.0-4.3)
- $B_z$: -134.0 nT
- $\omega_p$: $1.61 \times 10^{-4}$ rad/s (0.915 $\omega_d$)
- $\frac{\partial}{\partial r} (\delta \omega)$: $5.3323 \times 10^{-14}$ rad/m-s
- $\sigma$: $7.08 \times 10^{-11}$ kg/m
- $r$: $9.2411 \times 10^8$ m
- $\theta$: 19.15° (19.1°-19.2°)
- $\chi$: 6.62 (6.04-7.29)

Results:

| $\Sigma$: 0.31 mho | (0.21-0.44) |
| $S$: $8.3 \times 10^{30}$ amu/s | (5.6-11.8 $\times 10^{30}$) |
| $V_r$: 33.6 km/s | (22.5-47.9) |
Figures IV.4a,b
### TABLE IV.2

**Voyager 1 Inbound Crossing B**

**Data set covers:**

| distance: | $17.9861 \, R_j$ | $15.5003 \, R_j$ |
| z distance: | $-2.3626 \times 10^8 \, m$ | $2.3526 \times 10^8 \, m$ |
| $\lambda_{III}$ longitude | $69.14^\circ$ | $176.36^\circ$ |
| time: | $63d \, 17h \, 54m$ | $63d \, 20h \, 59m$ |

**Crossing point occurs at:**

| distance: | $16.91 \, R_j$ |
| $\lambda_{III}$ longitude: | $115.7^\circ$ |
| time: | $63d \, 19h \, 14m$ |

**Orientation of the normal:**

| tilt: | $14.8^\circ$ |
| $\lambda_{III}$ longitude: | $204.2^\circ$ |

**Data:**

- $<B_r>$: $46.0 \, nT$ (44.5-50.6)
- $<B_\phi>$: $1.4 \, nT$ (1.0-1.7)
- $B_z$: $-49.0 \, nT$
- $\omega_p$: $1.44 \times 10^{-4} \, rad/s$ (0.818 $R_j$)
- $\frac{\delta}{\delta \Omega} (\delta \omega)$: $6.2300 \times 10^{-14} \, rad/m-s$
- $\sigma$: $4.05 \times 10^{-11} \, kg/m$
- $r$: $1.2076 \times 10^9 \, m$
- $\theta$: $17.93^\circ$ (17.90$^\circ$-17.97$^\circ$)
- $\chi$: $6.16$ (5.58 - 6.40)

**Results:**

| $\Sigma$: | 0.10 mho (0.07-0.12) |
| $S$: | $2.3 \times 10^{30} \, amu/s$ (1.7-2.8 $\times 10^{30}$) |
| $V_r$: | $12.9 \, km/s$ (9.1-15.0) |
Figures IV.5a,b
### TABLE IV.3

**Voyager 1 Inbound Crossing C**

**Data set covers:**

<table>
<thead>
<tr>
<th>Distance:</th>
<th>22.6095 R(_J)</th>
<th>19.0681 R(_J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z distance:</td>
<td>5.6510 \times 10^8 m</td>
<td>-5.0447 \times 10^8 m</td>
</tr>
<tr>
<td>(\lambda_{III}) longitude:</td>
<td>221.30°</td>
<td>21.43°</td>
</tr>
<tr>
<td>Time:</td>
<td>63d 12h 1m</td>
<td>63d 16h 33m</td>
</tr>
</tbody>
</table>

**Crossing point occurs at:**

<table>
<thead>
<tr>
<th>Distance:</th>
<th>20.96 R(_J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{III}) longitude:</td>
<td>296.3°</td>
</tr>
<tr>
<td>Time:</td>
<td>63d 14h 8 m</td>
</tr>
</tbody>
</table>

**Orientation of the normal:**

<table>
<thead>
<tr>
<th>Tilt:</th>
<th>21.7°</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{III}) longitude:</td>
<td>207.1°</td>
</tr>
</tbody>
</table>

**Data:**

<table>
<thead>
<tr>
<th>(\langle B_r \rangle)</th>
<th>41.7 nT</th>
<th>(32.6-50.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\langle B_\phi \rangle)</td>
<td>2.1 nT</td>
<td>(1.4-2.8)</td>
</tr>
<tr>
<td>(B_z)</td>
<td>-25.7 nT</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\omega_p)</th>
<th>1.25 \times 10^{-4} rad/s</th>
<th>(0.710 \Omega(_J))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{\partial}{\partial r}(\delta \omega))</td>
<td>7.1353 \times 10^{-14} rad/m-s</td>
<td></td>
</tr>
<tr>
<td>(\sigma)</td>
<td>2.26 \times 10^{-11} kg/m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(r)</th>
<th>1.4968 \times 10^9 m</th>
<th>(17.2°-17.5°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta)</td>
<td>17.35°</td>
<td>(3.35-5.40)</td>
</tr>
<tr>
<td>(\chi)</td>
<td>4.15</td>
<td></td>
</tr>
</tbody>
</table>

**Results:**

<table>
<thead>
<tr>
<th>(\Sigma)</th>
<th>0.13 mho</th>
<th>(0.08-0.17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S)</td>
<td>3.4 \times 10^{30} amu/s</td>
<td>(2.2-4.5 \times 10^{30})</td>
</tr>
<tr>
<td>(V_r)</td>
<td>26.4 km/s</td>
<td>(17.4-35.2)</td>
</tr>
</tbody>
</table>
The first thing to note is that the tilts of the normals exceed the tilt of the magnetic dipole. This was at first thought to be in error. However, it was subsequently shown that only with such "excessive" tilts could the necessary sign changes of the components be achieved at the crossing points. The meaning of this will be explained further in the Discussion section.

Values of the mass outflow rate and radial velocity are larger in the A and C crossings which lie mostly in the active hemisphere. This result bears out the prediction by Hill, Goertz, and Thomsen (1982) of an enhanced outflow in the active hemisphere. This will also be discussed further in the conclusion.

It should be noted here the notational sequence of the Voyager 1 inbound crossing is backwards relative to the order in Hairston and Hill (1985).
V. RESULTS OF VOYAGER 2 INBOUND

The analysis of the Voyager 2 inbound data follows closely that of the Voyager 1 inbound data, but with a few differences. As explained in the Analysis section, the location of the plasma sheet crossing point for each data set was determined by finding the location where the spherical radial component of the magnetic field changes sign. The normals were calculated along with a standard deviation of the tilt and longitude. Figure V.1 shows the planetary equatorial plane with a spiral plot of the Voyager 2 inbound path plotted in r^-3 coordinates. The regions of the data sets are indicated on the curve. The data were then transformed into the new cylindrical coordinate system defined by the plasma sheet normal.

As with Voyager 1, the values of the mass density were taken from the curve (Figure V.2) from McNutt et al. (1981) and used to calculate \( \sigma \). Mass density data were missing for the A crossing in Figure V.2. However, since the mass density curve and the charge density curve tend to run parallel to one another, a mass density curve for the A crossing was extrapolated using the charge density curve as a guide.

Determination of values for \( \omega_p \) proved to be more difficult. Figure V.3 shows the angular velocity of the plasma sheet for both Voyager 1 and 2 inbound, reproduced from McNutt et al. (1981). At the time of the Voyager 2 encounter the plasma appears to be rotating slower at a given distance than it was during the Voyager 1 encounter. The Voyager 2 data also show fewer data points and more scatter than the Voyager 1 data. According to R. L. McNutt (private communication, April 1986) the plasma
Figure V.1 Plot of part of the inbound trajectory of Voyager 2 shown in the \( r-\lambda_{III} \) plane. The crossing points are indicated by circles and the accompanying letter, while the range of the spacecraft during each data set is shown by the solid line.
Figure V.2. Estimates of the total elementary-mass and elementary charge concentrations of positive ions in units of amu per cm$^3$ and elementary charges per cm$^3$, respectively, for the Voyager 2 inbound encounter. The top panel shows the distance of the spacecraft from the magnetic dipole equatorial plane and arrows in the bottom panel indicate the crossing of this plane. The regions for each plasma sheet crossing data set are marked and labelled. Dates are given at 1200 UT.

Reprinted from McNutt et al. (1981)
Figure V.3  Values for the azimuthal velocity of the plasma for both Voyager 1 and 2. The regions for each plasma sheet crossing data set are marked and labelled. Note that the Voyager 2 data are fewer in number and smaller in magnitude, and have a larger scatter than the Voyager 1 data.

Reprinted from McNutt et al. (1981)
during Voyager 2 inbound was hotter than during Voyager 1, which reduced the number of useful observations and increased the uncertainty of those used. Applying the analytic expression from Hill (1979), the characteristic distance for Voyager 2 inbound is estimated to be $r_o = 16 R_J$.

The magnetometer data from Voyager 2 inbound also showed a large amount of scatter. This, along with the scatter in the plasma data, suggests that the dayside plasma sheet was much more disorganized during this encounter. Although Voyager 2's slower traverse of the magnetosphere allowed for five crossings on the dayside that had reasonable orientations of the normals, only four of these could be analyzed, and one of them was marginal. The C crossing $B_\phi$ curve was so noisy that no amount of data manipulation could produce a signal. The data curves for this crossing (Figure V.6a, b) are included here for completeness. The D crossing $B_\phi$ curve produces a useful signal only in the region marked "I" (Figure V.7b). The B crossing gave a clear signal outside of roughly $\pm 1 R_J$; however, inside that region (labeled "III" in Figure V.5b) the $B_\phi$ component is the same sign as the $B_r$ component, which indicates an inward current and possible superrotation. Unfortunately, there are no useful plasma data in this region to confirm or contradict this (R. L. McNutt, private communication, April 1986). During this crossing period Voyager 2 passed by the satellite Ganymede at a distance of 62,000 km. As the satellite moves through the magnetic field of the planet's magnetosphere, the field lines are draped about the satellite, leaving a magnetic wake behind it (see Hill et al., 1983 for a discussion specifically about the Io-magnetospheric interaction). The magnetic wake from Ganymede can be seen as a spike in the $B_\phi$ curve.
between 80° and 90° System III longitude (Burlaga et al., 1980). This region was not included in the final analysis of the magnetic field averages. Crossings A and E were relatively normal.

The data curves of the transformed magnetic field in cylindrical coordinates are given in Figures V.4 through V.8. The relevant data and results for each crossing are presented in Tables V.1 through V.5. Again, please note that on the graphs increasing z-distance and increasing longitude do not always go in the same direction.
TABLE V.1
Voyager 2 Inbound Crossing A

Data set covers:

| distance: | 13.0308 RJ | 11.1506 RJ |
| z distance: | \(7.6111 \times 10^7\) m | \(-1.9666 \times 10^8\) m |
| \(\lambda_{III}\) longitude | 191.512° | 343.384° |
| time: | 190d 11h 36m | 190d 16h 20m |

Crossing point occurs at:

| distance: | 12.202 RJ |
| \(\lambda_{III}\) longitude: | 252.76° |
| time: | 190d 13h 29m |

Orientation of the normal:

| tilt: | 9.18° ± 0.03° |
| \(\lambda_{III}\) longitude: | 198.24° ± 0.09° |

Data:

| \(<B_r>\) | 117.0 nT |
| \(<B_\phi>\) | 2.3 nT |
| \(B_z\) | -172.9 nT |
| \(\omega_p\) | \(1.51 \times 10^{-4}\) rad/s |
| \(\frac{3}{3r}(6\omega)\) | \(7.3339 \times 10^{-14}\) rad/m-s |
| \(\sigma\) | \(6.84 \times 10^{-11}\) kg/m |
| \(r\) | \(8.6745 \times 10^8\) m |
| \(\theta\) | 18.6° |
| \(\chi\) | 5.04 |

Results:

| \(\Sigma\) | 0.15 mho |
| \(S\) | \(7.9 \times 10^{30}\) amu/s |
| \(V_r\) | 47.8 km/s |
Figures V.4a,b
### TABLE V.2

**Voyager 2 Inbound Crossing B**

Data set covers:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance:</td>
<td>15.4133 RJ</td>
<td>13.0061 RJ</td>
</tr>
<tr>
<td>z distance:</td>
<td>$-2.7623 \times 10^7$ m</td>
<td>$1.0862 \times 10^8$ m</td>
</tr>
<tr>
<td>$\lambda_{III}$ longitude</td>
<td>33.690°</td>
<td>193.261°</td>
</tr>
<tr>
<td>time:</td>
<td>190d 6h 53m</td>
<td>190d 11h 40m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance:</td>
<td>13.890 RJ</td>
</tr>
<tr>
<td>$\lambda_{III}$ longitude:</td>
<td>132.43°</td>
</tr>
<tr>
<td>time:</td>
<td>190d 9h 49m</td>
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</table>

Orientation of the normal:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tilt:</td>
<td>11.9° ± 0.1°</td>
</tr>
<tr>
<td>$\lambda_{III}$ longitude:</td>
<td>202.3° ± 0.9°</td>
</tr>
</tbody>
</table>

Data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;B_r&gt;$</td>
<td>76.0 nT</td>
<td>(58.7-93.7)</td>
</tr>
<tr>
<td>$&lt;B_\phi&gt;$</td>
<td>1.9 nT</td>
<td>(1.7-2.0)</td>
</tr>
<tr>
<td>$B_z$</td>
<td>-114.2 nT</td>
<td></td>
</tr>
</tbody>
</table>

$\omega_p$: $1.42 \times 10^{-4}$ rad/s ($0.804 \Omega_p$)

$\frac{\partial}{\partial r}(\delta \omega)$: $8.2768 \times 10^{-14}$ rad/m-s

$\sigma$: $4.77 \times 10^{-11}$ kg/m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>9.8979 \times 10^8 m</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>17.8°</td>
<td>(17.7°-17.9°)</td>
</tr>
<tr>
<td>$\chi$</td>
<td>5.44</td>
<td>(4.39-7.17)</td>
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</tbody>
</table>

Results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>0.11 mho</td>
<td>(0.09-0.12)</td>
</tr>
<tr>
<td>$S$</td>
<td>$5.5 \times 10^{30}$ amu/s</td>
<td>(5.1-5.9 \times 10^{30})</td>
</tr>
<tr>
<td>$V_r$</td>
<td>30.6 km/s</td>
<td>(28.5-33.3)</td>
</tr>
</tbody>
</table>
Figures V.5a,b
**TABLE V.3**  
Voyager 2 Inbound Crossing C

Data set covers:

<table>
<thead>
<tr>
<th>Distance</th>
<th>V2</th>
<th>V1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>18.7526 RJ</td>
<td>15.7648 RJ</td>
</tr>
<tr>
<td>z distance</td>
<td>2.4640 x 10^8 m</td>
<td>-2.3706 x 10^8 m</td>
</tr>
<tr>
<td>λIII longitude</td>
<td>188.225°</td>
<td>11.566°</td>
</tr>
<tr>
<td>Time</td>
<td>190d 0h 53m</td>
<td>190d 6h 14m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Distance</th>
<th>V2</th>
<th>V1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>17.263 RJ</td>
<td></td>
</tr>
<tr>
<td>λIII longitude</td>
<td>278.83°</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>190d 3h 29 m</td>
<td></td>
</tr>
</tbody>
</table>

Orientation of the normal:

<table>
<thead>
<tr>
<th>Tilt</th>
<th>V2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt</td>
<td>10.6° ± 0.4°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>λIII longitude</th>
<th>V2</th>
</tr>
</thead>
<tbody>
<tr>
<td>λIII longitude</td>
<td>192.5° ± 1.8°</td>
</tr>
</tbody>
</table>
Figures V.6a, b
### TABLE V.4

Voyager 2 Inbound Crossing D

Data set covers:

<table>
<thead>
<tr>
<th>Distance</th>
<th>21.4938 (R_J)</th>
<th>18.6612 (R_J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(z) Distance</td>
<td>(-2.0812 \times 10^8) m</td>
<td>(1.7536 \times 10^8) m</td>
</tr>
<tr>
<td>(\lambda_{\text{III}}) Longitude</td>
<td>22.940°</td>
<td>193.761°</td>
</tr>
<tr>
<td>Time</td>
<td>189d 20h 8m</td>
<td>190d 1h 2m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Distance</th>
<th>20.034 (R_J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{III}}) Longitude</td>
<td>110.85°</td>
</tr>
<tr>
<td>Time</td>
<td>189d 22h 39m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

<table>
<thead>
<tr>
<th>Tilt</th>
<th>8.3° ± 0.5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{III}}) Longitude</td>
<td>200.4° ± 3.2°</td>
</tr>
</tbody>
</table>

Data:

<table>
<thead>
<tr>
<th>(&lt;B_r&gt;)</th>
<th>39.3 nT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;B_\phi&gt;)</td>
<td>1.7 nT</td>
</tr>
<tr>
<td>(B_z)</td>
<td>-37.3 nT</td>
</tr>
</tbody>
</table>

\(|\omega|\) \(\times 10^{-6}\) rad/s (0.597 \(\omega_j\))

\(\frac{\partial}{\partial r}(\delta\omega)\)

\(7.6797 \times 10^{-14}\) rad/m-s

\(\sigma\)

\(1.001 \times 10^{-11}\) kg/m

\(r\)

\(1.4304 \times 10^9\) m

\(\theta\)

16.25° (16.20° - 16.30°)

\(x\)

4.11 (3.90 - 4.28)

Results:

\(\Sigma\)

0.08 mho

\(S\)

\(3.3 \times 10^{30}\) amu/s

\(V_r\)

60.1 km/s
Figures V.7a,b


### TABLE V.5

**Voyager 2 Inbound Crossing E**

Data set covers:

<table>
<thead>
<tr>
<th>Distance</th>
<th>(24.6631 \text{ RJ} )</th>
<th>(21.6643 \text{ RJ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z distance</td>
<td>(3.3761 \times 10^8 \text{ m} )</td>
<td>(-2.4366 \times 10^8 \text{ m} )</td>
</tr>
<tr>
<td>(\lambda_{III}) longitude</td>
<td>(191.621^\circ )</td>
<td>(12.669^\circ )</td>
</tr>
<tr>
<td>Time</td>
<td>189d 14h 42m</td>
<td>189d 19h 50m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Distance</th>
<th>(23.046 \text{ RJ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{III}) longitude</td>
<td>(289.38^\circ )</td>
</tr>
<tr>
<td>Time</td>
<td>189d 17h 28m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

| Tilt | \(9.6^\circ \pm 0.09^\circ \) |
| \(\lambda_{III}\) longitude | \(193.5^\circ \pm 2.9^\circ \) |

Data:

| \(<B_r>\) | 31.6 nT | (28.0-32.9) nT |
| \(<B_\phi>\) | 2.4 nT | (1.6-3.1) nT |
| \(B_z\) | -21.1 nT |
| \(\omega_p\) | \(8.98 \times 10^{-4} \text{ rad/s} \) | (0.510 \(\Omega_j\)) |
| \(\frac{\partial}{\partial r}(\delta\omega)\) | \(6.5932 \times 10^{-14} \text{ rad/m-s} \) |
| \(\sigma\) | \(7.94 \times 10^{-12} \text{ kg/m} \) |
| \(r\) | \(1.6452 \times 10^9 \text{ m} \) |
| \(\theta\) | \(15.7^\circ \) | (15.6°-15.9°) |
| \(\chi\) | \(3.73\) | (3.50-4.32) |

Results:

| \(\Sigma\) | 0.11 mho | (0.08-0.14) mho |
| \(S\) | \(3.2 \times 10^{30} \text{ amu/s} \) | (2.1-4.1 \times 10^{30}) amu/s |
| \(V_r\) | 64.7 km/s | (43.2-83.7) km/s |
Figures V.8a,b
The tilts of the normals for these plasma sheet crossings are much closer to the 04 dipole tilt than those calculated for the Voyager 1 inbound crossings; however, two of the five still exceed the dipole tilt. The values calculated here for the mass outflow rate, radial velocity, and height integrated Pedersen conductivity confirm the values calculated for the Voyager 1 inbound crossings. However, these results at first appear confusing and ambiguous with respect to the model of enhanced outflow in the active hemisphere. This will be examined in more detail in the Discussion section.
VI. RESULTS OF VOYAGERS 1 AND 2 OUTBOUND

After each spacecraft had passed its closest approach to Jupiter and swung around the planet, its trajectory took it out of the magnetosphere through the midnight to dawn quadrant. The outbound magnetometer data contained two useful crossings from Voyager 1 and six useful crossings from Voyager 2. As in the Voyager 2 inbound analysis, the crossing points were determined by finding the sign change of the spherical radial component of the magnetic field. The normals for the crossings were then calculated and each data set transformed into the new cylindrical coordinate system based on these normals.

Unfortunately, any quantitative analysis of the mass outflow rate, radial velocity, and Pedersen conductivity was precluded here by the lack of any useful plasma data in these regions. Figures VI.1 and VI.2 show the orientations of the D cup and the S-axis of the Voyager PLS during the Jovian encounters. The outbound regions covering the useful magnetometer data sets mentioned above are highlighted. Examination of these figures shows that during the outbound passages of the middle magnetosphere (~7 R_J to 30 R_J) the D cup was generally pointed opposite to the direction of the azimuthal plasma flow. According to J. W. Belcher (private communication, February 1986), during this portion of both flights the plasma flow into the A, B, and C cups around the S-axis was at such an oblique angle that any analysis for velocity and composition is extremely difficult and expensive in terms of computing time. Except for a small amount of Voyager 1 data in the Io torus, none of the PLS data in these regions have been reduced yet.
Figure VI.1  The track of the Voyager 1 spacecraft in the equatorial plane is shown along with the orientations of the D cup and the S-axis. The day number is given and tic marks are shown at every 12 hours. The region covered in this analysis is highlighted.

Reprinted from McNutt et al. (1981)

Figure VI.2  Same as figure VI.1 for the Voyager 2 encounter.

Reprinted from McNutt et al. (1981)
Thus, the only analysis possible for these sections is the transformation of the magnetometer data into the cylindrical coordinate system based on the plasma sheet normal. The resulting data curves for the eight crossing data sets are presented in Figures VI.3 through VI.10. The relevant data for each crossing are presented in Tables VI.1 through VI.8.
### TABLE VI.1

**Voyager 1 Outbound Crossing A**

Data set covers:

<table>
<thead>
<tr>
<th>Distance</th>
<th>Z Distance</th>
<th>( \lambda_{III} ) Longitude</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6596 RJ</td>
<td>-1.0941 ( \times 10^8 ) m</td>
<td>33.625°</td>
<td>64d 17h 36m</td>
</tr>
<tr>
<td>12.3069 RJ</td>
<td>1.9951 ( \times 10^8 ) m</td>
<td>214.528°</td>
<td>64d 23h 16m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Distance</th>
<th>( \lambda_{III} ) Longitude</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.704 RJ</td>
<td>111.64°</td>
<td>64d 20h 7m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

<table>
<thead>
<tr>
<th>Tilt</th>
<th>( \lambda_{III} ) Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2° ± 0.3°</td>
<td>206.6° ± 0.6°</td>
</tr>
</tbody>
</table>

### TABLE VI.2

**Voyager 1 Outbound Crossing B**

Data set covers:

<table>
<thead>
<tr>
<th>Distance</th>
<th>Z Distance</th>
<th>( \lambda_{III} ) Longitude</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4620 RJ</td>
<td>1.9469 ( \times 10^8 ) m</td>
<td>220.802°</td>
<td>64d 23h 27m</td>
</tr>
<tr>
<td>15.7975 RJ</td>
<td>-1.4811 ( \times 10^8 ) m</td>
<td>359.425°</td>
<td>65d 3h 31m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>Distance</th>
<th>( \lambda_{III} ) Longitude</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.609 RJ</td>
<td>309.25°</td>
<td>65d 2h 3m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

<table>
<thead>
<tr>
<th>Tilt</th>
<th>( \lambda_{III} ) Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4° ± 0.3°</td>
<td>208.6° ± 1.1°</td>
</tr>
</tbody>
</table>
Figures VI.3a,b
Figures VI.4a,b
TABLE VI.3

Voyager 2 Outbound Crossing A

Data set covers:

<table>
<thead>
<tr>
<th>distance:</th>
<th>10.1822 RJ</th>
<th>11.3170 RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$ distance:</td>
<td>$1.1019 \times 10^6$ m</td>
<td>$-2.5637 \times 10^8$ m</td>
</tr>
<tr>
<td>$\lambda_{III}$ longitude</td>
<td>219.912°</td>
<td>17.734°</td>
</tr>
<tr>
<td>time:</td>
<td>191d 0h 1m</td>
<td>191d 5h 7m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>distance:</th>
<th>10.186 RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{III}$ longitude:</td>
<td>221.19°</td>
</tr>
<tr>
<td>time:</td>
<td>191d 0h 4m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

| tilt:            | 10.2° ± 0.2° |
| $\lambda_{III}$ longitude: | 197.3° ± 0.1° |

TABLE VI.4

Voyager 2 Outbound Crossing B

Data set covers:

<table>
<thead>
<tr>
<th>distance:</th>
<th>11.4133 RJ</th>
<th>13.8247 RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$ distance:</td>
<td>$-2.6201 \times 10^8$ m</td>
<td>$7.8564 \times 10^7$ m</td>
</tr>
<tr>
<td>$\lambda_{III}$ longitude</td>
<td>26.601°</td>
<td>208.484°</td>
</tr>
<tr>
<td>time:</td>
<td>191d 5h 24m</td>
<td>191d 11h 0m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>distance:</th>
<th>13.011 RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{III}$ longitude:</td>
<td>152.31°</td>
</tr>
<tr>
<td>time:</td>
<td>191d 9h 18m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

| tilt:            | 10.6° ± 0.1° |
| $\lambda_{III}$ longitude: | 203.7° ± 0.8° |
Figures VI.5a, b
Figures VI.6a,b
### TABLE VI.5

**Voyager 2 Outbound Crossing C**

**Data set covers:**

- **distance:** 13.6807 $R_J$
- $z$ distance: $8.0586 \times 10^7$ m
- $\lambda_{III}$ longitude: 198.759°
- **time:** 191d 10h 42m

- **distance:** 16.0443 $R_J$
- $z$ distance: $-2.8113 \times 10^8$ m
- $\lambda_{III}$ longitude: 351.460°
- **time:** 191d 15h 15m

**Crossing point occurs at:**

- **distance:** 14.519 $R_J$
- $\lambda_{III}$ longitude: 254.42°
- **time:** 191d 12h 23m

**Orientation of the normal:**

- **tilt:** 10.7° ± 0.1°
- $\lambda_{III}$ longitude: 193.9° ± 0.4°

---

### TABLE VI.6

**Voyager 2 Outbound Crossing D**

**Data set covers:**

- **distance:** 16.7030 $R_J$
- $z$ distance: $-3.4549 \times 10^8$ m
- $\lambda_{III}$ longitude: 32.361°
- **time:** 191d 16h 27m

- **distance:** 19.5692 $R_J$
- $z$ distance: $2.2530 \times 10^8$ m
- $\lambda_{III}$ longitude: 207.059°
- **time:** 191d 21h 31m

**Crossing point occurs at:**

- **distance:** 18.325 $R_J$
- $\lambda_{III}$ longitude: 131.63°
- **time:** 191d 19h 20m

**Orientation of the normal:**

- **tilt:** 12.4° ± 0.7°
- $\lambda_{III}$ longitude: 204.6° ± 2.6°
Figures VI.7a,b
Figures VI.8a,b
### TABLE VI.7

Voyager 2 Outbound Crossing E

Data set covers:

<table>
<thead>
<tr>
<th>distance</th>
<th>19.3855 R(\text{J})</th>
<th>22.3232 R(\text{J})</th>
</tr>
</thead>
<tbody>
<tr>
<td>z distance</td>
<td>(4.9578 \times 10^8) m</td>
<td>(-6.6651 \times 10^8) m</td>
</tr>
<tr>
<td>(\lambda_{\text{III}}) longitude</td>
<td>195.945°</td>
<td>13.348°</td>
</tr>
<tr>
<td>time</td>
<td>191d 21h 12m</td>
<td>192d 2h 17m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>distance</th>
<th>20.739 R(\text{J})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{III}}) longitude</td>
<td>277.73°</td>
</tr>
<tr>
<td>time</td>
<td>191d 23h 33m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

| tilt | \(23.4° \pm 5.4°\) |
| \(\lambda_{\text{III}}\) longitude | \(192.0° \pm 10.4°\) |

\(\lambda_{\text{III}}\) longitude: \(202.4°\)

### TABLE VI.8

Voyager 2 Outbound Crossing F

Data set covers:

<table>
<thead>
<tr>
<th>distance</th>
<th>22.4471 R(\text{J})</th>
<th>25.5389 R(\text{J})</th>
</tr>
</thead>
<tbody>
<tr>
<td>z distance</td>
<td>(-7.3462 \times 10^8) m</td>
<td>(6.5819 \times 10^8) m</td>
</tr>
<tr>
<td>(\lambda_{\text{III}}) longitude</td>
<td>20.837°</td>
<td>208.390°</td>
</tr>
<tr>
<td>time</td>
<td>192d 2h 29m</td>
<td>192d 7h 47m</td>
</tr>
</tbody>
</table>

Crossing point occurs at:

<table>
<thead>
<tr>
<th>distance</th>
<th>24.138 R(\text{J})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{III}}) longitude</td>
<td>123.19°</td>
</tr>
<tr>
<td>time</td>
<td>192d 2h 29m</td>
</tr>
</tbody>
</table>

Orientation of the normal:

| tilt | \(23.7° \pm 6.2°\) |
| \(\lambda_{\text{III}}\) longitude | \(206.3° \pm 7.1°\) |
Figures VI.9a,b
Figures VI.10a,b
The most exciting discovery of this work occurred with the realization that there was a significant amount of data in the inactive hemisphere of System III longitude that showed the same sign for both azimuthal and radial components of the magnetic field. The prograde orientation of the magnetic field indicates an inflowing current in the plasma sheet which implies superrotation of the plasma (Hill et al., 1982; Hairston and Hill, 1986). This will be discussed in the next section.

All the tilts of the eight normals in the outbound region exceed the tilt of the 04 magnetic dipole, although most are in the 10°-12.5° range. The relatively large uncertainty in the orientations of the E and F crossings for Voyager 2 are due to the increasing level of noise relative to the total field strength in these outermost crossings. In the case of the E crossing, the data curve of $B_\phi$ using the tilt/longitude of (23.4°/192.0°) results in $B_\phi$ changing sign at the crossing point, but behaving bizarrely throughout much of the rest of the data set. Taking advantage of the range of uncertainty in the orientation, the normal was varied until a realistic curve was achieved. Using a tilt/longitude of (18.0°/202.4°) gives a $B_\phi$ curve in which the overall trend exhibits $B_\phi B_\phi < 0$ behavior throughout the data set. The overall trend also goes through zero at the crossing point even though the actual value for $B_\phi$ at the crossing point is significantly less than zero.

It should be noted that the spike in the $B_\phi$ curve in Figure VI.4b at $\lambda_{III} \sim 350°$ occurs at the spacecraft's closest approach to Ganymede and is due to the magnetospheric wake created by Ganymede (see Burlaga et al., 1980, for an analysis of the Ganymede wake observed by Voyager 2, and Hill et al., 1983, for a general discussion of satellite wakes).
A similar spike in Figure VI.3b at $\lambda_{III} \approx 100^\circ$ occurs at Europa's orbit and is assumed to be related to that satellite's wake. The spike at $\lambda_{III} \approx 60^\circ$ in the $B_\phi$ curve (Figure VI.3b) does not correspond to the orbit of any known satellite and is of unknown origin.
VII. DISCUSSION

The resultant values from all the dayside crossing data sets of the plasma mass outflow rate, the radial velocity, and the height integrated Pedersen conductivity are consistent. These results (presented in Table VII.1) are also consistent with previous order-of-magnitude estimates of these parameters, and provide an improvement in accuracy over those earlier values. Given the uncertainty in the data, each data set result shows a range of possible values that varies by about a factor of two with the preferred value falling somewhere in the middle. Thus these results are believed to be accurate within a factor of two.

Strobel and Atreya (1983) estimated values of $\Sigma$ ranging from 0.2 to 0.3 mho from aeronomy calculations. This work indicates somewhat smaller values of $\Sigma$, clustering around the range 0.08 to 0.15 mho, although there is one case in which $\Sigma = 0.31$ mho is the preferred value. Various researchers have estimated the plasma mass outflow rate to be on the order of $10^{30}$ amu/s (Dessler, 1980; Eviatar and Siscoe, 1980; Hill, 1980; Brown et al., 1983). The present results indicate that the mass outflow rate varies greatly with both time and location, but does remain within the expected order of magnitude, with values ranging from $2.3 \times 10^{30}$ to $8.3 \times 10^{30}$ amu/s. The only published estimate of the radial velocity of the plasma is that by McNutt et al. (1981) who use the measured plasma mass density at 17 R$_J$ and the estimate of $S = 10^{30}$ amu/s to arrive at $V_r = 13$ km/s. As the values for $S$ determined in this work are greater than this earlier estimate, so too are the values calculated here for radial velocities. Like the mass outflow rate, the radial
TABLE VII.1

Results of Calculations

<table>
<thead>
<tr>
<th>Crossing</th>
<th>S (10^{30} amu/s)</th>
<th>V_p (km/s)</th>
<th>Σ (mho)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voyager 1 Inbound:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A*</td>
<td>8.3 (5.6-11.8)</td>
<td>33.6 (22.5-47.9)</td>
<td>0.31 (0.21-0.44)</td>
</tr>
<tr>
<td>B</td>
<td>2.3 (1.7-2.8)</td>
<td>12.9 (9.1-15.0)</td>
<td>0.10 (0.07-0.12)</td>
</tr>
<tr>
<td>C*</td>
<td>3.4 (2.2-4.5)</td>
<td>26.4 (17.4-35.2)</td>
<td>0.13 (0.08-0.17)</td>
</tr>
<tr>
<td><strong>Voyager 2 Inbound:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A*</td>
<td>7.9 (2.4-11.8)</td>
<td>47.8 (14.7-71.6)</td>
<td>0.15 (0.04-0.21)</td>
</tr>
<tr>
<td>B</td>
<td>5.5 (5.1-5.9)</td>
<td>30.6 (28.5-33.3)</td>
<td>0.11 (0.09-0.12)</td>
</tr>
<tr>
<td>D</td>
<td>3.3</td>
<td>60.1</td>
<td>0.08</td>
</tr>
<tr>
<td>E*</td>
<td>3.2 (2.1-4.1)</td>
<td>64.7 (43.2-83.7)</td>
<td>0.11 (0.08-0.14)</td>
</tr>
</tbody>
</table>

*Denotes crossing in active hemisphere
velocities vary greatly from 12.9 to 64.7 km/s, but they do stay within the predicted order-of-magnitude range.

The first major surprise in this research came with the discovery of excessive tilts of the plasma sheet orientation at the crossing points. As the cold plasma leaves the Io torus it first tends to move toward the equilibrium plane at the centrifugal equator (Hill et al., 1974). If the plasma remained cold, it would continue to stay in the centrifugal equator as it flowed outward. However, experimental evidence shows that as the plasma migrates outward it becomes more energetic (Belcher, 1983). This hotter plasma tends to migrate from the centrifugal equator toward the magnetic equator (Cummings et al., 1980), thus causing the plasma sheet to tilt toward the direction of the dipole tilt. At large distances from the intersecting line of the rotational and magnetic equators, it would be expected that this tilt would be greater than the dipole tilt. However, as the trajectories of both Voyager spacecraft were essentially on the rotational equator, all of the plasma sheet crossings occurred at or near the intersecting line. In that region the tilt of the plasma sheet normal was thought to be some value between the centrifugal equator tilt of 7.2° and the dipole tilt of 9.6° (e.g., Vasyliunas and Dessler, 1981, and references therein). As can be seen from the values in Table VII.2 all of the normals point within 10° of the 04 dipole model's System III longitude of 201.7°, but most of the tilts exceed the 04 model's tilt of 9.6°. Five of the eight dayside crossings have tilts of the normal that equal or exceed the dipole tilt and all of the normals on the nightside crossings exceed the dipole tilt. Three of the normals have tilts which
TABLE VII.2
Orientation of the Plasma Sheet Normals

<table>
<thead>
<tr>
<th>Crossing</th>
<th>Orientation of the Normal</th>
<th>Crossing Point Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tilt</td>
<td>λ_{III}</td>
</tr>
<tr>
<td>Voyager 1 Inbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>11.4</td>
<td>204.2</td>
</tr>
<tr>
<td>B</td>
<td>14.8</td>
<td>204.2</td>
</tr>
<tr>
<td>C</td>
<td>21.7</td>
<td>207.1</td>
</tr>
<tr>
<td>Voyager 1 Outbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>11.2 ± 0.3</td>
<td>206.6 ± 0.6</td>
</tr>
<tr>
<td>B</td>
<td>11.4 ± 0.3</td>
<td>208.6 ± 1.1</td>
</tr>
<tr>
<td>Voyager 2 Inbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>9.18 ± 0.03</td>
<td>198.24 ± 0.09</td>
</tr>
<tr>
<td>B</td>
<td>11.9 ± 0.1</td>
<td>202.3 ± 0.9</td>
</tr>
<tr>
<td>C</td>
<td>10.6 ± 0.4</td>
<td>192.5 ± 1.8</td>
</tr>
<tr>
<td>D</td>
<td>8.3 ± 0.5</td>
<td>200.4 ± 3.2</td>
</tr>
<tr>
<td>E</td>
<td>9.60 ± 0.09</td>
<td>193.5 ± 2.9</td>
</tr>
<tr>
<td>Voyager 2 Outbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>10.2 ± 0.2</td>
<td>197.3 ± 0.1</td>
</tr>
<tr>
<td>B</td>
<td>10.6 ± 0.1</td>
<td>203.7 ± 0.8</td>
</tr>
<tr>
<td>C</td>
<td>10.7 ± 0.1</td>
<td>193.9 ± 0.4</td>
</tr>
<tr>
<td>D</td>
<td>12.4 ± 0.7</td>
<td>204.6 ± 2.6</td>
</tr>
<tr>
<td>E</td>
<td>23.4 ± 5.4</td>
<td>192.0 ± 10.4</td>
</tr>
<tr>
<td>F</td>
<td>23.7 ± 6.2</td>
<td>206.3 ± 7.1</td>
</tr>
</tbody>
</table>
are greater than twice the dipole tilt. Evidence for such excessive tilts is also indicated by Goertz (1981). In spite of their unexpectedly large magnitudes, these tilts are believed to be indeed accurate reflections of the orientation of the plasma sheet. This belief is based on the fact that only coordinate systems based on such tilts can satisfy the condition that both $B_r$ and $B_\phi$ change sign at the crossing points.

There is currently no theoretical explanation of why the plasma sheet tilt should exceed the dipole tilt, particularly by the large amounts seen in some of the crossings. None of the previous models of the plasma sheet, even those including a twisting component (Goertz, 1981; Jones et al., 1981), give rise to such large tilts. Thus, the analysis suggests that the overall shape of the plasma sheet is more complicated than previously believed and that further, more detailed attempts at modeling the plasma sheet geometry might be a worthwhile research endeavor.

One of the motivations for this research has been to look for any indication of systematic variations of $S$, $V_r$, and $I$ as a function of longitude as predicted by the corotating convection model (Hill et al., 1981; 1982). This prediction is based on the magnetic anomaly/active sector model of the Jovian magnetosphere first put forward by Dessler and Hill (1975) in order to explain the phenomenon of spin dependent pulses of relativistic electrons emitted from Jupiter. Since then a host of related magnetospheric and ionospheric phenomena have been shown to be associated with the active sector (see Hill et al., 1983). According to this model either an offset in the dipole or else higher order
multipoles in the internal magnetic field of Jupiter tends to cause a decrease in the surface field strength on one side of Jupiter relative to the other. This region of depressed field intensity is known as the "magnetic anomaly." As Pedersen conductivity is inversely propositional to magnetic field strength, such an anomaly in the ionosphere gives rise to a longitudinal asymmetry of the Pedersen conductivity where larger conductivities are associated with the magnetic anomaly region (Dessler and Hill, 1979). This magnetic anomaly region is associated with an enhanced plasma flow (see Figure II.6) from the ionosphere out to a region of the magnetosphere known as the "active sector." This enhanced flow of ionospheric plasma causes an increased ionization rate in the active sector of the Io torus. Thus the active sector is most commonly associated with observations of enhanced ion densities in the Io torus (Pilcher and Morgan, 1980; Trafton, 1980). The exact boundaries of the active sector vary depending on the author and the phenomenon under discussion. Figure VII.1 shows a cartoon of several phenomena associated with the magnetic anomaly model and the longitude range of their extent. Usually the active sector is defined as being roughly located in the range 180° to 270° in System III longitude (where the maximum density of the Io torus is at approximately 250° System III longitude). For the purpose of this thesis the hemisphere from System III longitude 130° to longitude 310° is defined as the "active hemisphere" in order to include any phenomenon associated with the active sector. Likewise, the opposite hemisphere will be referred to as the inactive hemisphere.

In all the dayside crossing data sets (except for the short period around the B crossing for Voyager 2) the $B_r$ and $B_\phi$ curves are of oppo-
Figure VII.1  Diagram showing the location and a description of various phenomena in the Jovian ionosphere and magnetosphere which are believed to be explainable in terms of the magnetic anomaly/active sector model. Please note that the angular range of each phenomenon is shown approximately to scale, while the radial distances have been expanded or compressed for clarity.

Reprinted from Hill et al. (1983)
site signs, thus indicating the presence of outflowing plasma in the plasma sheet. Hill et al. (1982) described a hybrid model where the earlier convection pattern was superimposed on a pattern of radial diffusion of the plasma. In this model the time-averaged plasma flux is outward at all longitudes, but with an enhanced flux in the active sector. Examination of equation II.29 for the mass outflow rate

\[
S = \frac{2\pi r B^2}{\mu_0 [\Omega_j - \frac{\delta \omega}{2} - \frac{r}{2} \frac{\partial}{\partial r} (\delta \omega)]}
\]

shows that an increase in outflow rate will be accompanied by an increase in \( B_\phi \). Thus an enhanced plasma flux in the active sector will be reflected by an increase in the magnitude of \( B_\phi \) in the active sector relative to the magnitude of \( B_\phi \) elsewhere.

Examination of Figure IV.1 for the inbound leg of Voyager 1 shows that crossing points A and C lie within the active hemisphere while the crossing point B lies in the inactive hemisphere. It can also be seen that all three data set regions straddle both the active and inactive hemispheres. Data sets for crossing A and C are predominantly in the active hemisphere (71% and 56%, respectively), while the B crossing data set is predominantly in the inactive hemisphere (57%). Thus the calculation for each of these crossings necessarily includes data from both regions.

Examination of Figure IV.4b for the A crossing data set shows a clear signal of enhanced outflow in the active sector. The magnitude of \( B_\phi \) in the "leveled off" region within the active hemisphere is indeed twice as large as the "leveled off" region in the inactive hemisphere.
However, this pattern is not repeated in the C crossing data set. Figure IV.6b shows the $B_\phi$ curve is roughly the same magnitude for both the active and inactive regions. Likewise, Figure IV.5b for the B crossing data set shows $B_\phi$ to be roughly symmetric in both the active and inactive regions.

Comparison of the calculated values for the Voyager 1 inbound data sets shows that the height integrated Pedersen conductivity is higher at the two active-hemisphere crossing points relative to the crossing point in the inactive hemisphere, as predicted by the magnetic anomaly model. Likewise, comparison of the mass outflow rates and the radial velocities for these three data sets shows higher values for the two crossings in the active hemisphere. All of this supports the model of Hill et al. (1982); however, with only three crossings from which to judge, it is impossible to say definitely whether this is a result of the corotating convection model or merely a temporal variation in the outflow.

Originally I anticipated that the results from the dayside crossings of Voyager 2 would provide a confirmation of the results from Voyager 1. Unfortunately both the magnetometer and plasma data from the Voyager 2 inbound portion exhibit so much noise that the plasma sheet and its flow must not have been as well organized as they were during the Voyager 1 encounter. For example, inspection of the azimuthal velocity data in Figure V.3 shows clear indications of velocity peaks at the plasma sheet crossings for Voyager 1, while no such peaks occur in the Voyager 2 data. Because of this noisy quality of the Voyager 2 dayside data the results appear ambiguous and sometimes contradictory. Crossing points A, C, and E all lie in the active hemisphere; crossing
point D lies in the inactive hemisphere; and crossing point B lies right at the boundary between the two. As the Voyager 1, the Voyager 2 crossing point data sets straddle both hemispheres with the A, C, and E sets lying primarily in the active hemisphere (80%, 67%, and 65% respectively), while the B and D sets lie primarily in the inactive hemisphere (63% and 65% respectively). Of the five crossing sets, the cleanest signals occur in the A and E crossings, indicating perhaps that the outflow is better organized in the active hemisphere. However, the most disorganized magnetic data curve occurs in the C crossing set, which also lies primarily in the active hemisphere.

The values of mass outflow and radial velocity show mixed results. Comparing the A crossing and B crossing results shows larger values for S and \( V_r \) for the A crossing in the active sector. However, comparing the D crossing and E crossing reveals they have essentially the same values for S and \( V_r \). As for the height integrated Pedersen conductivity, both the active hemisphere crossings, A and E, have higher conductivities than their adjoining inactive hemisphere crossings, B and D.

Figure V.8b shows that \( B_\phi \) has a larger magnitude in the active sector region of the curve (\( \lambda_{III} = 210^\circ \) to \( 250^\circ \)) than it does in the inactive hemisphere region of the curve (\( \lambda_{III} = 310^\circ \) to \( 0^\circ \)), thus showing a clear signal of enhanced outflow in the active sector. This matches the enhancement seen in the curve for the inbound Voyager 1 A crossing (Figure IV.4b). This enhancement is not repeated in the Figure V.4b curve for the Voyager 2 A crossing which covers the same range of longitude as the E crossing. One possible explanation for this lack of signal could be the fact that the spacecraft did not get farther than 1
$R_J$ above the plasma sheet crossing plane in the A crossing, and thus may not have gotten far enough outside the current carrying region to accurately measure the radial current. Examination of the $B_\phi$ curve for the E crossing (Figure V.8b) shows that in the active hemisphere $B_\phi$ does not vary much from zero until the spacecraft is 2-3 $R_J$ above the crossing plane.

While the data from Voyager 2 inbound do not offer strong confirming evidence of the Hill et al. hybrid model, they do offer some tantalizing indications that there is still enhanced flow in the active sector. In particular, the results give no strongly disconfirming evidence against the hybrid model. With only seven current-sheet crossings to judge from, it is apparent that there are not yet enough observations to make a final judgment. One hopes that this question can be addressed further in the future once this method is applied to the larger data set of plasma sheet crossing observations that will be made by the Galileo spacecraft.

The most exciting result of this research is the discovery of evidence of superrotation of the plasma in the nightside magnetosphere. Superrotation in the Jovian magnetosphere was first predicted on theoretical grounds by Hill, Dessler, and Maher (1981). However, the PLS experiment results for the Jovian encounter showed only subcorotational velocities at all observed points (McNutt et al., 1981; Belcher, 1983). It was in order to incorporate this observation that the convection-radial diffusion hybrid model was developed (Hill et al., 1982). Both works demonstrate that an outflowing plasma which is subcorotational is associated with an outflowing radial current in the plasma sheet which
causes a retrograde spiral of the magnetic field (i.e., the $B_r$ and $B_\phi$ components have opposite signs). Likewise, an inflowing plasma that is superrotational is shown to be associated with an inflowing radial current in the plasma sheet which causes a prograde spiral of the magnetic field (i.e., the $B_r$ and $B_\phi$ components have the same sign). All but one of the eight nightside plasma sheet crossing data sets show substantial regions where both components have the same sign. Figures VII.2 and VII.3 show the outbound trajectories of Voyager 1 and 2 (respectively) in $r^{-1/3}$ coordinates. The regions where $B_r$ and $B_\phi$ are opposite in sign are shown as a solid line and the regions where $B_r$ and $B_\phi$ are the same sign are shown in cross-hatching. Examination of the figures shows that the regions of superrotation do indeed line up preferentially in the inactive hemisphere as predicted by Hill et al. (1981). In Figure VII.3 superrotation occurs in 65% of the inactive hemisphere data, but only in 5% of the active hemisphere data.

In order for this result to be taken as valid evidence, it must first answer three objections. The first objection is that since most of the data showing superrotation are away from the crossing points themselves, and hence the orientation of the components is less certain, is there any evidence of inflowing currents occurring at the crossing points? The answer is yes. Both Voyager 1 outbound crossing B (Figures VI.4a,b) and Voyager 2 inbound crossing B (Figures V.5a,b) show the signature of $B_r$ and $B_\phi$ both having the same sign at and on both sides of the crossing point. Since the orientation of the plasma sheet is most certain at the crossing point, the evidence for an inflowing current must be accepted at these two crossings.
Figure VII.2  Plot of part of the path of Voyager 1 outbound in the $r-\lambda_{III}$ plane showing the locations of the crossing points (circles) and the range of the data sets. The solid portion of the curve is the region where the $B_r$ and $B_\phi$ components are opposite in sign (signifying current outflow) and the hatched portion is the region where the $B_r$ and $B_\phi$ components are the same sign (signifying current inflow). The active hemisphere is indicated by the dashed line and arrows.
Figure VII.3  Same as figure VII.2 for the Voyager 2 outbound path.
Note how the hatched regions signifying current inflow (and hence superrotation) line up in the inactive hemisphere.
The second objection arises from the first. Even accepting the evidence of inflowing current in the two crossing data sets above, this still leaves the rest of the data which show evidence of superrotation in regions of the other six data sets that are far away from the crossing point. Is it certain that this "signal" is not just an artifact of the coordinate transform of the O4 dipole? This is a particularly important question in the Voyager 2 outbound data sets where the spacecraft travels much farther south of the plasma sheet (where the superrotation signal is seen) than north of the plasma sheet. In order to find the contribution of the transformed O4 dipole field a comparison was generated on the computer. For the Voyager 2 outbound crossing B data set, the O4 dipole model field was calculated for each point, then transformed into the coordinate system based on the normal at the B crossing point. Comparisons of the $B_r$ and $B_\phi$ components for the actual Voyager 2 data and for the transformed O4 model are presented in Figures VII.4a and 4b. Note that for most of the region of the superrotational signal in the $B_\phi$ curve of Voyager 2 data ($\lambda_{III} = 25^\circ$ to $120^\circ$), the $B_\phi$ curve for the transformed O4 model has the opposite sign from the superrotational signal. Only in a small region from $\lambda_{III} = 25^\circ$ to $50^\circ$ does the $B_\phi$ component of the transformed O4 dipole make a positive contribution to the superrotational signal, and even then its contribution is much smaller than the actual signal. Since the primary sources of the magnetic field in this region of the Jovian magnetosphere are the internal dipole and the plasma sheet currents, it must be concluded that the regions where $B_\phi$ is the same sign as $B_r$ are indeed showing a signal from an inflowing current in the plasma sheet.
Figures VII.4a and 4b  Graphs of the radial and azimuthal magnetic-field components (respectively) showing a comparison of the transformed data from the Voyager 2 outbound crossing B data set and the curves resulting from a transformed 04 magnetic dipole field. Note in figure VII.4b that the negative $B_{\phi}$ signal at $\lambda_{III} \approx 20^\circ-120^\circ$ cannot be an artifact of the transformed dipole field.
The third objection is the most critical: how can the evidence for superrotation be reconciled with the lack of any evidence of superrotational flow from the Plasma Science experiment? First, all but one of the eight data sets that show a signal of inflowing current occur during the nightside passage through the middle magnetosphere. As was shown in the previous section and in Figures VI.1 and VI.2, the orientations of the plasma experiment cups during these portions of the encounters were not favorable to detect the azimuthal flow of the plasma. According to J. W. Belcher (private communication, February 1986) the plasma flow in these regions was at such large angles to all the sensors that any information about the azimuthal flow is difficult, if not impossible, to calculate. To further complicate matters, during the Voyager 2 encounter the plasma was much hotter than during the Voyager 1 encounter. The increase in the thermal widths of the peaks in the plasma data impaired the ability to accurately calculate the azimuthal velocity of the plasma. Inside of 15 $R_J$ on the inbound leg of Voyager 2 the peaks became so broad that determination of the azimuthal velocity became impossible (R. L. McNutt, personal communication, April 1986). Thus there is no useful plasma data at any of the nightside regions nor at the dayside Voyager 2 crossing B region where superrotation is seen. Currently, the Plasma Science experiment group at MIT is reassessing the Voyager 2 inbound azimuthal velocity data using an improved data reduction method which is expected to raise the values for the azimuthal velocities seen during the inbound encounter, though how much the velocities will be changed and when the results will be available is not known at this time (R. L. McNutt, private communication, April 1986).
Finally, there is evidence of superrotational velocities seen by both Voyager 1 and 2 in the Low Energy Charged Particle (LECP) experiment during the inbound portion of their encounters (Carbary et al., 1981). Figures VII.5 and VII.6 show the azimuthal velocity data as a function of distance for Voyagers 1 and 2 (respectively). While the overall average of the velocities remains subcorotational along the graph, it is apparent there are several individual data points that show superrotational velocities. Unfortunately, like the Plasma Science experiment, there are no data from the LECP experiment during the nightside region of interest of this thesis. During the closest approach and passage through the middle magnetosphere the experiments on both spacecraft were placed in "stow mode" which improved the compositional data from the plasma, but reduced the geometric data about the flow. While this does not directly support the evidence presented here in favor of superrotation in the nightside middle magnetosphere, it does show that superrotational velocities have been observed elsewhere in the Jovian magnetosphere.

Thus it is concluded that the evidence for superrotation is not an artifact of the analysis method nor at odds with the plasma flow data available. This leaves only systematic error as a possible alternative explanation. However, such a systematic error would have to occur only on the nightside, only in the southern region of the magnetosphere, preferentially in the inactive hemisphere, and during two spacecraft encounters four months apart. No such systematic error is readily apparent, while the corotating convection model can easily account for all of the observed phenomena. Thus it is concluded that inflowing
Figure VII.5 Azimuthal plasma velocity on the dayside calculated from data measured by the Low Energy Charged Paricle (LECP) experiment on board Voyager 1. The dashes at the top represent the regions where the spacecraft was north of the magnetic equator. A line indicates the corotational speed as a function of distance. Note there are a few points that show superrotational velocities.

Reprinted from Carbary et al. (1981)

Figure VII.6 Same as figure VII.5 except for Voyager 2 data. Again note that there are several more points here that show superrotational velocities.

Reprinted from Carbary et al. (1981)
currents and superrotation of the plasma are indeed being observed in the data.

From all these results a composite model of plasma flow in the Jovian magnetosphere can be constructed. In the dayside magnetosphere the plasma flow follows the hybrid model (Hill et al., 1982) where the plasma flux is outward at all longitudes, but with an enhanced flux in the active hemisphere, and there is a corotation lag at all longitudes. In the nightside magnetosphere, plasma is lost primarily by flux tubes from the active hemisphere, and the returning flux tubes with their lesser mass density superrotate. Of course, this simple model represents an average over many cycles, and there is certainly much variation in time and location for all these phenomena. Specifically, the evidence for superrotation in the Voyager 2 inbound crossing B occurs at about 0500 local time which is probably unusual, but not outside the realm of plausibility.

A detailed description of this model is based on a composite of previous work on planetary wind (Hill et al., 1974; Michel and Sturrock, 1974; Carberry et al., 1976), the magnetic anomaly model (Dessler and Vasyliunas, 1979; Vasyliunas and Dessler, 1981), and the corotating convection model (Vasyliunas, 1978; Hill et al., 1981; 1982). Figure VII.7 provides a qualitative cartoon of this flow pattern from Vasyliunas (1983). Flux tubes near the Io torus fill with plasma and, under centrifugal acceleration, begin to move outward. As the tubes move outward, the coriolis force causes the plasma to lag behind corotation with Jupiter. On the dayside the compression of the magnetic field by the solar wind provides a pressure that keeps the plasma from mi-
Figure VII.7  Qualitative cartoon of the plasma flow in the equatorial plane (left) showing near-corotational flow near Jupiter and the "planetary wind" flow in the tail region. The four diagrams on the right show meridonal cross sections (taken at the locations shown on the left) of the magnetic field configurations. These diagrams demonstrate the sequence of distention of the field lines, followed by reconnection which results in plasma inflow and outflow.

Reprinted from Vasyliunas (1983)
grating outward too rapidly. However, once the flux tubes rotate around to the nightside, they are free to expand out and down the magnetotail. As can be seen from Figure VII.7 the centrifugal acceleration of the plasma distends the magnetic field until it can no longer contain the plasma. At this point magnetic field reconnection occurs (cross section 3 in Figure VII.7) with most of the plasma in the flux tube being lost down the tail, thus creating the planetary wind. Some fraction of the plasma will remain trapped on the reconnected field lines and, as the inward magnetic tension now exceeds the centrifugal acceleration of the less dense plasma in the flux tube, the plasma will be compressed back towards Jupiter. As the plasma moves inward, conservation of angular momentum causes the plasma's azimuthal velocity to increase.

Superrotation arises from the fact that flux tubes which start out in the active hemisphere contain higher plasma densities than flux tubes that start out in the inactive hemisphere and, as such, lag further behind corotation than those that start out in the inactive hemisphere. These heavier flux tubes lag behind corotation until they reach the boundary between the active and inactive hemispheres before they release their plasma. The flux tube continues around the planet into the inactive region, but as the magnetic tension compresses the remaining plasma inward, conservation of angular momentum increases the plasma's azimuthal velocity until it passes corotation and begins superrotating. At this point the motion of the plasma through the magnetic field sets up a radially inward current that acts as a brake on the plasma. As the flux tubes return to the vicinity of the Io torus they are again loaded with plasma and the process repeats itself. Since most of the plasma is lost
in the dusk to midnight quadrant and the subsequent compression occurs in the midnight to dawn quadrant, superrotation should occur primarily in the midnight to dawn quadrant. This is consistent with the results of this analysis.

To repeat, this is only a qualitative, time averaged picture of plasma flow through the magnetosphere. However, this qualitative model serves to explain the results of this work, namely an enhanced plasma outflow within the active hemisphere when it is in the dayside magnetosphere and superrotation within the inactive hemisphere when it is in the midnight to dawn quadrant.
VIII. CONCLUSION

Our level of understanding of the Jovian magnetosphere can be placed in perspective by comparison with the terrestrial magnetosphere, where twenty-eight years of in situ observations and study have shown it to be a continuing source of surprises, questions, contradictions, understandings, and frustrations. It is instructive to imagine what the state of our knowledge would be if we had only four brief spacecraft fly-bys of the Earth’s magnetosphere. Seen from this vantage point, it is amazing that the Jovian magnetosphere has revealed as much as it has to our understanding.

This thesis represents an effort to extend earlier work by providing accurate determinations of several important mangetospheric and ionospheric parameters. This research has refined our knowledge of the plasma mass outflow rate and the height integrated Pedersen conductivity from order-of-magnitude estimates to values accurate within a factor of two. This research has also produced the first firm estimates of the radial velocity of the plasma in the plasma sheet. Considering the limitations of the available data sets the effort to calculate these parameters has not been trivial. These resultant values are important in providing boundary conditions for theoretical modelling of the Jovian magnetosphere.

This work has also provided the first firm evidence for superrotation in the nightside middle magnetosphere. This, along with the evidence for an enhanced outflow of plasma in the active longitude hemisphere within the dayside middle magnetosphere, provides evidence for
the corotating convection model of plasma transport in the Jovian magnetosphere (Hill et al., 1981; 1982).

It is hoped that this analysis method can be extended in the future to the Saturnian magnetosphere. Like Jupiter, Saturn has a rotationally dominated magnetosphere with an internal source of plasma from one or more of its moons, which in turn creates a plasma disk surrounding the planet. The role that equatorial radial currents in this plasma disk play in transporting the plasma is not fully understood at this time (Connerney et al., 1983). Application to the Saturnian magnetosphere of the analysis developed for this thesis should help to settle this question.

Further in the future, it is hoped this analysis will someday be applied to observations from the Galileo spacecraft. Currently scheduled to arrive in Jovian orbit sometime in the late 1980s or early 1990s, Galileo will conduct imaging and magnetospheric observations for at least twelve months. Such a mission should provide observations of over a thousand plasma sheet crossings. Such a data set would definitely settle many of the uncertainties inherent in the present work, but would also no doubt complicate the simple picture presented here.
IX. APPENDIX: XCSNML.FORT

Central to the analysis procedure in this thesis is the transformation of the magnetometer data from the spherical coordinate system in which the data are provided by NASA, into the cylindrical coordinate system based on the local plasma-sheet normal. The program XCSNML.FORT (X-form to Cylindrical Spin Normal coordinates) was written primarily to accomplish this transformation, along with other duties.

First the individual data record of the magnetic vector in spherical components \((B_r, B_\theta, B_\phi)\) is recast into \(xyz\) components where \(\hat{z}\) is parallel to the Jovian spin axis and \(\hat{x}\), perpendicular to \(\hat{z}\), lies in the meridional plane and points away from Jupiter. This coordinate system is then rotated twice such that \(\hat{z}''\) is now parallel to \(\hat{n}\), the northward normal to the plasma sheet, and \(\hat{x}''\) is perpendicular to \(\hat{z}''\) and directed toward a line parallel to \(\hat{n}\) running through the center of Jupiter. The program also finds the colatitude and longitude of the spacecraft in this new coordinate system. The 0°/180° longitude circle in the new coordinate system is the System III longitude line towards which the normal is tilted. Using the new longitude and latitude values the magnetic field vector is recast from \(x''y''z''\) components into cylindrical \(r\phi z\) components. The program calculates the position of the spin axis for each data record and then rotates the \(\hat{r}\) and \(\hat{\phi}\) components such that \(-\hat{r}\) is now pointed toward the spin axis.

The components are then smoothed using a five channel smoothing technique (Bevington, 1969). The program also finds the spacecraft's distance \(z\) from the crossing plane in meters. The program then stores
and prints the new data set.

This program was used for Voyager 2 data and Voyager 1 outbound data. Voyager 1 inbound data were analyzed by several smaller programs that accomplished essentially the same analysis. A listing of the program follows.
THIS PROGRAM XCSNL,FORT (TRANSFORM TO CYLINDRICAL SPIN NORMAL).
IS ESSENTIALLY XCSML,FORT WITH A CORRECTION TO POINT THE NEGATIVE
RADIAL COMPONENT TOWARDS THE JUPITER SPIN AXIS. IT
TAKES THE SPHERICAL DATA FROM THE SYSTEM III DATA FROM THE
VOYAGER 1 OUTBOUND AND ALL VOYAGER 2 DATA SETS. AND
TRANSFORMS THEM INTO CYLINDRICAL COMPONENTS USING THE NORMAL
ORIENTATION AT THE PLASMA SHEET CROSSINGS AS ORIENTATION.

THE Z COMPONENT HERE IS PARALLEL TO THE NORMAL VECTOR AT THE
CROSSING AND THE NEGATIVE RADIAL COMPONENT POINTS TOWARDS THE
SPIN AXIS WHERE IT CROSSES THE Z-PLANE THAT THE SPACECRAFT IS
CURRENTLY IN. THE DRAWBACK HERE IS THAT THE COORDINATE SYSTEM
IS NO LONGER QUITE A RIGHT ANGLE SYSTEM SINCE THE LINE CONNECTING
ALL THE ORIGIN POINTS IN EACH Z-PLANE (IE--THE SPIN AXIS ITSELF)
IS AT AN ANGLE TO THE Z-AXIS OF THE COORD SYSTEM.

DIMENSION TBL(1000),TB2(1000),TB3(1000)
DIMENSION TWLXL(1000),TLAT(1000),TQOLAT(1000),DIST(1000)
DIMENSION CYLAT(1000),RCR(1000),ICR(1000),PHICR(1000)
DIMENSION ZDISTF(1000),ZDIST(1000),CCAF(1000)
DIMENSION RADCS(1000),ZCCS(1000),PHICS(1000)

HERE WE READ THE DATA INTO A DATA SET USING A ROUTINE
FOR DRAWING OFF OF EITHER ONE OR TWO SYSTEM III
DATA SETS. START AND STOP ARE THE SYSTEM III WLONG BOUNDARIES

START=93
STOP=206
ISET=1
IF (ISET.EQ.2) GO TO 25

HERE IS THE ROUTINE FOR READING FROM ONE DATA SET (95)

I=0
READ (95) A1,A2,A3,A4,A5,A6,11,12,13,14
READ (95) A1,A2,A3,A4,A5,A6,11,12,13,14
IF (A1.LT.START) GO TO 10

I=1
READ (95) TB1(I),TB2(I),TB3(I),TWLXL(I),TLAT(I),DIST(I),
*11,12,13,14
IF (TWLXL(I).LT.STOP) GO TO 20

WRITE (6,211) I

21 FORMAT (" THE NUMBER OF RECORDS READ IS ",I4)
GO TO 50

GO TO 50

25 I=0
READ (95) A1,A2,A3,A4,A5,A6,11,12,13,14
IF (A1.LT.START) GO TO 30

35 I=1+1
READ (95,END=40) TB1(I),TB2(I),TB3(I),TWLXL(I),TLAT(I),DIST(I),
*11,12,13,14
GO TO 35

40 I=1+1
READ(96) F1,F2,F3,F4,F5,F6,11,12,13,14
READ(96) F1,F2,F3,F4,F5,F6,11,12,13,14
IF (A1.LT.START) GO TO 45
WRITE (6,46) I
46 FORMAT (" THE NUMBER OF RECORDS READ IS ",14)
40 CONTINUE
HERE IS THE TILT AND WAVE ROTATION O= THE NORMAL VECTOR AT

000670 C EACH CROSSING AND DEFINE SOME CONSTANTS. DTOR IS THE CONVERSION

000680 C FACTOR DEGREES TO RADIANS. IN USED TO DIFFERENTIATE BETWEEN

000690 C INBOUND (IN=1) AND OUTBOUND (IN ANYTHING BUT 1)

000700 C TILT=9.6

000710 WNROT=201.7

000720 XDIST=20.0341

000730 ENROT=360.-WNROT

000740 PI=3.141592654

000750 DTOR=PI/180.

000760 IN=1

000770 C

000790 C HERE WE LOOP THROUGH ALL THE DATA POINTS TO TRANSFORM THEM

000790 C INTO THE CYLINDRICAL COORDINATE SYSTEM.

000800 C

000810 C

000820 C

000830 C DO 300 K=1,110

000840 ELONG=360.-TNLONG(K)

000850 DLONG=ELONG-ENROT

000860 COLAT=90.-TLAT(K)

000870 IF (DLONG.GT.0.) GO TO 110

000880 DLONG=DLONG+360.

000890 110 RDLONG=DLONG+DTOR

000900 RCOLAT=COLAT+DTOR

000920 RELONG=ELONG+DTOR

000930 CSCLAT=COS(RCOLAT)

000940 CSPCLT=COS(RPCLT)

000950 SCLAT=SIN(RCOLAT)

000960 SNPCLT=SIN(RPCLT)

000970 CSCLNG=COS(RDLONG)

000980 SCLNG=SIN(RDLONG)

000990 ARG1=(CSCLAT*CSPCLT)+(SNCLAT*SNPCLT*CSDLNG)

001000 CCCLAT=ARCOS(ARG1)

001010 SNMCLT=SIN(CCCCLAT)

001020 ARG2=(CSPCLT*SNCLAT*CSDLNG-SNCLAT*CSCLAT)/SNMCLT

001030 CECLONG=ARCOS(ARG2)

001040 ARG3=SNCLAT*SCLNG/SNMCLT

001050 CHEKLG=ARG3

001060 IF (CHEKLG.LT.0.) GO TO 120

001070 CHLONG=2*PI-CHELONG

001080 GO TO 121

001090 120 CHLONG=CECLONG

001100 121 CECLONG=2*PI-CHLONG

001110 CCLAT(K)=CECLONG

001120 SNCLAT=SIN(CCCCLAT)

001130 CSCLAT=COS(RCOLAT)

001140 SCLONG=SIN(RELONG)

001150 CSLONG=COS(RELONG)

001160 PHIX=-(TB3(K))*SCLONG

001170 PHIX=TB3(K)*CSLNG

001180 RADX=TB3(K)*CSLNG*SNCLAT

001190 RADY=TB3(K)*SCLNG*SNCLAT

001200 RADZ=TB3(K)*CSCLAT

001210 IF (CCCLAT.GT.90.) GO TO 200

001220 SNTCLT=SIN((CCCLAT+90.)*DTOR)

001230 CSTCLT=COS((CCCLAT+90.)*DTOR)

001240 SNTLNG=SCLNG

001250 CSTLNG=CSCLNG

001260 GO TO 210

001270 200 SNTCLT=SIN((270.-CCCLAT)*DTOR)

001280 CSTCLT=COS((270.-CCCLAT)*DTOR)

001290 SNTLNG=SIN((180.-RDLONG(K))*DTOR)

001300 CSTLNG=COS((180.-RDLONG(K))*DTOR)

001310 210 THETA1=TB3(K)*CSTLNG*SNTCLT

THETA1=THETA1+SNTCLT
HERE THE PROGRAM TAKES THE CROSSING DISTANCE AND DETERMINES
THE CROSSING COLATITUDE IN THE NORMAL'S COORDINATE SYSTEM,
THEN USES THAT TO FIND THE Z-DISTANCE FROM THE CROSSING POINT
TO THE 90 DEGREE PLANE OF THE NORMAL'S COORD SYSTEM

IF (IN.EQ.1) GO TO 325

OUTBOUND CASE

K=0

IF (DIST(K).LT.XDIST) GO TO 320

GO TO 340

INBOUND CASE

K=0

IF (DIST(K).GT.XDIST) GO TO 330

FRAC=(DIST-DIST(K-1))/DIST(K)-DIST(K-1))

RCLAT=CYCLAT(K-1)*DTOR

RCLAT2=CYCLAT(K)*DTOR

XCOLAT=(FRAC*(RCLAT2-RCLAT1))+RCLAT1

XDIST=XDIST+7.14E7*COS(XCOLAT)

HERE THE PROGRAM FINDS THE Z-DISTANCE FROM THE 90 DEGREE
PLANE OF EACH OF THE DATA POINTS, THEN SUBTRACTS OUT THE
Z-DISTANCE OF THE CROSSING POINT FROM EACH ONE IN ORDER TO
DETERMINE THE Z-DISTANCE FROM THAT DATA POINT TO THE CROSSING
PLANE.

DO 350 K=1,1

ZDISTF(K)=ZDISTI(K)-XDIST

CONTINUE

HERE THE PROGRAM FINDS THE SYSTEM THREE COLAT FOR THE DATA

DO 355 K=1,1

TCOLAT(K)=90-TLAT(K)

CONTINUE
HERE THE PROGRAM RUNS A CHECK TO SHOW HOW CLOSE THE RADIAL COMP.
IS TO THE TRUE SPIN DIRECTION. THEN TRANSFORMS THE RCR AND PHICR
COMPONENT SO THAT NEGATIVE RAD IS POINTING TOWARDS THE SPIN.
AXIS. THE CHECK WITH THE WEST LONGITUDE OF THE NORMAL AND ITS
COMPLIMENT TESTS TO DETERMINE WHETHER THE FINAL ANGLE OF ROTATION
OF BBA IS POSITIVE OR NEGATIVE. IN THE CYLINDRICAL PLANE OF THE
SPACECRAFT (IN THE NORMAL'S COORD SYSTEM) THE PROGRAM CALCULATES
THE RADIAL DISTANCE FROM THE SPACECRAFT TO THE NORMAL AXIS (AA) &
THE DISTANCE FROM THE NORMAL AXIS TO THE POINT IN THE PLANE WHERE
THE SPIN AXIS CROSSES (BB). USING THE LAW OF COSINES THE THIRD
LEG OF THE TRIANGLE IS FOUND (CC) AND THEN THE ANGLE BETWEEN AA
AND CC IS DETERMINED. THIS IS THE ANGLE WE MUST ROTATE R AND PHI.
COMPS IN ORDER TO HAVE A TRUE SPIN CENTERED COORD SYSTEM. BBA MAX
IS THE UPPER LIMIT ON THESE ANGLES USING AA AND BB AS BEING
AT RIGHT ANGLES. THIS IS DONE SINCE THERE IS SUCH A CHANCE FOR
ERROR IN BB-ANGLES DUE TO THE VERY SMALL ARGUMENTS THEY POSSESS.

TILTAN=TAN(TILT*DTOR)
WNROTO=WNRTO-180.
WRITE (6,395)
FORMAT ('/'' DISTANCE SPIN ANGLE MAX SPIN ANGLE'')
DO 400 K=1,1
200 BB=TILTAN*IDISTI(K)
201 IF (BB.GE.0.) GO TO 390
202 BB=-1*BB
203 AA=DIST(K)*SIN(CCOLAT)*7.14E7
204 IF (CCAI(K).LT.PI) GO TO 392
205 CCC=2*PI-CCAI(K)
206 GO TO 394
207 CCC=CCAI(K)
208 CCA=PI-CCC
209 CCSD=AA**2*BB**2-(2*AA*BB*COS(CCA))
210 CC=SQR(CCSD)
211 ARG=(AA**2+CC**2-BB**2)/(2*AA*CC)
212 BBA=ARCOS(ARG)
213 IF ((TMLONG(K).LE.WNROTO).AND.(TMLONG(K).GT.WNROTO)) GO TO 398
214 BBA=-1*BBA
215 CONTINUE
216 RI=RCR(K)*COS(BBA)-PHICR(K)*SIN(BBA)
217 PHII=RCR(K)*SIN(BBA)+PHICR(K)*COS(BBA)
218 RCR(K)=RI
219 PHICR(K)=PHII
220 BBAD=BBA/DTOR
221 ARG=BB/AA
222 BBA MAX=(ATAN(ARG2))/DTOR
223 WRITE (6,396) DIST(K),BBAD,BBA MAX
224 CONTINUE
225 FORMAT (F12.4,1P2E12.4)
226 CONTINUE
227 CONTINUE
228 CONTINUE
229 CONTINUE
230 IMAX=I-2
231 RADCS1=RADCR1
232 RADCS2=RADCR2
233 RADCS3=RADCR3
234 PHICS1=PHICR1
235 PHICS2=PHICR2
236 PHICS3=PHICR3
237 C
238 C
239 C
240 C
241 C
002620       ZCCS(J)=ZCR(J)
002630       PHICS(I)=PHICR(I)
002640       RADCS(I-1)=RCR(I-1)
002650       ZCCS(I-1)=ZCR(I-1)
002660       PHICS(I-1)=PHICR(I-1)
002670       DO 310 J=0,IMAX
002680       RADCS(J)=(Rcr(J-2)+Rcr(J+2))/16+(Rcr(J-1)+Rcr(J+1))/4+0.375*Rcr(J)
002690       ZCCS(J)=(Zcr(J-2)+Zcr(J+2))/16+(Zcr(J-1)+Zcr(J+1))/4+0.375*Zcr(J)
002700       PHICS(J)=(PHICR(J-2)+PHICR(J+2))/16+(PHICR(J-1)+PHICR(J+1))/4
002710    +=0.375*PHICR(J)
002720      310 CONTINUE
002730      C
002740      C
002750      C     HERE WE PRINT OUT THE HEADING FOR THE FINAL RESULTS
002760      C
002770      C
002780      C     WRITE (6,55)
002790      55 FORMAT (6X,'RADCS',4X,'ZCCS',6X,'PHICS',5X,'TWLONG',4X,'TCOLAT',
002800        4X,'DIST',5X,'CYL-COLAT',4X,'Z-DIST')
002810      C
002820      C
002830      C
002840      C     HERE THE PROGRAM TAKES THE FINISHED DATA AND DUMPS TO DISK AND
002850      C     DOES A PRINT OUT.
002860      C
002870      C
002880      C     DO 370 K=1,I
002890      C     WRITE (99) RADCS(K),ZCCS(K),PHICS(K),TWLONG(K),TCOLAT(K),DIST(K),
002900        CYL-COLAT(K),Z-DIST(K)
002910      C     WRITE (6,360) RADCS(K),ZCCS(K),PHICS(K),TWLONG(K),TCOLAT(K),
002920        CYL-COLAT(K),Z-DIST(K)
002930      360 FORMAT (7F10.4,1PE12.4)
002940      370 CONTINUE
002950      C
002960      C
002970      C     DA...DAA....DA...DAA....DA...DAT'S ALL FOLKS!!!!
002980      C
002990      C
003000      C
003010      C     STOP
003020      C
003030      C     END
003040      C
003050      C     END OF DATA
003060      C
003070      C     READY
X. REFERENCES


