Mass release at Jupiter: Substorm-like processes in the Jovian magnetotail

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[1] The Jupiter orbiting spacecraft Galileo has provided evidence that the Jovian magnetotail is subject to a periodic process with typical timescales of several days by which the Jovian system is presumably releasing its excess iogenic mass. The mass release process resembles a terrestrial substorm in the sense of a global reconfiguration of the magnetotail. During the initial “loading” phase the plasma convection is at a moderate speed in the corotation direction and the Jovian plasma sheet appears to be in a stable configuration. In the release phase, reconnection through a thinned current sheet leads to radially inward and outward plasma flows and the ejection of plasmoids. Storage of magnetic energy in the lobe region seems not to be the prime driver of the reconfiguration process. Therefore the role of the solar wind as energy source is of less importance than for terrestrial substorms. Instead, it can be envisaged that plasma loading of fast rotating magnetic flux tubes and the associated centrifugal forces drive the reconfiguration process.


1. Introduction

[2] In the Earth’s magnetosphere, a geomagnetic substorm represents a dynamical process in which energy loading and subsequent dissipation occurs on a global scale. The process consists of the extraction of energy from the solar wind, the storage of this energy in the magnetotail leading to an increase of the lobe magnetic flux, the formation of a thin current sheet within the tail plasma sheet, the disruption of the tail current, and the release of a plasmoid [Baker et al., 1999]. The terrestrial substorm growth phase starts with a southward turning of the IMF. Onset is often triggered by northward turning of the IMF; less often internal processes might also initiate the expansion phase.

[3] There is increasing evidence that substorm-like processes in the sense of a global instability of the magnetotail or even the whole magnetospheric-ionospheric system occur also in the Jovian magnetosphere [Nishida, 1983; Woch et al., 1998, 1999; Louarn et al., 1998; Russell et al., 2000]. The overall morphology of a substorm process in the Jovian magnetosphere appears at first sight very much similar to the terrestrial one. The onset of auroral wave emissions, outward and inward flows of plasma, and magnetic field distortions resembling plasmoid structures have all been reported [Louarn et al., 1998; Woch et al., 1999]. Potential auroral signatures of these magnetospheric phenomena have recently been identified [Grodent et al., 2004].

[4] In contrast to the “classical” substorms at Earth, which under favorable conditions happen randomly every several hours, substorm-like disturbances at Jupiter seem to reoccur with a characteristic time constant of 2 to 4 days [Woch et al., 1998; Louarn et al., 1998; Krupp et al., 1998]. This intrinsic periodicity has led to the suggestion that the Jovian substorms are not driven by solar wind-magnetosphere interactions but represent an internally driven process. In this respect they might resemble the recently reported periodic substorms at Earth with typical repetition periods of several hours. These type of terrestrial substorms were also suggested to be driven by an internal plasma instability [Huang et al., 2004].

[5] At Earth, in the classical, externally driven case, reconnection of tail flux tubes which constitutes the prime relaxation process of a substorm is driven by addition of magnetic flux in the tail. At Jupiter, it is believed to be the centrifugal force on rapidly rotating, mass-loaded flux tubes leading to a thinning of the plasma sheet which enables spontaneous reconnection. This centrifugally driven reconnection process was first proposed by Vasyliunas [1983], as a steady state process inherent to the Jovian magnetotail.

[6] Voyager 1 and 2 indeed detected signatures of reconnection in the Jovian magnetodisk. Antisunward streaming particle events associated with northward field inclinations
were observed beyond about 80 Jovian radii (Rj). They were interpreted as the need to adjust the length of the extended nightside field lines to the dimension of the dayside magnetosphere of 40 Rj to 70 Rj [Huddleston et al., 1998], which leads to the separation of the tip of the flux tubes by reconnection [Nishida, 1983]. Since the events showed considerable variability, they were suggested not to be due to a steady-state process. The observed field component across the neutral sheet exceeded the dipole field strength, which was proposed to be the product of the tearing mode.

[7] Zimbardo [1993] shows that observations of particle streaming, auroral emissions and radio bursts support the growth of the tearing instability in Jupiter’s magnetosphere as a frequent and widespread phenomenon.

[8] Further evidence for transient magnetic field reconnection across the current sheet beyond 50 Rj was provided by Russell et al. [1998]. Localized regions of strong northward and southward magnetic field components were attributed to episodic reconnection of confined patches of the near Jovian magnetotail. These disturbances appear to be spatially large but not global events, with the patches having a size of about 25 Rj in radial and azimuthal direction. The events clearly indicate that fast rotation of the Jovian magnetosphere produces important differences between Earth’s magnetotail and Jupiter’s magnetodisk. Angular momentum conservation leads to predictable perturbations in the azimuthal component of the magnetic field because the magnetized plasma is convected either inward or outward to Jupiter by the reconnection process.

[9] Southwood and Kivelson [2001] pointed out the influence of compression and rarefaction of the Jovian magnetosphere induced by solar wind shocks on the stability of the Jovian plasma disk. They suggested that specifically during times of rapid expansion forces on mass-loaded flux tubes will lead to the formation of detached plasma “blobs” breaking off at the outer edge of the middle magnetosphere and to subsequent outward transport of plasma.

[10] Krupp et al. [1998] reported on energetic particle bursts frequently occurring in the Jovian magnetotail. They discovered a quasi-periodical modulations of these events. The typical recurrence period on the Galileo orbit G2, studied by Krupp et al. [1998], was 2 to 3 days. A 3-day modulation of energetic hot plasma fluxes associated with changes of the particle energy spectra and flow pattern in the middle magnetosphere was revealed by Woch et al. [1998]. These modulations were presumed to reflect a quasi-periodic transition between two basic states of the magnetotail which occur with an internal time constant. A single case study of a prominent particle burst event was carried out by Woch et al. [1999] by combining energetic particle, magnetic field, and plasma wave data. Woch et al. [1999] suggested that this event represented a global instability of the Jovian magnetotail and in that sense the Jovian counterpart of a terrestrial substorm. This event was interpreted as a dynamical process where the Jovian magnetotail becomes unstable due to mass loading of magnetic flux tubes leading to reconnection. Likewise, Russell et al. [2000] referred to magnetic field disturbances attributed to irregular transient reconnection events as Jovian substorms. Woch et al. [2002] deduced the most probable location of a near-Jupiter neutral line from a statistical study of particle flow bursts directions. It was shown that reconnection in the Jovian magnetotail is rather a transient than a continuous, steady state process, essentially driven by an internal mass loading-unloading processes of the Jovian system [Woch et al., 2002].

[11] On the basis of Galileo energetic particle and high-resolution magnetic field data we will further characterize the morphology of the Jovian magnetotail reconfiguration process. A detailed single case study will exemplify the overall magnetotail consisting in a transition from “quiet” state to a “disturbed” state. We will generally characterize the features of the reconfiguration process based on 34 events observed on 7 Galileo orbits. We will show that localized reconnection, radial plasma streaming, and the intensification of auroral radio emissions are an integral part of a global cyclic mass release process.

2. Instrumentation

[12] The present study is based on observations performed by the Energetic Particles Detector (EPD) and the magnetometer (MAG) on board Galileo from mid-1996 to end of 1998 (Galileo orbits G2 to E16). During this period the apojove of the Galileo orbit rotated from predawn to premidnight, providing coverage of most of the Jovian magnetotail up to distances of 150 Rj.

[13] EPD consists of two double-headed detector systems, CMS and LEMMS, using Time-of-Flight, dE/dx versus E, and magnetic deflection techniques to separate different ion species and electrons from ions, respectively. The measurable energy range is 15 keV to 11 MeV for electrons and 22 keV to 55 MeV for ions. The whole instrument is mounted on top of a turntable so that its rotation, combined with the spacecraft spin, produces measurements from almost all directions in space. In general, in the real-time data mode used in this study, EPD provides measurements from 16 different directions covering nearly the whole unit sphere. Exception is a small solid angle (<0.1 sr) along the spin axis to avoid direct sunlight at the detector. A scan of the unit sphere is performed within 3 to 11 min dependent on the transmission rate to Earth. A complete description of the instrument can be found in the work of Williams et al. [1992].

[14] The energy dependence of the omnidirectional ion intensities \( I_{\text{omni}}(E) \) can be described by a power law with spectral index \( \gamma \):

\[
I_{\text{omni}}(E) = I_0 \left( \frac{E}{E_0} \right)^{-\gamma}.
\]

The angular distribution of convected ions at Jupiter could be interpreted in terms of low-order spherical harmonics as long as \( 2v_F/v_{\text{ion}} < 1 \), where \( v_F \) is the convection velocity, \( v_{\text{ion}} \) is the ion speed. The 16-sector measurements of ions are analyzed by using spherical harmonics. The direction and amplitude of the anisotropy are derived as follows: Assuming that the particle intensity \( I(E, \theta, \phi) \) can be described by a continuous function on a sphere, the spherical harmonic expansion can be written as

\[
I(E, \theta, \phi) = I_{\text{omni}} \sum_{n=-\infty}^{\infty} \sum_{m=-n}^{n} A_{nm}(E) Y_{nm}(\theta, \phi),
\]
where $l_{\text{aniso}}$ is defined above, so that $A_{00} = 1$. The functions $Y_{nm}$ are defined as

$$Y_{nm}(\theta, \phi) = P_{nm}(\cos \theta) \cos(m\phi) \text{ for } m > 0,$$

$$Y_{nm}(\theta, \phi) = P_{nm}(\cos \theta) \sin(m\phi) \text{ for } m < 0,$$

where $P_{nm}$ are the normalized Legendre polynomials, the angles $\theta$ and $\phi$ are given by the motor position of EPD and spin rotation of the spacecraft, respectively [Krupp et al., 2001]. Details on this technique can be found in the work of Sanderson and Page [1974]. The study is restricted by using the vector of the first-order anisotropy $A_1 = (A_{1-1}, A_{10}, A_{11})$. The first-order anisotropy vector is generally composed of a combination of vectors such as ion convective flow, including field-aligned streaming, intensity gradient effects, and other usually small components. No evidence was found of large contributions from gradients in the analysis of EPD data. In a first approximation the flow component appears to dominate the first-order anisotropy. Under specific conditions the derived anisotropies are a measure of particle flow velocities (for a detailed discussion, see Krupp et al. [2001]).

The magnetometer instrument (MAG) measures magnetic field vectors in three different sensitivity ranges with sampling frequency dictated by available downlink [Kivelson et al., 1992]. During the intervals presented here, MAG was in its ±512 nT range with resolution of 0.25 nT. The magnetic field data will be presented in the SIII-system. The radial component is positive in outward direction, the azimuthal component is positive in the direction of Jupiter’s rotation, and the south-north (meridional) component is positive southward.

### 3. Observations

[16] We scanned the EPD data set from Galileo orbits G2, E6, G7, G8, C9, C10, and E16 for the occurrence of particle flow burst events, i.e., intervals with significant deviation of the particle flow from the usual corotational direction. From these we selected the 34 most prominent events for further analysis. Essentially, they comprise those events which last longest; short-lasting events consisting of singular flow spikes were discarded. The 34 periods with flow bursts are usually associated with considerable structural changes of the plasma sheet/current sheet, which indicate a general configuration change of the Jovian magnetotail. We will refer to these events as reconfiguration events. The wobble of the Jovian magnetodisc provides the possibility for a latitudinal scan through the entire plasma sheet/lobe region twice for each 10-hour rotation. Since a magnetotail reconfiguration process generally lasts for several planetary rotation (see below), it is possible to monitor the evolution of plasma and magnetic field properties in all key regions of the magnetotail throughout the process.

#### 3.1. Reconfiguration Event: Single Event Study

[17] Figure 1 shows data for the time interval from DOY 269, 0500 to DOY 272, 0500. Galileo was in the predawn sector of the magnetotail (0230 LT) at around 103 $R_J$. The first panel shows omnidirectional ion intensities in seven energy channels covering the energy range from 42 keV to 3.2 MeV. The second panel displays the radial and azimuthal components of the ion directional flow anisotropy. The next four panels show the magnetic field magnitude and its components in the SIII-system. The time resolution of the particle measurements is 11 min. The magnetic field is displayed with a time resolution of 24 s.

[18] Over the whole displayed interval we observe large-amplitude periodic fluctuations in the magnitude of the magnetic field and its direction (primarily visible in the radial component) on the planetary rotation period. These are caused by the wobble of the flattened Jovian magnetosphere and its current sheet topology [Dessler, 1983]. Simultaneously, changes of the intensities are seen, with largest intensities around the current sheet center and decreasing intensities when the spacecraft is moving toward the lobe region.

[19] At the beginning of the displayed interval from 0500 UT on DOY 269 up to 0900 UT on DOY 270 the ion intensities vary gradually in response to the changing relative position of the spacecraft and plasma sheet center imposed by the planetary rotation. No distinct plasma sheet/lobe boundaries are encountered. During the first two rotations, Galileo is south of the plasma sheet center with the exception of a brief dip through the current sheet at 1000 on day 269, as evidenced by the polarity change of the radial magnetic field component. Thus the plasma sheet is displaced northward from its nominal position. Except for times of close proximity to the current sheet, the magnetic field shows a persistent and significant southward tilt. The azimuthal component of the ion directional flow anisotropy is dominating throughout this interval. It indicates that the plasma flow can be estimated to be in the corotational direction. The average flow speed is about 300 km/s. The magnetic field is consistently in the expected swept-back orientation as evidenced by the anticorrelation between azimuthal and radial component. This initial phase can be characterized in many aspects as a quiet, undisturbed period, with a plasma sheet being in a stable configuration. The lack of plasma heating, particle beams or flow bursts, and transient magnetic field distortions supports this view.

The plasma sheet is possibly also rather extended in latitude with a magnetic field showing a significant southward tilt, i.e., a residual dipole component.

[20] Possibly by the change of the Galileo location with respect to the equatorial plane, the spacecraft crosses the current sheet at around 0400 UT on day 270, and Galileo is for the first time substantially above the current sheet engulfed in the northern plasma sheet. During this period the azimuthal flow anisotropy component rises gradually, indicating higher corotational flows, and at the current sheet encounters an increase in the particle intensities is seen to values higher as those seen before. Shortly after this crossing of the current sheet, the magnetotail transits abruptly from a “quiet” into a disturbed state. The corotational flow breaks down. Instead, a large radial flow anisotropy component is observed together with a component in anticorotation direction. The plasma is now streaming tailward, with high velocities. Simultaneously, ion intensities rise significantly. Right at the onset of the tailward flow, the magnetic field, which has been primarily current sheet-like before, with a dominant radial and a small...
Figure 1. Energetic particle and magnetic field observations on Galileo orbit G2 from DOY 269, 0500 to DOY 272, 0500 in 1996. From top to bottom are displayed: omnidirectional ion intensities (0.042–3.2 MeV) (first panel); first-order ion anisotropies in the radial (positive is outward) and corotational direction (second panel); the magnetic field components (third to fifth panels) in SIII coordinates (the radial component is positive in the outward direction, the azimuthal component is positive in the direction of Jupiter’s rotation, and the south-north component is positive southward) and its magnitude (sixth panel) as measured by EPD and MAG on Galileo orbit G2; continuous horizontal lines outline “quiet” and disturbed periods, dashed lines labelled (Q and D) to specific times referred to some representative current sheet crossings; in the text and Figure 5.
southward component, now shows short spike-like intensity increases by several nT, above values seen during the adjacent lobe encounters. The increases are primarily due to a significant bipolar excursion of the south-north component which indicates that the magnetic field is a strongly tilted in the meridional plane for short periods of time. For about 20 min before the onset of the northward turn the magnetic field is in a swept-forward configuration, since the azimuthal and radial component show the same polarities. From this time onward, also a different topology of the plasma sheet is observed.

[21] Instead of ion intensities gradually decreasing toward higher latitudes, now distinct boundary layers between the plasma sheet and the lobes have developed. The core plasma sheet appears to be thin and strongly collimated at the current sheet position. The boundary layers consist of high-intensity beams of tailward streaming ions and electrons. Whereas during the “quiet” time interval, ion intensities peaked at the current sheet center, highest intensities now are observed in the boundary layers (see bursts labeled D1, D2, and D3 in Figure 1).

[22] Until 2000 UT on day 270 the strong tailward anisotropy (flow) persists. During this period a further spike in the magnetic field intensity is seen. This time the spike is primarily produced by a substantial component in the northward direction. During the spike the magnetic field becomes swept forward out of the meridian plane.

[23] Between 2000 and 2200 UT on day 270 the particle flow anisotropy has reversed its direction. A large radial inward component with a significant corotational component is observed during the subsequent plasma sheet crossings, which is indicative of sunward moving plasma. The first plasma sheet crossing with inward motion shows the highest particle intensities encountered during the whole event and the strongest confinement of the plasma at the current sheet center. At the subsequent crossings the plasma sheet widens and distinct boundary layers with inward streaming particle beams again become discernible (burst D5).

[24] Around 1700 on day 271, the plasma sheet has returned to its “quiet” topology. The ion intensity has dropped, the sheet has widened in latitude, and the flow is back to corotation direction.

[25] Figure 2 combines ion intensities and observations of the Galileo PWS experiment previously published by Louarn et al. [1998]. It shows that the disturbed time interval is associated with the onset and intensification of B-KOM emissions which are associated with auroral activity.

[26] A striking feature of the presented time interval is the rough constancy of the magnetic field intensity in the lobe encounters throughout the event, specifically during the time period preceding the disturbance. From the “quiet” to the disturbed and back to the “quiet” condition the magnetic field remains at approximately the same level. In contrast, the ion intensities exhibit an increase shortly before the disturbed interval.

3.2. Reconfiguration Events: Statistical Study

[27] We have selected 34 reconfiguration events. The events generally show a complex of sequence radially outward and inward bursts, associated with increasing particle intensity, thinning of the plasma sheet, bipolar fluctuations of the north-south magnetic field, and a distortion of the azimuthal magnetic field. Some of the characteristic properties of the events (date, radial distance, local time, duration, flow direction, and change of the total magnetic field at the presubstorm phase in respect to the field of the corresponding preceding “quiet” period of the magnetotail) are summarized in Table 1. Figure 3 presents a map of the location of the 34 events. The figure shows that most of the events are located in the predawn sector, consistent with the location of the statistical x-line derived by Woch et al. [2002].

[28] Of specific importance with respect to the physical processes behind the reconfiguration events is the behavior of the magnetic field. Out of the 34 selected reconfiguration events, 15 events show no increase or even a decrease of the magnetic field intensity (for one event which included in this group it is hard to define a value of the magnetic field change, but it will be in the range less than 10%). The magnetic field intensity stays essentially constant in the period prior to disturbance onset. An increase in the order of 1 nT to 2 nT (10 to 20%) was observed for 14 events. This increase was for the majority of events limited in time, essentially just affecting the last lobe encounter (or a fraction of it) before disturbance onset. Such magnetic field increases can be attributed to an increase of the plasma pressure in the plasma sheet during plasmoid formation.

[29] Only a small number of events, about 5 out of 34, show a distinctively different behavior of the magnetic field, namely a substantial, long-lasting increase of the magnetic field in the lobe regions prior to the disturbed time periods.
Figure 4 demonstrates the well known quasi-periodic nature of the magnetotail reconfiguration events, [Woch et al., 1998; Krupp et al., 1998]. It shows the variations of the ion directional flow anisotropy (top), and the south-north component of the magnetic field data is presented as a highly smoothed time series (middle) and additionally with high temporal resolution (bottom), in the time interval from DOY 265, 1200 to DOY 280, 0000. A pronounced 2 to 3 day modulation of the anisotropy and magnitude is seen, indicating alternating times of corotational flow and outward/inward flow. Times of outward/inward flow are generally associated with transient bipolar south-north magnetic field distortions. The smooth data clearly shows quasi-periodic oscillations of the magnetotail field. The magnetic field changes its polarity from southward to northward just before the onset of the burst events. Then, after the disturbed period the magnetic field gradually returns to a southward configuration and continues to increase until the next flow direction change. These magnetic field changes imply a change of the plasma sheet topology from a thin postplasmoid type configuration to a “dipolarized” thicker structure. The “dipolarized” configuration is stretched out by the centrifugal force, leading to reconnection, plasmoid formation, and then mass release.

### Table 1. Reconfiguration Events and Their Properties

<table>
<thead>
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<th>Time Interval, Y DOY UT</th>
<th>Radial Distance, R_j</th>
<th>Local Time</th>
<th>Duration</th>
<th>Direction</th>
<th>Increase/Decrease B_tot</th>
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<tr>
<td>1998 259070 – 2591630</td>
<td>78 0120</td>
<td>9.5 0</td>
<td>o</td>
<td>20</td>
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*aThe increase of the total magnetic field at the presubstorm phase is given with respect to the field of the corresponding preceding “quiet” period of the magnetotail.

*bPrime direction of the burst events relative to the planet (o: outward, i: inward).

*cIn this case it was hard to define change of the magnetic field.

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[30] Figure 4 demonstrates the well known quasi-periodic nature of the magnetotail reconfiguration events, [Woch et al., 1998; Krupp et al., 1998]. It shows the variations of the ion directional flow anisotropy (top), and the south-north component of the magnetic field data is presented as a highly smoothed time series (middle) and additionally with high temporal resolution (bottom), in the time interval from DOY 265, 1200 to DOY 280, 0000. A pronounced 2 to 3 day modulation of the anisotropy and magnitude is seen, indicating alternating times of corotational flow and outward/inward flow. Times of outward/inward flow are generally associated with transient bipolar south-north magnetic field distortions. The smooth data clearly shows quasi-periodic oscillations of the magnetotail field. The magnetic field changes its polarity from southward to northward just before the onset of the burst events. Then, after the disturbed period the magnetic field gradually returns to a southward configuration and continues to increase until the next flow direction change. These magnetic field changes imply a change of the plasma sheet topology from a thin postplasmoid type configuration to a “dipolarized” thicker structure. The “dipolarized” configuration is stretched out by the centrifugal force, leading to reconnection, plasmoid formation, and then mass release.

Figure 3. The G2, E6, G8, C9, C10, E16 orbits of Galileo in Jupiter Solar Ecliptic coordinates. The locations of the 34 selected reconfiguration events are marked. Time periods with periodical behavior of the spectral index γ are indicated by a wavy line.
4. Discussion

4.1. General Characteristics of the Reconfiguration Events

[32] With the present study, based on 34 events, we are able to establish the fundamental properties of the reconfiguration events. It consists of a quasi-periodic transition between two elementary different states of the magnetotail. The general topology and properties of these two phases are sketched in Figure 5.

[33] In the initial “quiet” state the plasma flow is in the corotational direction. The plasma sheet is thick, i.e., largely expanded in latitude around the current sheet, without a distinct boundary toward the lobe region. The current sheet itself resides in a stable configuration without significant large- or small-scale disturbances. The magnetic field is in a swept-back configuration, as expected for angular momentum transfer to the magnetospheric plasma [Russell et al., 1998; Dougherty et al., 1993]. The ion intensities in the plasma sheet center is initially at a low level. The “quiet” phase usually persists for 3 to 5 Jupiter rotations.

[34] Toward the end of the “quiet” phase, the ion intensity rises and the flow velocity slowly increases both in the corotational direction and in the radial outward direction. The “quiet” phase ends with a breakdown of the corotational pattern of the plasma flow and the magnetotail transits into a “disturbed” phase.

[35] At a given location the transit occurs abruptly, within minutes. In the disturbed phase particles initially are streaming tailward. Subsequently, in the course of the events, the streaming direction reverses to planetward streaming. A continuous thinning of the plasma sheet is observed, with the strongest confinement of the plasma around the current sheet reached at the point of flow reversal. Distinct boundary layers at the plasma sheet-lobe interfaces evolve, which consist of intense, high-velocity particle beams. The magnetic field topology shows to first order a current sheet configuration. However, during the period of tailward streaming the magnetic field in the plasma sheet has a persistent northward tilt, i.e., oppositely to what is expected from the normal planetary field orientation. After reversal of the flow direction the tilt changes back to southward tilt. Transient, small-scale disturbances are superimposed on this average field configuration.

[36] The particle and field characteristics are consistent with a reconnection scenario. Whereas in the “quiet” phase plasma convection in the corotational direction is sustained in the magnetotail, in the disturbed phase the magnetotail has evolved into a configuration which enables the onset of reconnection and allows for the release of plasma. That reconnection is indeed occurring is primarily evidenced by the distinct tailward and inward streaming particle beams. They are presumably observed on field lines which have recently been reconnected. Furthermore, characteristic mag-
4.2. Temporal and Spatial Scales

Through it, and finally ends up at a location tailward of the observation point, then progresses with the result that the actual active x-line is generally first an apparent outward motion of the reconnection region, temporally static. Inherent to the plasma release process is a sequence of individual relatively short-lived reconnection events. We have presented evidence herein that they are part of a global mass reconfiguration process.

The configuration favoring reconnection is maintained from several hours to several tens of hours, with a maximum detected duration of 30 hours and an average duration of approximately 15 hours. This means that the reconnection configuration is observed usually for several, in some cases up to six, consequent current sheet crossings. We cannot exclude the possibility that reconnection is persistently occurring as a quasi-steady state process throughout the entire interval of the reconnection configuration. The comparatively low resolution of the particle measurements does not allow detection of processes with timescales of the order of 10 min or less. It is possible that with EPD we only observe the cumulative effect of a sequence of individual relatively short-lived reconnection bursts. High-resolution magnetic field data supports this conjecture.

Figure 6 shows as an example a close-up view of a current sheet crossing tailward of a reconnection line. Superimposed on a consistently northward inclined field, a series of small-scale disturbances occur. These are either sporadic increases of the magnetic field intensity (above lobe levels), primarily due to a substantial increase of the south-north component, or bipolar deflections in the south-north component. They are often associated with the magnetic field changing from a swept-back to a swept-forward configuration. The leading configuration is consistent with the field rotating faster than corotation. This indicates transfer of momentum from high to low altitudes and thus the planet’s ionosphere gains momentum from the magnetospheric plasma [Dougherty et al., 1993]. Such events where discussed by Russell et al. [1998] as indication for small-scale reconnection events. We have presented evidence herein that they are part of a global mass reconfiguration process.

The apparent tailward motion of the reconnection region, which can be deduced from the flow reversal from tailward to inward seems to be an intrinsic feature of the reconfiguration/mass release events. A flow reversal in this sense is observed for the large majority of events. It suggests that inherently the breakup of flux tubes first starts relatively close to the planet. In the course of the mass release process the x-line retreats further downtail, whereas the inward mass-emptied region might already return to the “quiet” corotational state. The outward motion could be associated with a progression of the local time sector affected by the process toward dusk. Such a combination of outward and azimuthal motion of the reconnection region could explain the average location of the x-line deduced in statistical studies [Woch et al., 2002], which was shown to be located closer to the planet at predawn compared with premidnight.

4.3. Spatial Evolution

The magnetic field distortions, most readily explained by the passage of plasmoid-like structures, confirm ongoing reconnection.

[37] The reconnection topology is neither spatial nor temporally static. Inherent to the plasma release process is an apparent outward motion of the reconnection region, with the result that the actual active x-line is generally first planetward of the observation point, then progresses through it, and finally ends up at a location tailward of the observation point.

4.4. Relation to Auroral Phenomena

Russell et al. [1998] as indication for small-scale reconnection events. We have presented evidence herein that they are part of a global mass reconfiguration process.

The overall auroral activity at Jupiter is well correlated with the disturbance level of the magnetic field in the meridian plane.

Figure 6. The magnetic field variations during a current sheet crossing tailward of a reconnection line for the time period DOY 264 1000 to DOY 264 1730 in 1996. Distortions of the field which can be attributed to plasmoids are marked by dashed lines. The vertical lines indicate the time period of the magnetic field swept forward out of the meridian plane.

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Jovian magnetosphere [Prangé et al., 2001]. The activity showed a variability with timescales of days. Thus these observations also suggest that a dynamic process with cyclic nature affects the Jovian magnetosphere. A detailed relation of individual auroral features with the various signatures of the mass release process has yet to be established. However, it is tempting to speculate that isolated auroral spots frequently observed poleward of the main auroral oval, the so-called “Nightside Polar Spots” [Grodent et al., 2004], may be the auroral imprint of the transient reconnection events. The apparent magnetic conjugacy of the two phenomena and their compatible duration corroborates such a relation. It has been suggested that the subcorotational part of the dark polar region, an ionospheric region at dawn void of auroral emissions [Stallard et al., 2001; Grodent et al., 2003b], is connected to the return flow of emptied flux tubes [Cowley et al., 2003] from Vasyliunas’ x-line. However, it could also be speculated that the upward current necessarily associated with the braking of the fast return flow in the high-pressure subcorotational regime in the middle magnetosphere could lead to intensive emissions. Those may be associated with the so-called auroral dawn storms [Clarke et al., 1998] or multiple dawn arcs [Grodent et al., 2003a].

[42] Owing to the orbital characteristics of the Galileo orbit we have identified the mass release events in the magnetotail region only. However, the occurrence of plasma release events may not necessarily be restricted to the Jovian magnetotail. They might occur also on the dayside, specifically during times of magnetospheric expansion, when outward stretching of mass-loaded flux tubes is no longer prevented by solar wind pressure forces. Thus mass release events might also account for dayside auroral intensifications.

5. Summary

[45] The plasma flow in the Jovian magnetosphere is generally dominated by the fast planetary rotation. However, in the magnetotail at distances beyond 60 R_J the corotational flow is often disrupted by the occurrence of flow bursts in which particles are streaming away from or toward the planet. We used energetic particle data from the EPD instrument in combination with magnetic field observations to analyze the flow burst events.

[46] This multicase study confirms the previous idea [Woch et al., 1999] that the particle flow bursts are an outstanding signature of a large-scale process leading to a substantial reconfiguration of the Jovian magnetotail and enabling mass release from the Jovian system. With respect to its global nature and its dramatic impact on the tail topology, the process can be regarded as the Jovian counterpart of the terrestrial substorm. We selected 34 of the most prominent substorm-like events to unravel the fundamental properties. The reconfiguration process consists of a quasi-periodic transition between two different states of the magnetotail: a “quiet” and a “disturbed” state. The “quiet” state is characterized by plasma flow in the corotational direction, a stable, latitudinally extended plasma sheet, and a current sheet magnetic field configuration. The “disturbed” state is defined by particles streaming tailward or planetward, a strongly confined plasma sheet, and, in the initial phase, a generally northward tilted magnetic field configuration with transient small-scale disturbances superimposed. During this period, which lasts generally from several up to several tens of hours, the magnetotail is in a reconnection favoring configuration. Reconnection and consequently mass release are occurring not continuously as a steady-state process of several hours duration but rather as a series of singular intermittent events. The reconnection region seems to move outward in combination with an azimuthal motion.

[47] We could show that with respect to the driving mechanisms at least some of the Jovian reconfiguration events exhibit striking differences to terrestrial substorms. Classical terrestrial substorms are driven by the interaction of the solar wind with the magnetosphere leading to storage of magnetic energy in the lobes. For most of the Jovian magnetotail reconfiguration events we see no evidence for significant storage of additional magnetic flux in the lobe region. This fact, the presence of the inherent quasi-periodicity of the mass-release events, suggest that solar wind-magnetosphere interactions are not the prime driving mechanism. The reconfiguration is an integral part of a cyclic mass release process which allows the Jovian magnetosphere to eject excess mass and return magnetic flux to the inner magnetosphere. Such a process has long been predicted as inherent and necessary feature of the Jovian magnetosphere [Vasyliunas, 1983].

[48] Although the events are primarily internally driven, we cannot exclude that a minority of the Jovian reconfiguration events are triggered by solar wind interaction. A solar wind induced compression or expansion of the magnetosphere will affect the plasma corotational flow [Southwood and Kivelson, 2001] which certainly will have an impact on the plasma sheet topology, leading to delayed or premature mass release.

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