Reconnection and flows in the Jovian magnetotail as inferred from magnetometer observations

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[1] In Jupiter’s magnetosphere, events such as flow bursts and changes to the magnetic field are thought to be driven predominantly by internal processes. Analysis of energetic particle data has established that flow bursts are associated with magnetic reconfiguration in the Jovian magnetotail. Here we use magnetometer data throughout the Jovian magnetotail to identify events that we relate to reconnection and flow. Using quantitative criteria, we have identified 249 reconnection events that are characterized by reversals or significant increases in $B_{y}$, the north-south component of the magnetic field, over background levels. We discuss the distribution of the events, their occurrence rate, and location inside or outside of a putative neutral line, as functions of radial distance and local time. Using the sign of $B_{y}$ as a proxy for the flow direction, we establish the location of a statistical separatrix and find that its radial distance varies with local time. Where particle signatures of events in our data set have also been analyzed, they generally show increases of anisotropy. However, we have identified scores of additional events that have not been previously identified in the particle data; many of these new events occur in the premidnight local time sector. Finally, we examine our events for the 2–3 day periodicity that has been reported for flow bursts and auroral polar dawn spots and find that this periodicity is present only intermittently and is not statistically significant.


1. Introduction

[2] Global reconfigurations of the terrestrial magnetosphere, called substorms, discharge energy and momentum introduced by magnetospheric interaction with the solar wind on time scales of hours. At Jupiter changes to the magnetic field on time scales of hours are also observed, but these dynamics tend to be more localized than the terrestrial substorms. Following a terrestrial substorm the magnetic and plasma configuration of the magnetotail changes (e.g., dipolarizes), but at Jupiter there are no evident changes in the magnetic configuration of the magnetotail subsequent to the events that we consider. The Jovian events are thought to be driven by internal processes rather than by the solar wind.

[3] Flow bursts and dynamics in the Jovian system have been studied rather extensively through analysis of energetic particle data. In situ particle and magnetic field measurements are available from the Galileo mission, which orbited Jupiter from late 1995 to 2003. Data from Galileo’s Energetic Particle Detector have established a global flow pattern, primarily in the direction of corotation [Krupp et al., 2001], and revealed intermittent particle flow bursts in the magnetotail. Studies of the flows associated with so-called “reconfiguration events,” or periods of increased particle anisotropy, have included a discussion of the magnetic field changes [Kronberg et al., 2005]. Dynamics in the magnetic field data have been studied for isolated events or orbits [Russell et al., 1998; Ge et al., 2007], but this is the first thorough survey of all available magnetotail magnetic field data.

[4] In this paper we present a survey of reconnection events identified in all of the available magnetometer data from the Jovian magnetotail. Section 2 describes the models of dynamics and plasma transport in the Jovian magnetotail, and the motivation for this work. In section 3 we introduce the data used in this study, most of which came from the Galileo spacecraft though data from Pioneer 10, Voyager 1, and Voyager 2 are also used. Because of their orbits, Pioneer 11 and Ulysses did not provide data pertinent to our examination of processes at low latitudes on the nightside. Also in section 3 we describe our quantitative selection methods and the quantities that we use to infer plasma flow from the magnetometer data. In section 4 we present the identified reconnection events, and consider their spatial and temporal distribution. Finally, we discuss...
how our work relates to previous studies, what our results imply about a near-Jupiter neutral line, and whether or not our events exhibit any characteristic periodicity.

2. Background and Motivation

[5] Dynamics in the Jovian magnetosphere are likely rotationally driven rather than solar wind-driven as at the Earth. This in part results from Jupiter’s short rotation period (~10 h) and the vast size of the Jovian magnetosphere, both of which contribute to the dynamical importance of rotational stresses.

[6] An additional factor distinguishing Jupiter’s magnetosphere is the presence of an internal plasma source from the volcanically active moon Io, which releases about one ton of plasma per second. Ultimately the plasma must be removed from the system; one likely mechanism is magnetic reconnection and subsequent plasmoid release.

[7] The principal cause of magnetic reconnection in the Jovian magnetosphere is still under discussion. In the model of rotationally driven dynamics first proposed by Vasyliunas [1983], reconnection occurs on mass-loaded flux tubes, which are stretched, pinch off, and form a plasmoid. The stretching of the flux tubes dragged from Jupiter’s dayside results from centrifugal acceleration of rotating particles. The stretched flux tubes eventually pinch off, releasing a plasmoid that can escape down the tail. In the model of Vasyliunas [1983], a magnetic x-line forms across the tail, beginning just before midnight local time and extending forward in local time and until it encounters the magnetopause. The x-line is accompanied by a magnetic o-line at larger radial distances. More recently, observations of local time asymmetries in the plasma sheet thickness have been shown to result from dynamics that are consistent with the Vasyliunas model [Kivelson and Southwood, 2005]. The plasma sheet is observed to be thinnest at dawn and to thicken as it rotates through the dusk sector, where it is thickest. On the nightside where the plasma is no longer constrained by the magnetopause and is free to flow down the tail, the plasma field configuration is unstable and plasma is centrifugally accelerated outward down the tail. As a result, the plasma sheet thins. Flux tubes break and are depleted of plasma then continue to rotate through the nightside to dawn. The empty flux tubes are carried inward via interchange motions as they rotate through the nightside, while full flux tubes are carried outward. Kivelson and Southwood [2005] suggest that the stretching and pinching-off continues for all nightside local times across the tail, and that the location for the stretching and pinching off moves radially inward as the flux tubes rotate from dusk to dawn.

[8] Other models suggest that reconnection at Jupiter is to a significant degree solar wind-driven [e.g., Cowley et al., 2003]. Solar wind-driven reconnection would occur on the dayside low-latitude magnetopause for a northward oriented interplanetary magnetic field. The opened flux would close owing to reconnection at an x-line in the tail, similar to the process in the Dungey cycle at Earth. However, the Dungey cycle x-line at Jupiter would be restricted to the dawnside because of the strong outward flows, associated with corotation and the Vasyliunas cycle, that oppose sunward flow in the dusk and midnight sectors.

[9] McComas and Bagenal [2007] suggest that at Jupiter the magnetic flux opened via dayside reconnection with the solar wind does not need close in the magnetotail as at the Earth. Instead, they propose that the flux closes on the magnetopause, near the polar cusps, rendering tail reconnection unnecessary. They also argue that at Jupiter tail reconnection is an ineffective method of returning flux to the dayside, based on calculations of length of time it would take for the return flow of plasma from a distant neutral line, ~750–1,000 h (~75–100 rotation periods). From this calculation, McComas and Bagenal [2007] conclude that there must exist another mechanism for closing and returning the flux that is opened on the dayside rather than return flow from a distant x-line. They argue that reconnection near the cusps allows for the plasma flow in the magnetotail to be primarily directed outward.

[10] Ultimately the models of Jovian magnetospheric dynamics must account for the reconnection and plasma flows that have been observed in magnetic field and particle data from the Jovian magnetotail. Much of what we currently know about dynamics on a global scale is based on analysis of data from Galileo’s energetic particle detector (EPD) instrument. The EPD data can provide particle anisotropies, which can in turn be used to infer flow. Woch et al. [2002] studied such inferred flow bursts at distances out to 150 R_J (1 R_J = 1 Jovian radius = 71,492 km) in the tail and identified a statistical separatrix separating inward and outward flow bursts. Outside of ~100 R_J in the postmidnight sector they observed primarily outward flow bursts. In the premidnight sector they drew two possible lines that could separate flow directions, recognizing that the limited data in the dusk sector did not establish its location in that region.

[11] Particle anisotropies have also been studied by Kronberg et al. [2005, 2007, 2008] with good agreement between the inferred flows and magnetic field data. The authors identify 34 reconfiguration events which include disturbed intervals that are characterized by increases in the radial and corotational anisotropies occurring at the same time as increases to the north–south component of the magnetic field. Large, positive (negative) radial anisotropies occur at the same time as large negative (positive) B_0 signatures, both of which are consistent with outward (inward) flow. The reconfiguration events can be as short as 3 h or as long as 39 h and they occur at radial distances from 63 to 142 R_J. With one exception, the reported reconfiguration events are located in the postmidnight sector. The disturbed intervals described by Kronberg et al. [2007] also display a ~2–3 day periodicity consistent with the periodic modulations in the plasma flux described by Woch et al. [1998].

[12] Whereas particle data have been used to examine magnetospheric dynamics on a global scale, studies that make primary use of the magnetometer data have thus far focused on individual events or orbits. Two of the most prominent reconnection events were reported by Russell et al. [1998]. The events occurred a few days apart in the G8 orbit, both in the postmidnight sector. These events are characterized by an increase in the magnitude of B_0, the north–south component of the magnetic field, and in the total field magnitude. In one event the spacecraft was tailward
of the x-line, and in the other the spacecraft was planetward of the x-line. In both events there were changes to the bendback angle that were large compared to the background fluctuations. The bendback angle represents how swept back (opposite the direction of planetary rotation) the field line is with respect to the radial direction. Changes to the bendback angle can be used to infer the direction of plasma flow, as will be discussed in section 3.4.

[13] Ge et al. [2007] studied the total field magnitude in the days leading up to reconnection events in orbits E6 and C10. They found that the field strength gradually increased ~3 days prior to the reconnection event. They interpreted the gradually increasing field magnitude as analogous to a substorm growth phase. Examination of Ulysses observations showed little change in the solar wind dynamic pressure during the growth phase. However, the Ulysses observations had to be shifted in time by 10 days or more because the spacecraft was located ~150° east of Jupiter in Heliographic Inertial coordinates, almost on the other side of the Sun. Nevertheless, because the solar wind dynamic pressure did not increase during the period of increasing field magnitude, Ge et al. [2007] concluded that the growth phase is likely driven by an internal dynamic process rather than by the solar wind.

[14] Since previous studies of the magnetometer data have been restricted to individual orbits or events, this work provides the first complete survey of reconnection events in the Jovian magnetotail from the magnetometer data. We present a statistical analysis of the reconnection event distribution that can be compared with the results of previous analyses of energetic particle distributions (such as the separatrix in the work of Woch et al. [2002] and the distribution in the work of events in Kronberg et al. [2005, 2007]). The results will help establish where and how often reconnection occurs in the Jovian magnetotail and obtain a better understanding of what drives dynamics there.

3. Methods

[15] In this section we describe our quantitative methods for identifying reconnection events and the ways we have used the magnetometer data to infer flow. First we describe the data we used in our analysis. Next we outline our event identification criteria, which include an increase in the magnitude of $B_\theta$, the north–south component of the magnetic field. Changes of $\Delta B_\theta$ may be consistent with reconnection if they result in reconfiguration to a more dipolar field or a field reversal. Therefore we examine the elevation angle, or the angle that the field makes with respect to the equatorial plane, to confirm that the $\Delta B_\theta$ increase in our events corresponds to a field reversal or a more dipolar field configuration. We then discuss how the bendback angle can serve as a proxy for flow and a useful tool in interpreting our events. Finally, we describe how the sign of $B_\theta$ can be used to infer the spacecraft’s probable location with respect to an x-line and a statistical separatrix.

3.1. Data Sources

[16] For this analysis we include magnetometer data from Galileo orbits G1 (June 1996) through A34 (Jan. 2003), as well as magnetometer data from Pioneer 10, Voyager 1 and Voyager 2. We restrict ourselves to data with time resolution 60 s per vector or better, radial distances 30 RJ or greater, and nightside local times (from 1800 to 0600 h). We also restrict ourselves to intervals when the spacecraft was within 15 degrees of the equatorial plane. As most of the data from the Galileo spacecraft were taken near the equator, this latter restriction is mostly relevant to data from the other spacecraft.

[17] We have excluded magnetosheath, bow shock, and solar wind data, as well as intervals 5 h before or after a boundary crossing (Pioneer 10, Intriligator and Wolfe [1976]; Voyager 1 and Voyager 2, Lepping et al. [1981]; Ulysses, Bame et al. [1992]; Galileo, S. Joy (personal communication, 2009)). Periods when the spacecraft only briefly (fewer than 10 h) crossed back into the magnetosphere from the magnetosheath have also been excised. The boundary crossing restrictions ensure that we select only magnetospheric events and not processes occurring because of interaction with the magnetosheath or solar wind.

[18] After selecting for high time resolution data at the appropriate radial distances, local times, and latitudes, we were left with fewer than 200 h of data from Voyager 1 and Pioneer 10.

[19] Figure 1 shows the number of hours of data used in this study, divided into bins of 15 RJ in radial distance by

![Figure 1](image.png)

Figure 1. The number of hours of available data plotted in bins of 15 RJ in radial distance by 1 h in local time. This is an equatorial plane view, and the Sun is to the left. At small radial distances (~75 RJ) the data are relatively evenly distributed in local time, but beyond ~75 RJ more data are available in the dawn sector than in the dusk sector. Beyond ~105 RJ the dusk sector coverage decreases, and several bins lack data entirely. White represents bins with no available data.
Reconnection in the Jovian magnetotail, illustrated here in a meridional view. (a) The initial field configuration, which is primarily in the radial direction except near the current sheet. (b) The reconfiguration to reconnected field lines, noting the expected field orientation and flow directions. On either side of the x-line the field is more dipolar than prior to reconnection. The effect corresponds to an increase of $|B_0|$. A positive $B_0$ is found when the spacecraft is either located planetward of the x-line (position 1) or far down the tail, while a negative $B_0$ is observed if the spacecraft is located tailward of the x-line (position 2).

1 h in local time and plotted in the equatorial plane. Figure 1 shows that the data are well distributed over all local times for radial distances inside of $\sim 75$ R$_J$. From $\sim 75$ R$_J$ to $\sim 120$ R$_J$ more data are available postmidnight than premidnight, and at the largest distances ($R > 120$ R$_J$) most of the data are within 1 h of midnight. Beyond $\sim 105$ R$_J$ the dusk sector coverage decreases, and several bins lack data entirely. In section 4 we normalize the duration of events in each sector by the duration of available data, thereby obtaining an estimate of the event frequency in different regions of the magnetotail.

3.2. Event Identification Methods

[20] We have identified reconnection events in the Galileo magnetometer data by requiring that the magnitude of $B_0$, the north–south component of the magnetic field, increase over background levels. A positive increase in $B_0$ without corresponding changes to the magnitude of the other field components implies reconfiguration to a more dipolar field. Such a reconfiguration is shown in Figure 2. In Figure 2a we have drawn the initial field configuration, which is primarily radial except near the current sheet. In Figure 2b we have drawn reconnected field lines, noting the expected field orientation and flow directions. On either side of the reconnection point the field becomes more dipolar than prior to reconnection, and $|B_0|$ increases. A large, positive $B_0$ indicates that the spacecraft is located on the planetward side of the x-line (position 1 in Figure 2b). A reversal in $B_0$ indicates that the spacecraft is located on the tailward side of a reconnection x-line (position 2 in Figure 2b). On short time scales, such reconfigurations are consistent with reconnection.

[21] We defined the reference background field by taking a 1 day running average of $|B_0|$. This provides a relatively smooth background that varies slowly in time but allows for large-scale radial and local time variations. As such, the background $|B_0|$ decreases with radial distance, is largest in the premidnight sector, and decreases with local time toward dawn.

[22] With a working definition for the background $|B_0|$ established, the next step was to select a quantitative criterion for the $B_0$ increase over background levels. This proved to be a delicate task because there are many ways to define an increase over background levels. In the course of this study we tested a variety of criteria for identifying the signature of an increase over background levels, such as requiring: an absolute increase of a few nanotesla, an increase proportional to the background level, or an increase with a specified dependence on the radial distance. Each method selected several hundred events in the data. Although the number and duration of the events varied with the identification criteria, the strongest events were selected by all methods applied.

[23] In this paper we will describe the characteristics of events in which $|B_0|$ increases over background levels by at least a factor of 2, and typically by a factor of 3. The events selected by this method include the largest and most convincing events and exclude some of the possibly spurious events that were identified by other the selection methods we tested.

[24] We began our event identification by searching for intervals in which $|B_0|$ was enhanced above the background level. Each event satisfied the following relation shown in equation (1):

$$\frac{|B_0|}{\langle |B_0| \rangle} \geq 2,$$

where $\langle |B_0| \rangle$ is the reference background field (a 1 day running average of $|B_0|$). If the background $|B_0|$ was small ($< 5$ nT) we required a threefold increase over background levels. If the background $B_0$ was larger than 5 nT we required only a factor of 2 increase over the background. Furthermore, we required $B_0 > 3$ nT or $B_0 < -2$ nT in order to ensure a robust event selection even when the background was small. (The background magnitude was frequently less than 1 nT at large radial distances in the postmidnight sector.) Although the selection criteria may have excluded some cases of magnetic activity, we believe that they are sufficiently rigorous that the events selected would be hard to account for other than as signatures of tail reconnection.

[25] After identifying an initial $|B_0|$ enhancement, we required that $|B_0|$ remain enhanced for at least 60 s. We defined the event duration as the time before and after the initial enhancement where the field remained disturbed. For events in which the initial $|B_0|$ enhancement was during a period of positive $B_0$, we defined the event as the time when $|B_0|$ remained larger than 1 nT or 1.25 times the background, whichever was larger (again, allowing for brief excursions below the threshold value). For events in which the initial $|B_0|$ enhancement was during a period of negative $B_0$, we defined the event duration as the time when $B_0$ remained negative (allowing for brief - less than 2 min - positive $B_0$ excursions). These criteria provided a preliminary list of events and specified their duration. To obtain our final event list, we considered two events that occurred within 30 min of each other to be part of the same new event. We then removed 47 events that lasted fewer than 10 min.
These quantitative identification conditions yielded 249 events, all characterized by an increase of $|B_{/C18}|$ over background levels. The events have an average duration of 59 min, with durations ranging from our lower cutoff of 10 min to just over 5 h. Events occur at nearly all nightside local times (∼1900 to ∼0600 h) and at radial distances between 33 to 155 RJ, the latter merely a reflection of the range of radial distances with good data coverage (as seen in Figure 1 there is little data beyond 150 RJ).

Examples of the identified events are given in Figures 3–5. For Figures 3–5, the first panel shows the radial ($B_R$, in black) and azimuthal ($B_{/C30}$, in blue) components of the magnetic field, in nT. The second panel shows $B_{/C18}$, the north–south component of the magnetic field, plotted in black with the event interval overplotted in red. The background $|B_{/C18}|$, which was used in the event identification procedure, is plotted in blue and is ∼1 nT. The bendback angle is shown in the third panel, and the elevation angle is shown in the fourth panel. We do not plot either angle when $|B_R| < 3$ nT. The elevation angle and bendback angle are defined in sections 3.3 and 3.4, respectively. The spacecraft was at ∼0200 LT and ∼87 RJ when it observed this event. $B_{/C18}$ changes sign during this event, which we interpret to be the signature of an x-line moving in over the spacecraft. The bendback changes in the third panel appear to be consistent with our interpretation (see section 3.4 for discussion). The fifth panel shows the field magnitude.

In the event of Figure 3, the spacecraft was located at a radial distance of ∼87 RJ and at nearly 0200 local time. This event, on Galileo’s G2 orbit, occurred on 20 September 1996, starting at approximately 1300 UT and lasting for 3 h. The background $|B_{/C18}|$ was ∼1 nT as shown by the blue trace in the second panel. During this event $B_{/C18}$ reached −11.6 nT, more than 10 times the background level. This event is interesting because we observe both positive and negative $B_{/C18}$ during the period of enhanced $|B_{/C18}|$. The event occurs during the 20 September 1996 1230–2230 UT reconfiguration event from Kronberg et al. [2005].

The second example, shown in Figure 4, comes from Galileo orbit C23, when the spacecraft was located at ∼42 RJ in radial distance and just past 1900 local time. This event occurred on 18 September 1999 at approximately 2000 UT and lasted for 20 min. The background $|B_{/C18}|$ was ∼5 nT, much larger than the background value from the 20 September 1996 event, when the spacecraft was in the post-midnight sector.

A third example is given in Figure 5. This event occurred on 21 September 1996 at approximately 0800 UT, under circumstances similar to those of the 20 September 1996 event: both occurred during orbit G2, near 0200 local time, and just before 90 RJ. In both events $B_{/C18}$ changes sign, but the reversal occurs in opposite directions. In the 20 September 1996 event, $B_{/C18}$ changes sign from positive to negative, and in this event $B_{/C18}$ changes sign from negative to positive. Therefore we interpret the reversal as the sig-
nature of an x-line associated with a plasmoid moving out over the spacecraft and down the tail.

[31] The two events from the G2 orbit occurred during an interval of disturbed magnetic field with corresponding auroral observations studied by Prangé et al. [2001]. The 20 September 1996 event was also included in the list of reconfiguration events published by Kronberg et al. [2005]. Though these events have been previously mentioned in the literature, we present them here in further detail because they are among the largest of our events, which facilitates illustrating both the $|B/|C_18|$ increase that we require in selecting our events and the associated bendback and elevation angle changes.

### 3.3. Elevation Angle Changes in Our Events

[32] An increase of $|B/|C_18|$ is insufficient by itself to demonstrate that the field reconfiguration is consistent with nearby reconnection; we must also consider how the other field components change to ensure that the field has become more dipolar. A good quantity to consider is the elevation angle, which is the angle that the field makes with respect to the radial in the $R-\theta$ plane. At the equator the elevation angle is the angle that the field makes with respect to the horizontal. In this discussion we will define the elevation angle as

$$\theta_{\text{elevation}} = \tan^{-1} \left( \frac{-B_\theta}{|B_R|} \right).$$

[33] We use $-B_\theta$ in the numerator so that a northward field has a positive elevation angle, and $|B/|C_18|$ rather than $B_R$ in the denominator so that the angle changes smoothly as the spacecraft goes through the current sheet. When $B_R$ is small the elevation angle changes rapidly with small fluctuations in $B_R$ and such changes may not be meaningful. This is clear from our definition of $\theta_{\text{elevation}}$. We therefore evaluate $\theta_{\text{elevation}}$ only for $|B/|C_18| > 3$ nT.

[34] Using this definition of $\theta_{\text{elevation}}$, a field line with an elevation angle of $-90^\circ$ is purely southward, $0^\circ$ is radial, and $90^\circ$ is northward. At the equator, a large, negative elevation angle indicates a dipolar field configuration; a large, positive elevation angle indicates a nearly northward field on the tailward side of an x-line. Both signatures are consistent with reconnection. The equatorial $B_{/}\mid C_18|$ is typically southward ($B_\theta > 0$) and in the postmidnight sector $B_{/}\mid C_18|$ is small compared to $B_R$, so the quiet time, lobe field elevation angle in this region is approximately $-10^\circ$.

[35] In Figures 3, 4, and 5, $|\theta_{\text{elevation}}|$ increases during the event, indicating that the field has become more dipolar compared to the background, or, if $B_\theta$ is negative, that the field has reversed and is strongly northward. For the G2 (dawn sector) events of Figures 3 and 5, the background elevation angle is roughly $+/-10^\circ$. The median $|\theta_{\text{elevation}}|$ during these events is $\sim 20^\circ$, roughly twice the magnitude of the background, and for both events $|\theta_{\text{elevation}}|$ gets as large as $\sim 55^\circ$. For the C23 (dusk sector) event of Figure 4, the
background elevation angle is roughly $-30^\circ$, and is larger than the background in the other two events because the background $B_B$ is larger. The median $|\theta_{\text{elevation}}|$ during the 18 September, 1999 event is $\sim 54^\circ$, and $|\theta_{\text{elevation}}|$ gets as large as $66^\circ$.

Similar increases of the elevation angle are characteristic of most of our events. Figure 6 shows the median $|\theta_{\text{elevation}}|$ in each event (black trace) and the background $|\theta_{\text{elevation}}|$ (red trace). Here we define the background as the median of $|\theta_{\text{elevation}}|$ over the previous 10 h, excluding intervals with other events. For Figure 6 we have excluded events where we were unable to calculate the elevation angle (because $|B_B| < 3$ nT) for at least half the event duration. The median $|\theta_{\text{elevation}}|$ in the events is typically at least twice the background $|\theta_{\text{elevation}}|$. The elevation angles in Figure 6 are plotted versus event number, which increases with time, from March 1979 to December 2004. Later events (large event numbers) have larger background elevation and event elevation angles; these events generally come from premidnight local times, where $B_B$ is larger than in the postmidnight sector. That we observe increases to the elevation angle along with the $|B_B|$ increase in our events indicates that the field reconfiguration is consistent with our interpretation.

### 3.4. Bendback Angle and Sign of $B_B$ as Proxies to Flow

It is of interest to compare our events and their properties and distribution to those of intermittent flow bursts inferred from particle anisotropies in previous studies [Kronberg et al., 2005, 2007]. Though the magnetometer does not directly measure flow, we expect there to be a high correlation between inward and outward radial flows and properties of the bendback angle and the sign of $B_B$. In this section we will outline how we interpret these quantities as evidence for flow, allowing us to compare our results with Kronberg et al. [2005, 2007] and others.

Measured changes of the bendback angle of the magnetic field provide a good proxy to measurements of flow bursts. The bendback angle, $\alpha$, is defined by

$$\alpha = \tan^{-1}\left( \frac{B_\phi}{B_R} \right).$$

(3)

Its value indicates the azimuthal sweep back of the field lines with respect to the radial direction. By this definition, because the field is typically swept back and $B_\phi$ and $B_R$ are of opposite sign, the bendback angle is usually negative. A positive bendback angle would indicate that the field is swept forward.

Angular momentum conservation arguments link changes of the bendback angle to changes of radial flow. In the middle and outer Jovian magnetosphere (beyond 20 R$_J$) the field lines typically lag corotation at the equator because, in a steady state, plasma is slowly but continuously being transported radially outward; current systems linking the equator with the ionosphere act to maintain isorotation [Hill, 1979]. On time scales short compared with the communication time with the ionosphere the coupling
with the ionosphere is ineffective [Vasyliunas, 1994]. The outflowing plasma decreases its angular velocity in order to conserve angular momentum. The long time scale for communication with the ionosphere implies that it requires at least of order several hours for currents linking equatorial regions to the ionosphere to reaccelerate the outflowing plasma to the local rotation speed. As a result, the field lines, which are frozen into the flow, increase the angle at which they drape back. Evidently, inward flowing bursts will experience acceleration of the angular velocity and the bendback angle will decrease.

[40] On the basis of the above argument, we use changes of the bendback angle to infer changes of the radial plasma flow by assuming that in events lasting less than 5 h the flow will conserve angular momentum and that the field is frozen into the flow. We then expect that \(|B_{\phi}|\) will increase and \(\alpha\) will decrease (become more negative) in association with bursts of radial outflow and that \(|B_{\phi}|\) will decrease, and \(\alpha\) will increase (become less negative) in association with bursts of radial inflow.

[41] There are some challenges to quantitatively assessing changes to the bendback angle so that we can infer flow. As with the elevation angle, we can confidently calculate \(\alpha\) only for \(|B_{\phi}| > 3\) nT. However, this poses difficulties in determining the bendback angle during the identified events because many of them are observed when the spacecraft is in or near the center of the current sheet and \(|B_{\phi}|\) is small. Second, though we would like to compare the change in bendback to the sign of \(B_{\phi}\), we cannot reasonably expect complete, instantaneous agreement between the inferred flow and the magnetic signature. For example, in studies of bursty bulk flow events at Earth, the flow direction and the north-south direction of the magnetic field agree frequently but not invariably [Angelopoulos et al., 1994].

[42] The second way in which we can infer probable flow from the magnetometer data is to use the sign of \(B_{\phi}\) to identify the spacecraft’s location with respect to the magnetic x-line. Although the correspondence between flow direction and the sign of \(B_{\phi}\) is not invariable, it is most likely that inward of an x-line, flow is planetward and the associated perturbation in \(B_{\phi}\) is positive and that outward of an x-line, flow is antiplanetward and the associated perturbation of \(B_{\phi}\) is negative. This association is illustrated in Figure 2, which shows the configuration of reconnected field lines in the tail. A positive increase over background levels in \(B_{\phi}\) suggests that the spacecraft is planetward of the x-line (position A), where we expect inward flow. The event shown from orbit C23 in Figure 4 is an example of this type of event, where the enhanced \(B_{\phi}\) is positive and we expect inward flow. Similarly, we interpret a negative \(B_{\phi}\) signature to mean that the spacecraft is tailward of the x-line (position B), and therefore expect outward flow. When \(B_{\phi}\) changes sign during an event, as occurred in the events of Figures 3 and 5, we interpret that change to be the x-line and/or plasmoid crossing over the spacecraft.

[43] We use primarily the sign of \(B_{\phi}\) to infer the direction of flow in this study because our estimates of the bendback angle are not continuous and are very sensitive to small fluctuations. This approach is not without ambiguity. For example, although we expect to see a positive \(B_{\phi}\) associated with a dipolar field planetward of the x-line, the tailward edge of a plasmoid could also produce a positive \(B_{\phi}\) signature. However, the reversed signature of a Jovian plasmoid is likely to be found far antisunward of the most distant Galileo orbits, so we believe that few such events are likely. Furthermore, x-lines need not remain stationary, and x-line motion could invalidate the relationship between the sign of \(B_{\phi}\) and the flow direction that we have assumed.

Figure 6. Median \(|\theta_{elevation}|\) for events (black) and the background (red), plotted versus the event number, which increases with time. The median event \(|\theta_{elevation}|\) is typically larger than the background \(|\theta_{elevation}|\) by a factor of 2 or more. The event and background \(|\theta_{elevation}|\) are largest for the later events because they occurred in the premidnight local time sector. We only include events in which we calculate the elevation angle (\(|B_{\phi}| \geq 3\) nT) for at least half the event duration.
However, analysis of the reconfiguration events from Kronberg et al. [2005] has confirmed that the sign of $B_{C18}$ is a good indicator of the flow direction [Kronberg et al., 2008]. In all of their events that do not exhibit a bipolar $B_{C18}$, the flow direction obtained from the ion bursts matched the flow direction inferred from the sign of $B_{C18}$ (i.e., tailward flow was accompanied by a negative $B_{C18}$ magnetic signature, and planetward flow was accompanied by positive $B_{C18}$).

To further validate this assumption, we have analyzed the relation between the $B_{C18}$ signature in our own events and radial anisotropies from the same periods. These radial anisotropies were measured by the Galileo EPD and can be used to estimate flow velocities [Krupp et al., 2001]. In Figure 7 we have plotted $B_{C18}$ versus radial anisotropy during our events, excluding years 1997 and 1998 (156 of 249 events) because high-resolution anisotropy data were unavailable. $B_{C18}$ is the median value from the interval within 5 min of each anisotropy data point, because the time resolution of the magnetic field data (up to 24 s) is higher than that of flow anisotropy (12 min). Anisotropies between $-0.3$ and $0.5$ do not represent a significant departure from corotation (E. Kronberg, personal communication, 2010), and these are drawn in gray. There is a clear trend between the median $B_{C18}$ and the radial anisotropy, such that large positive (negative) radial anisotropy is typically accompanied by negative (positive) median $B_{C18}$. Radial anisotropies were kindly provided by N. Krupp.

4. Results

Using the identification criteria described in section 3.2, we have obtained an initial list of 249 events. These events are characterized by an increase in $|B_{C18}|$ over background levels and an accompanying increase in the elevation angle, indicating a field reconfiguration that is consistent with magnetic reconnection. The events are distributed over nearly all radial distances and local times that we surveyed (outward 30 RJ, and from 1800–0600 LT). Events were observed in radial distance from 33 to 155 RJ, and in local time from $\sim$1900 to $\sim$0600 h. We did not identify any events from 1800 to 1900 LT but data coverage in this region

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Figure 7. Scatterplot of median $B_{C18}$ (nT) versus radial anisotropy from 93 of our events. We have excluded events from years 1997 and 1998 (156 of 249 events) because high-resolution anisotropy data were unavailable. $B_{C18}$ is the median value from the interval within 5 min of each anisotropy data point, because the time resolution of the magnetic field data (up to 24 s) is higher than that of flow anisotropy (12 min). Anisotropies between $-0.3$ and $0.5$ do not represent a significant departure from corotation (E. Kronberg, personal communication, 2010), and these are drawn in gray. There is a clear trend between the median $B_{C18}$ and the radial anisotropy, such that large positive (negative) radial anisotropy is typically accompanied by negative (positive) median $B_{C18}$. Radial anisotropies were kindly provided by N. Krupp.

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1Auxiliary material is available in the HTML. doi:10.1029/2009JA015098.
Event Duration and Spatial Distribution

Events in the Pioneer 10 data, but this is not significant because only 150 h of data remained after selecting for the appropriate location (radial distance, local time, latitude) and high time resolution, as outlined in section 3.1. A complete list of the event start and end times, locations (radial distance and local time), and Bθ signatures are provided as auxiliary material (Table S1).1

This section begins by describing the event spatial distribution, frequency, and occurrence rate, and how these properties change with radial distance and local time. We then discuss the distribution of inward and outward flow events, as inferred from the sign of Bθ. Finally, we examine changes to the bendback angle in our events.

4.1. Event Distribution and Frequency

The 249 reconnection events we have identified are well distributed in radial distance and occurred at nearly all nightside local times. An equatorial plane view of the event locations is given in Figure 8. The spatial distribution of events is also summarized in Table 1. Events that were also identified by Kronberg et al. [2005] are represented by empty triangles while new events from this study are represented with solid circles. The color coding indicates the inferred position planetward or tailward of an x-line as determined by the sign of Bθ; events in which Bθ is negative (positive) for more than 85 percent of the event duration are considered to be tailward (planetward) of an x-line. A blue symbol in Figure 8 indicates a tailward event; a red symbol indicates a planetward event. Events that exhibit a bipolar Bθ signature (Bθ is neither positive nor negative for more than 85 percent of the total event duration) are shown in green. Event locations have been shifted radially by −2 R J for Bθ positive events (red) and by +2 R J for Bθ negative events (blue) for visibility; bipolar Bθ events (green) remain at their original distances.

It is clear from inspection of Figure 8 that more events are observed in the postmidnight local time sector than in the premidnight sector. From a total of 249 events, only 57 events occurred premidnight. However, we must also consider the distribution of available data and the duration and frequency of the events in order to fully understand the distribution of these dynamic processes. The amount of available data varies with R and LT, so it is useful to consider the event occurrence rate rather than just the number and duration of events. For example, though fewer events were observed premidnight than postmidnight, more data are available in the postmidnight region at large radial distances (see Figure 1) so one might naturally expect to find more events in this region. We therefore examine the event occurrence rate, or the sum of the event durations for all events within a bin divided by the duration of data within a bin, throughout different regions of the magnetotail.

TABLE 1. Event Duration and Spatial Distribution

<table>
<thead>
<tr>
<th></th>
<th>All Events</th>
<th>Bθ Positive Events</th>
<th>Bθ Negative Events</th>
<th>Bθ Bipolar Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events (percent of all events)</td>
<td>249</td>
<td>130 (52.2)</td>
<td>74 (29.7)</td>
<td>45 (18.1)</td>
</tr>
<tr>
<td>Average duration (min)</td>
<td>59</td>
<td>47</td>
<td>75</td>
<td>66</td>
</tr>
<tr>
<td>Median LT (h)</td>
<td>0152</td>
<td>0050</td>
<td>0218</td>
<td>0221</td>
</tr>
<tr>
<td>Number of events postmidnight (percent of total)</td>
<td>192 (77.1)</td>
<td>81 (62.3)</td>
<td>69 (93.2)</td>
<td>42 (93.3)</td>
</tr>
<tr>
<td>R range (R_J)</td>
<td>33.25–145.6</td>
<td>33.25–145.6</td>
<td>47.03–142.86</td>
<td>44.09–124.2</td>
</tr>
<tr>
<td>Median R (R_J)</td>
<td>84</td>
<td>61.6</td>
<td>100.22</td>
<td>89.26</td>
</tr>
</tbody>
</table>
Figure 9. Event occurrence rate for bins of 15 R_J in radial distance by 1 h in local time. The occurrence rate, or frequency, is the duration of all events in each bin divided by the duration of all data in each bin. Gray is used for bins in which we have not identified events but there are available data. White is used for bins with no available data. Black is used for bins with 1–2 events or with fewer than 10 h of data. This is an equatorial plane view, and the Sun is to the left.

Figure 10. Event frequency as a function of local time. The colors represent the relative amount of time for tailward (blue), planetward (red), and bipolar B_θ (green) events in each bin. There is no significant asymmetry in event frequency about midnight, though the decrease at midnight is puzzling. Negative B_θ events are more prevalent on the dawnside, though this may be due to the fact that there are more data available at large radial distances postmidnight than premidnight.

4.2. Evidence of Inward and Outward Flow

Thus far in our analysis we have noted whether events are dominated by a positive, negative, or bipolar B_θ without remarking on the inferred flow pattern. As introduced in section 3.3, a positive (negative) B_θ is likely to correspond to inward (outward) flow as anticipated when the spacecraft is planetward (tailward) of a neutral line. There are events in which B_θ changes sign (the bipolar B_θ signature events) and the reversal can be interpreted as...
arising from the movement of a plasmoid or the x-line over the spacecraft. We return to the event distribution illustrated in Figure 8 to examine the relative spatial distribution of $B_\theta$ positive (red), $B_\theta$ negative (blue), and bipolar $B_\theta$ (green) events and discuss possible locations of an x-line. Again, the spatial distribution of events is summarized in Table 1, which is also organized according to the $B_\theta$ signature in each event.

All but a handful of the events that exhibit a negative $B_\theta$ signature (shown in blue) are observed in the postmidnight sector and beyond 60 $R_J$. $B_\theta$ positive events are generally observed inside of ~100 $R_J$ and are more evenly distributed in local time. The median radial distance is 61.6 $R_J$ for $B_\theta$ positive events, 100.22 $R_J$ for $B_\theta$ negative events, and 89.26 $R_J$ for bipolar $B_\theta$ events.

For the premidnight local time sector, events that exhibit a positive $B_\theta$ signature (shown in red) dominate inside of ~60 $R_J$, and events that exhibit a negative $B_\theta$ signature dominate outside of ~90 $R_J$. Between ~60 and ~90 $R_J$ the observed $B_\theta$ signature is both positive and negative, with many bipolar $B_\theta$ events. This is a likely region for the location of an x-line in the postmidnight sector. From the sign of $B_\theta$ we infer planetward flow inside of ~60 $R_J$, tailward flow outside of ~90 $R_J$, and a neutral line between ~60 and ~90 $R_J$. Figures 3 and 5 present cases that are representative of the events in this region. In those events, which were observed just inside of 90 $R_J$, the $B_\theta$ signature suggests that the x-line passed over the spacecraft.

It is difficult to describe the distribution of inferred inward and outward flow events in the premidnight sector because the data there are limited in radial distance. In general, the positive $B_\theta$ events dominate out to at least ~90 $R_J$ (compared to ~60 $R_J$ postmidnight). Positive, negative, and bipolar $B_\theta$ events (corresponding to the 60–90 $R_J$ region in the postmidnight sector) are seen beyond ~90 $R_J$ and inside of 120 $R_J$ (the outward radial limit of data premidnight). The data do not extend sufficiently far in $\theta$ to determine the location of an x-line beyond which negative $B_\theta$ dominate. We can, however, conclude that an x-line would have to be beyond ~90 $R_J$ and would likely be outside of ~120 $R_J$.

Figure 11 shows the spatial distribution of the dominant $B_\theta$ signature in each event and the location of an inferred x-line separating inward and outward flow. Bins of 1 h (azimuthally) in local time by 15 $R_J$ (radially) are colored according to the dominant direction of flow among the events in each bin. At all local times and inside of 75 $R_J$ the bins are red, meaning positive $B_\theta$ events, or inferred inward flows, dominate. In the postmidnight sector one finds red, green (bipolar $B_\theta$), and blue (negative $B_\theta$, inferred outward flow) bins between 75 and 105 $R_J$, and exclusively blue bins outside of 105 $R_J$. We interpret this to mean that the most likely location of an x-line is close to 90 $R_J$ in this local time sector. Within 1 h of midnight the transition between red/ green and blue bins (and likely location of an x-line) moves radially outward, starting at 90 $R_J$ and ending near 105 $R_J$. At earlier local times we do not observe the transition to exclusively negative $B_\theta$ events (blue bins), suggesting that the location of the x-line continues to move radially outward, beyond the range of available data in this sector. This is also supported by the observation that the red bins, indicating positive $B_\theta$ events, are also located farther out (up to 105 $R_J$) premidnight than postmidnight.

The other quantity we use to infer flow direction is the change to the bendback angle, also described in section 3.4. We interpret a significant positive change of the bendback angle as an indication of inward flow, and we interpret a significant negative change of the bendback angle as an indication of outward flow. Data from the 20 September 1996 event shown in Figure 3 provides a good illustration of the bendback changes we observe in many events, and their qualitative agreement with the flows inferred from the sign of $B_\theta$. During the quiet time before
and immediately after the event, the field is swept back at a steady angle of approximately \(-40^\circ\) with respect to corotation. However, during the event the bendback angle experiences large, fast changes, and even changes sign (the field becomes swept forward). The flow directions inferred from these changes agree with the flow directions as inferred from the sign of \(B_{\parallel,0}\), initially, when \(B_{\parallel,0}\) is positive, the field is swept forward, a positive increase over the background. Then, the bendback angle becomes more negative, indicating outward flow, and \(B_{\parallel,0}\) changes sign, suggesting that the x-line has moved out over the spacecraft. Similarly, during the 18 September 1999 event illustrated in Figure 4, the bendback angle becomes more positive, even changing sign so that the field is swept forward. The bendback angle change coincides with the large, positive \(B_{\parallel,0}\), and both signatures can be interpreted as evidence of inward flow.

As previously noted, we do not calculate the bendback angle when \(|B_{\parallel,0}| < 3\) because in that situation small changes in \(B_{\parallel,0}\) produce large changes in the bendback angle. This means that bendback information is wholly or partially unavailable for many events, as the events tend to be observed when the spacecraft is in or near the current sheet and \(B_{\parallel,0}\) is small. In roughly 30 percent (70 out of 249) of events the bendback angle information is insufficient to determine whether any inferred flow matches our expectations.

Despite the challenges to using the bendback angle as a proxy to flow, we do find qualitatively that large, fast changes of the bendback angle occur in most of the events for which we can measure the bendback. In just over 60 percent (106 of 179) of events with nearly full bendback information we see large bendback changes that qualitatively suggest inward or outward flow consistent with the \(B_{\parallel,0}\) signature.

5. Analysis

In this section we will discuss how our results compare to previous studies of particle anisotropies and flow bursts. Of particular interest is how the local time distribution of our events differs from that of the Kronberg et al. [2005] reconfiguration events and the comparison of our separatrix, inferred by the \(B_{\parallel,0}\) signature in our events, with one defined by the direction of particle bursts [Woch et al., 2002]. Next we use the velocity and event duration to calculate for each event the width of the flow channel (in the azimuthal direction). Finally, we will examine our events for evidence of a 2–3 day periodicity.

5.1. Comparison With Particle Data

Many of our reconnection events occur during the disturbed intervals identified by analysis of particle anisotropies in the work of Kronberg et al. [2005]. That work identifies 34 periods with reconfiguration events, having an average duration of 14 h. In comparing our events to the specific cases illustrated there and following studies [Kronberg et al., 2007, 2008] we find that our events occur in conjunction with increases in the particle anisotropies, though our strict selection criteria miss some intervals of increased anisotropy. In only four of the 34 reconfiguration event intervals from Kronberg et al. [2005] do our selection criteria fail to identify any reconnection events. The remaining 30 reconfiguration event intervals encompass 61 of our 249 events.

A direct comparison between our events and the specific cases studied in Kronberg et al. [2005, 2007, 2008] ensures that our events coincide in time with theirs and show good agreement between the increases of \(\mid B_{\parallel,0}\) and the particle anisotropies. In Figure 12 we have plotted the magnetic field data and first-order radial and azimuthal ion anisotropies from 1200 UT on 21 September through 5 October 1996. The anisotropies were kindly provided by E. Kronberg and were measured by the Galileo EPD. This 15 day period is described by Kronberg et al. [2007] and includes both disturbed and quiet times. Times where we have identified events are highlighted in red in the third panel, which shows \(B_{\parallel,0}\). Most of our events in this interval occur at the same time as large radial anisotropies and large flows; these are the same intervals identified as “disturbed,” or the reconfiguration events, in the work of Kronberg et al. [2007]. In similar comparisons with other cases we find that most of our events occur in conjunction with increases in the particle anisotropies, though our strict selection criteria miss some intervals of increased anisotropy.

Our results not only show good agreement with the Kronberg reconfiguration events but also expand on that work with the identification of additional events, particularly in the premidnight sector. We identified 57 reconnection events at premidnight local times. Only one of the Kronberg et al. [2005] reconfiguration events occurred premidnight, and that event was at a local time of 2300, on day 237 of 1998. Interestingly, this premidnight reconfiguration event is one of the four Kronberg et al. events that does not match the reconnection events that we have identified in this study. The event did not meet our selection criteria because \(B_{\parallel,0}\) was never less than \(-2\text{ nT}\) or greater than 3 nT.

One possible explanation of why more events were found in the magnetometer data than in the particle anisotropy data is that the magnetic field is measured at much higher time resolution than is particle anisotropy. In this study we have restricted ourselves to magnetometer data at a time resolution of 60 s per vector or better; the time resolution in the particle data is 3 to 11 min. This can also explain why our identification methods sometimes select more than one event in each reconfiguration event interval of Kronberg et al. [2005]. Most of the magnetometer data we have used in this study have a time resolution of 24 s per vector, and this allows us to resolve finer features and find more individual events than were found in the particle anisotropy study.

Woch et al. [2002] studied flow bursts observed with the EPD instrument and determined the location of a statistical separatrix separating inward and outward flow bursts (see their Figure 3a). This separatrix is located at \(\sim 80–120\ R_J\) in the postmidnight sector, and moves radially out as with local time from dawn to midnight. Outside of this line the flow bursts were primarily outward. Our results qualitatively agree with their findings postmidnight. As discussed in section 4.2, the distribution of our reconnection events with positive and negative \(B_{\parallel,0}\) signatures suggests a possible x-line location near 90 \(R_J\) on the dawnside (see Figure 10). The radial distance of our separatrix also appears to change...
with local time, and it is closer to the planet at dawn than at midnight.

[66] In the premidnight region Woch et al. [2002] draw two possible separatrices, starting from \( \sim 125 \) RJ at midnight. One line continues to move radially outward, beyond \( 150 \) RJ, as it moves in local time from midnight to dusk. The other potential separatrix moves radially inward with local time for local times earlier than \( \sim 2300 \), returning to \( \sim 100 \) RJ at \( \sim 2000 \) LT. Like the magnetic field data, the EPD data cover a limited range of radial distances in the dusk sector, making it impossible to firmly establish the location of a separatrix in this region. Our results would favor the separatrix that continues to move outward in the dusk sector, since in this sector inside of \( 105 \) RJ almost all bins correspond to positive \( B/\|C_18 \) signatures and the negative and bipolar \( B/\|C_18 \) signatures extend from that distance to beyond \( 120 \) RJ.

5.2. Flow Channel Width

[67] The flow channel width of bursty bulk flows at the Earth is known to be \( \sim 1–2 \) \( R_E \), Angelopoulos et al. [1996] or less than 10 percent of the width of the Earth’s magnetotail (\( \sim 25–30 \) \( R_E \)). In this section we calculate the flow channel widths for our reconnection events at Jupiter and draw comparisons to BBFs at the Earth.

[68] The flow channel width is taken as the event duration (in seconds) multiplied by the average of the azimuthal velocity magnitude, \( V_{\phi} \), during the event (in \( R_J \) per second). Because the velocity data have a time resolution of \( \sim 2 \) h and the mean duration of our events is 59 min, velocity data are not available for all of our events. As a result, we are able to calculate the flow channel width for only 102 of 249 events. The flow channel width distribution is plotted in Figure 13.

[69] For most events the flow channel width is less than 20 \( R_J \). The mean flow channel width is 14.4 \( R_J \) and the mean is 18.3 \( R_J \). The mean duration of the 102 events for which we calculated the flow channel width is 92 min (\( \sim 5500 \) s), and the mean \( V_{\phi} \) during those events is 236 km/s (\( \sim 0.003 \) RJ/second). The largest flow channel width, 106.6 \( R_J \), comes from an event on 10 October 1996 which lasted for 143.6 min and had a mean \( V_{\phi} \) of 884.7 km/s.

[70] How does this compare to BBFs at the Earth? The Jovian magnetopause standoff distance has two probable locations, 60 and 90 \( R_J \), depending on the solar wind dynamic pressure Joy et al., 2002. Assuming a magnetotail width of 3 times that distance, or \( \sim 180–270 \) \( R_J \), we find that the mean flow channel width (\( \sim 18 \) \( R_J \)), is \( \sim 6.67–10 \) percent of the magnetotail width. This is comparable to the relative width of BBF flow channels at Earth, where, assuming a \( \sim 2 \) \( R_E \) flow channel width and a \( \sim 30 \) \( R_E \) magnetotail width, the flow channel is \( \sim 6.67 \) percent of the magnetotail width.

[71] Our calculation is only a rough estimate for the flow channel width. The flow channel width depends strongly on the event duration, which is defined by the event selection criteria outlined in section 3.2. Our definition for the event start and end points is subjective and may overestimate or underestimate the interval of the disturbed field configura-
tion. Additionally, the spacecraft may only be observing the event for a fraction of its total duration, so the flow channel width we calculate here is likely a lower bound for the actual value.

[72] Finally, we would like to estimate the amount of flux transported during our events and draw further comparisons to terrestrial BBFs. Unfortunately the low time resolution of the velocity data (~2 h) is insufficient for this calculation.

5.3. Event Periodicities

[73] Dynamics in the Jovian magnetosphere have been observed to occur with a 2–3 day periodicity; this periodicity has been documented in flow bursts [Krupp et al., 1998; Woch et al., 1998], reconfiguration events [Kronberg et al., 2007], and auroral polar dawn spots [Radioti et al., 2008]. The periodicity is thought to be related to the time scale of the internally driven mass-loading and release process at Jupiter [Kronberg et al., 2007].

[74] Many of the studies that noted the 2–3 day periodicity have considered only isolated intervals or a subset of spacecraft orbits. The Kronberg et al. [2007] reconfiguration events displaying this periodicity came from ~15 day intervals in Galileo orbits G2 (September–October 1996) and E16 (August–September 1998). At these times Galileo was at local times ranging from ~2350 to ~0310 LT. The periodic auroral polar dawn spots [Radioti et al., 2008] were observed between 20 February and 10 March 2007, and also map to the postmidnight sector, but at later local times, 0400–0900 LT, than the periodic reconfiguration events. The 2–3 day periodicity has also been seen at premidnight local times; for example, Woch et al. [1998] found quasi-periodic behavior in energetic ion fluxes from orbits C9 (~1800–2300 LT) and C10 (~2130–0030 LT). Additionally, Kronberg et al. [2009] report that quasiperiodic variations of the ion spectral index $\gamma$ are commonly observed, though not always with the 2–3 day period. They cite periodic behavior on 12 Galileo orbits, finding periods that range from 1.5 to 7 days are commonly observed, though a 2.5–4 day period is typical.

[75] Visual inspection of our reconnection events during selected intervals or orbits, such as the 15 day interval shown in Figure 12, suggests that the 2–3 day periodicity is present for at least part of orbits G2, G8, C9, and E16. It is more difficult to visually estimate the event periodicity on a longer time scale, so we have calculated the Rayleigh power spectrum. The Rayleigh power spectrum can be used to determine whether a statistically significant periodic signal is present among the occurrence times of discrete events. It has been used to study periodicities in quantities such as proton flare occurrences [Bai and Cliver, 1990]. In this section we will briefly introduce the Rayleigh power spectrum and explain how we have used it to investigate event periodicities; a more complete discussion of the Rayleigh power spectrum, its usage, and its limitations is given by Mardia [1972] and Lewis [1994].

[76] The Rayleigh power $z$ as a function of period $T$ is given by the following equation:

$$z(T) = \frac{1}{n} \left[ \left( \sum_{i=1}^{n} \cos\left(\frac{2\pi t_i}{T}\right) \right)^2 + \left( \sum_{i=1}^{n} \sin\left(\frac{2\pi t_i}{T}\right) \right)^2 \right]$$

(4)

where $n$ is the number of discrete events and $t_i$ is the time of the $i$th event. The Rayleigh power can be calculated for a range of user-specified periods $T$, and its significance depends in part on the number of independent Fourier frequencies within that range of periods. For a set of $n$ events observed during a time interval $\tau$, the independent Fourier spacing $\Delta \nu = 1/\tau$. The number of independent Fourier frequencies $N$ is the number of independent Fourier spacings $\Delta \nu$ within the range of user-specified frequencies (corresponding to the range of user-specified periods $T$). The

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Histogram of the flow channel width in $R_J$ for 102 of our reconnection events. The flow channel width is taken as the event duration multiplied by the average of $\left| V_\phi \right|$. During the event. The median flow channel width is 14.4 $R_J$, and the mean is 18.3 $R_J$.}
\end{figure}
The significance of a periodic signal with power \( z \) is given in the literature by the following expression:

\[
1 - \left(1 - \exp(-z)\right)^N,
\]

which represents the probability that the power of a randomly distributed data set will exceed \( z \) by chance. Thus by this definition a small significance value (\( \ll 1 \)) indicates that a periodic signal is statistically meaningful. If one chooses to oversample, or calculate the Rayleigh power for frequencies at a higher resolution than \( \Delta \nu \), equation (5) must be modified to including the effects of oversampling. For an oversampling factor \( A \), equation (5) becomes

\[
1 - \left[1 - A \exp(-z)\right]^N.
\]

[Lewis, 1994]. In our calculations we will use an oversampling factor of 5.

We have calculated the Rayleigh power for selected events from Galileo orbit G2, which includes the 15 day interval of Kronberg et al. [2007]. The selected events are the largest as measured by the integrated \( |B_p| \) power, \( \Sigma |B_p| \Delta t \). In selecting the “largest” events we required that the integrated \( |B_p| \) power surpass a threshold value; roughly one third of all 249 events meet this criterion. We have restricted our analysis to the largest events from the interval because many of the smaller events occur within a few hours of larger events and, as previously noted, in some instances we have identified more than one event for each of the Kronberg et al. [2005] reconfiguration event intervals. Therefore in this part of our analysis we include only the largest events because they are typically separated in time by ~days and are likely to be independent. Figure 14 shows the time spacing of the large events, which occurred from 11 September to 22 October 1996. Visual inspection supports an event periodicity of ~2–3 days, though the mean separation between events is 2.2 days and the median separation is 1.9 days. Dashed vertical lines have been drawn every 2 days to guide the eye.

[78] The Rayleigh power spectrum for these events is plotted in Figure 15. Sample significance levels are noted by the dashed horizontal lines. Since we would like to know whether there is a statistically significant periodic signal close to 2–3 days, we have chosen to examine the power for periods between 1 and 4 days. The largest peak in the Rayleigh power comes just before a period of 2 days, and there are two smaller peaks between 2 and 3 days. However, none of these peaks is statistically significant. For this interval, 11 September to 22 October 1996, \( \tau = 41 \) days and \( \Delta \nu = 2.823 \times 10^{-7} \) Hz. The range of frequencies corresponding to periods of 1 to 4 days is \( 1.157 \times 10^{-5} \) Hz to \( 2.893 \times 10^{-6} \) Hz, meaning that the number of independent Fourier frequencies \( N = \left(1.157 \times 10^{-5} - 2.893 \times 10^{-6}\right)/2.823 \times 10^{-7} \sim 30 \). The largest Rayleigh power is ~5.95 (at \( T = 1.8 \) days) and has a significance of \( 1 - \left[1 - 5 \exp(-5.95)\right]^{30} \sim 0.32 \) (recall that a significance value \(<1\) indicates that the periodic signal is unlikely to be due to chance). The Rayleigh power peak for periods of 2–3 days is 4.9 (at \( T = 2.2 \) days), and has a significance of 0.67. Such high significance levels suggest that none of the Rayleigh power peaks is statistically meaningful. Rejection of the null hypothesis generally requires a significance of 0.05 or better, that is, a probability of 5 percent or less that an occurrence is due to chance.

[79] We have expanded our analysis to other orbits (not shown) but still do not observe a statistically significant periodic signal between 1 and 4 days, though in some cases a 2–3 day periodicity is apparent visually, as noted above. We have also computed the Rayleigh power spectrum for all large events in Galileo orbits G1 through I24 to exam-
The peak power for the Rayleigh power spectrum from Figure 16 is 10.55 at a period of 1.8 days; with an oversampling factor of 5 there are 856 independent Fourier frequencies in this interval, so the significance of the peak

Figure 15. Rayleigh power spectrum for large events from Galileo orbit G2. The largest power comes at a period of 1.8 days, with two smaller peaks between 2 and 3 days, but none of the peaks is statistically significant. Select significance levels, or the probability that the power reaches a certain level by chance alone, are noted by the horizontal dashed lines.

Figure 16. As in Figure 15, the Rayleigh power spectrum for large events in Galileo orbits G1 through G24. Events occurred from 11 September 1996 to 30 October 1999. There is a peak in the power at a 1.8 day period, but it is not statistically significant.
power is 0.105 and the peak cannot be considered to be statistically meaningful.

6. Discussion

[s1] In section 4.1 we presented the spatial distribution of the events and their occurrence rate, and in section 4.2 determined the location of a separatrix. We also concluded that our events do not occur with any statistically significant periodicity. In this section we will briefly comment on how these results fit with or change the current understanding of Jovian magnetospheric dynamics.

[s2] What do our events and their properties tell us about the processes that drive global dynamics at Jupiter? Our results are consistent with both internally driven and solar wind-driven reconnection, and we do not find strong evidence that one process is favored over another.

[s3] At Jupiter we expect that the x-line associated with solar wind-driven reconnection to be restricted to the dawn sector [Cowley et al., 2003]. This x-line is analogous to the terrestrial near-Earth neutral line, and as in the terrestrial case, we would expect a distant reconnection line to exist farther down the tail. The available spacecraft observations are limited in their radial extent, so we do not expect to find direct evidence of the distant x-line. However, our events do support the presence of a near-Jupiter x-line that favors the dawn local time sector, where we observe planetward reconnection events inside of an x-line at ~90 R_J and tailward events outside. Events in the dusk sector are primarily planetward, and can be interpreted equally well as coming from the distant x-line or from centrifugally driven reconnection.

[s4] Our observations, particularly the event occurrence rate variation with local time, are well explained by the model of Kivelson and Southwood [2005]. In this model reconnection occurs when flux tubes rotate through the dusk sector, stretch due to centrifugal acceleration down the tail, and break. Our events occur with similar frequency in both the premidnight and postmidnight sectors. The occurrence rate drops just prior to midnight local time, and increases with local time until it peaks at 0230-0330 LT. These observations can be interpreted according to the qualitative model of Kivelson and Southwood [2005] as follows: flux tubes rotate through the dusk sector and are centrifugally accelerated outward down the tail. The plasma sheet thins and flux tubes break and are depleted of plasma, accounting for the high event occurrence rates observed at 2030-2230 LT. The empty flux tubes continue to rotate through the nightside and via interchange motion they are carried inward, while full flux tubes are carried outward. Reconnection does not occur during this time; this would be consistent with the sharp decrease in event occurrence rate just after 2230 LT. As the flux tubes continue to rotate, they refill and the stretching and pinching off process begins again after the full flux tubes have moved outward, though by this time they will have rotated several hours in local time. Thus we expect the event occurrence rate to increase, as it does beginning at 0130 LT.

[s5] Finally, what can we say about the 2–3 day periodicity? It has been identified in flow bursts, auroral polar dawn spots, the Kronberg et al. [2005] reconfiguration events, and can be found visually in some of our reconnection events. But using the Rayleigh power spectrum analysis we do not find any statistically significant periodicity in our events, including for periods between 2 and 3 days. Furthermore, in this and other studies the 2–3 day periodicity appears to be present only in specific orbits or intervals. Given the absence of a persistent, statistically significant periodic signal, it seems unlikely that the 2–3 day time scale is characteristic of internal processes driving reconnection in the Jovian magnetotail. This is consistent with the report by Kronberg et al. [2009] that the ion spectral index displays periodic behavior with periods ranging from 1.5 to 7 days. We suggest that the reconnection events during intervals displaying the 2–3 day periodicity could be at least partly influenced by external factors such as magnetospheric interaction with the solar wind. This would be an interesting topic for further study.

7. Conclusions

[s6] We have identified reconnection events in the Jovian magnetotail by surveying magnetometer data. These events are characterized by an increase in $|B_d|$, the north–south component of the magnetic field, over background levels. Furthermore, the $|B_d|$ increase is accompanied by an increase of the elevation angle magnitude compared to the quiet time background. Such increases in $|B_d|$ and the elevation angle magnitude indicate a field reconfiguration consistent with magnetic reconnection.

[s7] The magnetometer does not directly measure flow, so we have employed the backbend angle and the sign of $B_0$ as proxies to flow. Many of the events are accompanied by changes to the backbend angle that are qualitatively consistent with expectations from assumed radial flow and conservation of angular momentum, and which agree with the flow direction as inferred from the sign of $B_0$.

[s8] A direct comparison between our work and studies that used particle anisotropies to study dynamics in the tail shows good agreement between our events and intervals of large radial anisotropies. New events have been identified in the premidnight sector, supplementing the distribution of the reconfiguration events studied by Kronberg et al. [2005]. We also have compared the distribution of the radial flows, as inferred from the sign of $B_0$, to the distribution of particle flow bursts by Woch et al. [2002]. In the postmidnight local time sector the x-line is likely located near 90 R_J, in qualitative agreement with the statistical separatrix from Woch et al. [2002]. In the premidnight sector the radial distribution of data is insufficient to determine the distance of an x-line, but we can conclude that the x-line is likely to lie near or beyond ~120 R_J.

[s9] Finally, we have discussed the periodicity of our events and the absence of the 2–3 day periodicity seen in flow bursts, reconfiguration events, and auroral polar dawn spots. For certain specific intervals, such as orbits E16 and G2, including the Kronberg et al. [2007] interval, we observe the 2–3 day periodicity visually in our events. However, the Rayleigh power spectrum does not show any statistically significant periodicities in our events, either for these individual orbits or on a longer time scale. Therefore we conclude that reconnection does not generally occur with any periodicity that is representative of the internal processes driving dynamics in the Jovian magnetotail.
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