The mass-release process in the Jovian magnetosphere: statistics on particle burst parameters

E. A. Kronberg, J. Woch, N. Krupp, and A. Lagg

E.A. Kronberg, Max-Planck-Institut für Sonnensystemforschung, Max-Planck Str., 2, Katlenburg-Lindau, 37191, Germany.

1 Max-Planck-Institut für Sonnensystemforschung,
Katlenburg-Lindau, Germany.
Abstract. The Jovian magnetosphere undergoes periodic reconfiguration processes mainly driven by the fast planetary rotation and mass-loading from the moon Io. These reconfiguration processes of the Jovian magnetosphere are associated with the release of plasmoids discernible as ion flow bursts associated with bipolar magnetic signatures. We investigate these plasma flows statistically using data from the Energetic Particles Detector (EPD) and from the Magnetometer (MAG) onboard Galileo. The plasma flows are observed in different magnetospheric regions: the current sheet center, the plasma sheet boundary layers and the lobe. We show that the bulk velocity of all species is the same for most of the magnetic field bipolar signatures associated with these plasma flows. The average speed of the observed plasmoids in the plasma sheet associated with the ion flow bursts is between 350 and 500 km s\(^{-1}\) and the duration of the events is between 10 and 20 minutes. The associated plasmoid length is correspondingly \(\sim 9R_J\). The plasmoids are moving approximately with Alfvénic speed. The convection electric field during the plasmoid release is about an order of magnitude higher than the ambient value of the Jovian convection electric field.
1. Introduction

The mass-release process is an important feature of magnetospheric dynamics. Mass and energy is provided through the solar wind interaction with the magnetosphere in the terrestrial case, while at Jupiter the most important mass source is the moon Io and the energy is extracted from the fast planetary rotation of the gas giant. Reconnection in the magnetotail is a key process responsible in both magnetospheres for explosive mass-release, and subsequent loss of plasma mass from the system. Reconnection generates different characteristic signatures in the magnetotail such as ion bulk flow bursts, field-aligned beams and plasmoids.

These phenomena are well studied observationally by different spacecraft missions in the terrestrial magnetosphere [e.g., Baumjohann et al., 1990; Angelopoulos et al., 1994; Ieda et al., 1998; Zong et al., 2004; Manapat et al., 2006]. In the Jovian magnetotail the ion flow bursts were first detected onboard Voyager 2 [Krimigis et al., 1980]. More features on ion particle bursts have been revealed by measurements onboard the Galileo mission [Krupp et al., 1998]. The particle bursts appear to be associated with substorm-like processes at Jupiter [Woch et al., 1998]. The substorm-like processes in the Jovian magnetosphere are mainly internally driven and appear to be periodic with a repetition period of 2 to 3 days [Woch et al., 1998; Kronberg et al., 2007]. The associated ion bursts were distinguished into ion bulk flow bursts, field-aligned beams and plasmoids in single events studies of the substorm-like process [Woch et al., 1999; Kronberg et al., 2005]. Other studies were concentrated on the investigation of the plasmoids using magnetometer data Russell et al. [1998, 2000]. The understanding of plasma release processes in the Jovian magnetotail
are of current interest for the scientific community. We got exciting new insights by the New Horizons spacecraft, which traversed the Jovian magnetotail from February to May 2007 and observed variations in the plasma flow velocity caused by plasmoids at distances between \( \sim 600 \) and 1000 \( R_J \) and at a repetition period of about 3 to 4 days [McComas et al., 2007; McNutt et al., 2007]. Inside the plasmoids similar ion composition was found by Radioti et al. [2007] using Galileo data closer to the planet at 80 - 100 \( R_J \) in the region close to the x-line where reconnection takes place [Woch et al., 2002].

In this paper we first present a Jovian plasma release event. Thereafter, we statistically study the ion bursts detected with Galileo EPD on G2, G8, C9, C10, E16 orbits and then concentrate on those burst events which are associated with plasmoid signatures in the magnetic field. The characteristic parameters of these plasmoids, like velocity, length, duration and others, are estimated.

2. Instrumentation

Ion fluxes were measured in the Jovian magnetosphere by the Energetic Particles Detector (EPD) in the energy range from 22 keV to 55 MeV for ions on board Galileo. The EPD instrument provided almost full \( 4\pi \) directional information with a time resolution of 3 to 11 min, dependent on the transmission rate to Earth [Williams et al., 1992]. The magnetic field was measured by the fluxgate magnetometer onboard Galileo with a temporal resolution of 24 s [Kivelson et al., 1992]. Using the Plasma Wave Spectrometer (PWS), which measures the varying electric and magnetic fields characteristics in the frequency range 5 Hz to 5.6 MHz and 5 Hz to 160 kHz, respectively, for the identification of plasma waves (see instrument description in Gurnett et al. [1992]) we compute the electron density.
The bulk velocities were calculated using a technique described in Krupp et al. [2001] and references therein.

3. Reconfiguration event as a mass-release event

First we present an example for an event by which the Jovian magnetosphere releases excess mass. The event is associated with particle bursts and in particular the release of a plasmoid. During this event Galileo was located in the tail region at about 95\(R_J\), in the predawn sector (02:00 LT). Figure 1 covers 4 days of observations from day 159 to day 163 in 1997.

Over the whole displayed interval the consequences of the magnetodisc wobbling [Smith et al., 1975] are observed in the energetic particles and the magnetic field. As the spacecraft crosses the tail current sheet center plane (denoted as CSC in Figure 1) we observe the highest ion intensities, and the lowest magnetic field values. As the spacecraft approaches the edge of the current sheet and moves into the tail lobe the inverse situation takes place: we observe a peak in the magnetic field strength and reduced ion intensities. The thin magnetodisc is well seen from the short duration of the current sheet crossings (∼ 1) hour and by the long lobe encounters of ∼ 4 hours.

Before day 159, 21:00 UT the magnetic field and the energetic particle population show variations which are characteristic for a quiet plasma sheet. From day 159, 02:00 UT to 21:00 UT Galileo is south of the plasma sheet center. Thus the plasma sheet is shifted somewhat northward from its nominal position. The magnetic field strength in the lobe regions is moderate, 7-7.5 nT, and at a level characteristic for these distances [Kivelson and Khurana, 2002]. The plasma flow is in the corotational direction, as shown by the dominant azimuthal component of the ion anisotropy. The south-north component of the
magnetic field is small and consistently southward as expected for an undisturbed Jovian magnetic field topology (except for times of close proximity to the current sheet). Thus this phase can be characterized in many aspects as a quiet, undisturbed period. The lack of ion bursts and transient magnetic field distortions supports this view.

This situation changes after 21:00 on day 159 (marked by the first vertical line from the left, in Figure 1). In the lobe the total magnetic field has increased by a factor of 1.5 and remains enhanced during the next four lobe encounters. Likewise, for the first two current sheet crossings there is an indication for a stronger confinement of the plasma sheet (narrower peaks in the particle intensities). However, plasma flow remains corotational.

About 20 hours later at 18:00 on day 160 (outlined by the second vertical line from the left, in Figure 1), first indications for a complete reconfiguration of the magnetotail are observed. The magnetic field changes from predominantly southward orientation to a mainly northward direction implying the change in the plasma sheet structure. At 00:00 UT on day 161 the breakdown of a plasma flow in corotation direction and the first ion burst flow event are observed. Just before the flow breakdown and the flow burst event the magnetic field intensity drops. An ion intensity enhancement is seen simultaneously with a strong increase of the ion anisotropy in the radial outward direction, which exceeds the co-rotational anisotropy by far. The particle event is associated with the northward tilt of the magnetic field and a swept-forward configuration, since the azimuthal and radial component show the same polarities. We will discuss the association of the tailward bursts with the northward direction in the Section 4.1.

At ~ 12:00 UT the most pronounced burst in terms of ion intensity and radial anisotropy magnitude (highlighted in yellow in Figure 1) is observed. It again has a radial outward
direction and a small azimuthal component in anticorotational direction, indicating a close
to tailward directed flow. At the same time a clear bipolar change of the south-north
component of the magnetic field is seen. A bipolar magnetic deflection of the meridional
direction \( B_\theta \) is the typical observational signature of a plasmoid in the magnetic field.
The ion intensities reach their highest values for the displayed interval. This type of event
with strong radial anisotropy, increase of the particle intensities and the bipolar signature
of the south-north magnetic we call henceforth a plasmoid event. We will consider this
event with more details in the next Section.

After the intense plasmoid event the magnetic field intensity in the lobe has dropped
significantly to a level even below that of the undisturbed time period. As during reconnec-
tion magnetic flux is transported from the lobe region into the reconnection zone (and
redistributed there). Correspondingly the field strength in the lobe region decreases. The
ion intensities exhibit a sharp boundary towards the lobe and strong confinement around
the current sheet, indicating again a thin plasma sheet.

A fourth ion burst event is seen after the next plasma sheet encounter right at the
northern lobe boundary. This time the burst is directed towards Jupiter (negative radial
anisotropy) indicating that the x-line is moving tailward and already passed Galileo. The
meridional magnetic field component is clearly southward (will be discussed in Section
4.1). Following this last burst the plasma flow is returning to the corotational direc-
tion. Further behavior of anisotropies and magnetic field corresponds to the undisturbed
magnetotail state. The ion intensities return to the predisturbed level.

This event displays many significant features similar to terrestrial substorms. However,
as discussed in Kronberg et al. [2008] this reconfiguration event is an event where a sig-
significant magnetic pressure increase was observed prior to the onset of the disturbance which might indicate that this event is solar wind driven. However, the event is part of a sequence of events occurring with the characteristic repetition period of the Jovian reconfiguration process and this specific event does not change the overall periodic intrinsic dynamics, therefore it seems that the internal cause prevails also for this event.

This example demonstrates the context in which the burst events and plasmoids occur. Further we will make statistics on these burst events. Particularly the third particle burst associated with the prominent bipolar signature is a typical example of the plasmoid events which we will investigate further in Section 4.2.

4. Reconfiguration process - features in details

In this section we focus on the particle bursts and in particular with bipolar magnetic field disturbances as the most prominent features of those processes. We compare them (where applicable) with well known features of terrestrial substorms.

4.1. Characteristics of ion burst events

Each reconfiguration and substorm-like event consists of a series of radially outward and/or radially inward ion burst events. In the set of the substorm-like events from Kronberg et al. [2005] 48 radially inward and 61 radially outward bursts were identified. We deduced the general magnetic field variations during these burst events.

In the terrestrial magnetosphere fast tailward plasma sheet flows are often correlated with southward meridional magnetic field component. Such flows supply evidence that a neutral line forming earthward of the observational point [Hones, 1979; Angelopoulos et al., 1994]. At Jupiter the magnetic field has the opposite direction as at Earth. We
therefore expect tailward (planetward) flows when the meridional magnetic field component directed northward (southward), respectively. The study of the correlation between the flow direction and the $B_\theta$ shows that all flows obey to this rule (we excluded the flows associated with the bipolar signature in the meridional magnetic field component, which were interpreted as plasmoids from this study. The physical interpretation is shown in Figure 2. Therefore these flows can be related to the flows along the field lines between the edge of the plasma sheet and the magnetic field separatrix mapping to the neutral line, forming a "separatrix layer" as discussed by Richardson et al. [1987].

Figure 3 displays the occurrence rate of the particle burst events versus the event duration. The average duration of the radially inward events is $1.0 \pm 0.7$ hours and $1.8 \pm 1.3$ hours for the outward events. The occurrence rate of radially inward burst events maximizes at the shortest duration interval, $\leq 30$ min (although we can resolve a minimum duration interval of 11 min, for a statistics we binned all events with 30 min intervals) and drops rapidly towards longer duration whereas the outward burst show a much broader distribution. The most likely interpretation is that the outward mass-release process takes longer than the radially inward transport of emptied flux tubes.

The radially outward and inward ion bursts selected from the anisotropy data were detected at the dawn region (see distribution in [Kronberg et al., 2005]) and at all latitudes. They were observed when the spacecraft passed the lobe region, then the plasma lobe boundary layers, (when $B_r$ starts to decrease from the approximately constant value), see PSBL label in Figure 1, the plasma sheet (the region between the PSBL and the current sheet center) and also during the crossing of the current sheet center.
The following study will concentrate on those ion burst events associated with plasmoid signatures in the magnetic field.

4.2. Characteristics of plasmoids

4.2.1. Definition of the plasmoids

The typical observational signatures of a plasmoid are defined by a bipolar magnetic deflection of the meridional direction $B_\theta$. This magnetic signature is usually associated with high-speed tailward directed energetic ion and electron beams [Zong et al., 2004]. Such a large tailward-moving loop-like magnetic structure is generated as the result of x-type reconnection in the near magnetotail [Hones, 1979]. The examination of the three dimensional topology and morphology of plasmoids in the Earth’s magnetotail showed that they contain a rather complicated configuration [Zong et al., 2004]: a helical flux rope (simple or embedded in a loop) or a travelling compression region.

The main signature of Jovian plasmoids also appears to be a bipolar deflection of the meridional component, similar as to Earth’s case [Russell et al., 1998]. However, a major difference occurs due to the fast rotation of Jupiter. The conservation of the angular momentum leads to predictable perturbations in the azimuthal component of the magnetic field as the magnetized plasma is convected either toward or away from Jupiter by reconnection.

In Figure 4 we present two examples for plasmoids. The first example represents the plasmoid denoted by yellow color in Figure 1. We show by the left vertical line the start of the plasmoid $\sim 11:27$, as an enhancement of the southward directed magnetic field component. The right vertical line denote the end of the plasmoid $\sim 12:01$, as the
northward directed magnetic field became zero. The further northward turning of the
meridional magnetic field component we consider as the post plasmoid plasma sheet.

Here we can see that the definition of plasmoids is not always robust. By two dashed
vertical lines we denote the other probable locations of the start signature of the plasmoid.
Therefore the error in the definition of the plasmoid duration and correspondingly the
velocity can be up to 30 %.

The second example in the same way as the first shows the start of the plasmoid at
\( \sim 09:16 \) (left vertical line), as an enhancement of the southward directed magnetic field
component. The end of the plasmoid we determined at \( \sim 10:00 \) (right vertical line), as
the meridional magnetic field component turned strongly southward. As in the previous
example the further northward turning of the meridional magnetic field component we
interpret as the post plasmoid plasma sheet.

4.2.2. Velocity of plasmoids

It is expected that the plasma confined in a plasmoid has the same speed for different
species, i.e., the macroscopic plasma flow velocity. To derive this flow velocity, ion burst
events associated with a strong bipolar signature in the \( B_\theta \) component of the magnetic field
were analysed. We limit our study to those events which have a field-aligned anisotropy
(the ion directional flow anisotropy component in the magnetic field direction) close to
zero. In these events the ion bulk motion is essentially perpendicular to the instantaneous
magnetic field direction. Most of the plasmoid signatures are observed in the plasma sheet
center (19 events) and in the plasma sheet (11 events), in the plasma sheet boundary layers
(3 events).
Figure 5 presents a comparison of the derived velocities for different ion species for such burst events in different plasma sheet regions: the current sheet center, the central plasma sheet and the plasma sheet boundary layers. The lobe region we excluded from the study. Obviously the flow burst events which satisfy the above conditions (a field-aligned anisotropy close to zero together with a strong bipolar signature) have approximately the same velocities for different ion species. The distribution of the velocities for the different species and different events line up with the solid line which corresponds to the same velocities for the different species (see Figure 5). Thus the ion velocities derived from the anisotropy measurements indeed correspond to bulk flows. There are some tendency for the velocity distributions of protons versus sulfur and oxygen versus sulfur that lighter ions are accelerated faster at the higher energies, starting approximately from 600 km s$^{-1}$. This is somewhat expected, as accelerated by the electric field heavy ion will have lower velocity as the lighter one.

In Figure 6 (top panel) we present the occurrence rate of the 33 plasmoids with respect to the ion bulk velocity measured in the plasmoid. The plot was constructed by binning the plasmoid velocities into 100 km s$^{-1}$ wide intervals. The range of velocities and the shape of the velocity distribution (the occurrence rate of the plasmoids versus the ion bulk velocity measured in the plasmoid) starting from 400 km s$^{-1}$ are very similar to the results found for high speed flows in the terrestrial plasma sheet [Baumjohann et al., 1990]. A typical plasmoid speed in the Jovian magnetosphere is in the range between 400 and 500 km s$^{-1}$ and the mean speed of the plasmoids together with statistical error are 461 ± 173 km s$^{-1}$ in the current sheet, 463 ± 142 km s$^{-1}$ in the plasma sheet. In comparison, the average local plasma speed in non-plasmoid intervals is about ∼ 250 km s$^{-1}$. The similarity of the
velocities in the current sheet center and the plasma sheet is because plasmoids propagate simultaneously in both regions and it is actually sometime difficult to define to which region belongs a plasmoid. In the plasma sheet boundary layers the bulk velocity is much higher, $887 \pm 142 \text{ km s}^{-1}$. Richardson et al. [1987] also reported more strongly streaming ions in the boundary layer at Earth. At Jupiter this region conducts the main plasma transport [Kronberg et al., 2005]. Probably we observe in this case imprinted signature of the plasmoid passing in the central plasma sheet but measure the velocity of the fast surrounding flows.

4.2.3. Duration and length of plasmoids

The distribution of the duration of plasmoids is presented in Figure 6. The figure was constructed by first determining the difference between the end time and start time of the plasmoids, i.e. end of the northward and start of the southward tilts of the magnetic field (as in [e.g. Ieda et al., 1998; Scholer et al., 1984] for the terrestrial case), and then by binning these events into 10-min-wide intervals. For this study the events with the most prominent bipolar signature were chosen. It is necessary to avoid the mixture of less prominent events with e.g. surface waves. The number of events included in this statistics is less than in the case of the velocity statistics because of the restricted availability of the high-resolution magnetic field data. The majority of plasmoid events lasts between 10 and 20 minutes. For comparison: the typical duration at Earth is $\sim 1.5$ min [Ieda et al., 1998].

The length of plasmoids (presented in Figure 6, bottom panel) has been calculated by multiplying the plasmoids downtail velocities over the plasmoid duration in each event
Most events have a length in the range between 5 and 10 $R_J$, with the mean plasmoid length being around $9 \pm 2.6 R_J$.

4.2.4. Alfvén Mach number of plasmoids

To compare the speed of plasmoids $V_p$ with the Alfvén speed $V_A$. The Alfvén Mach number $M_A$ can be estimated as follows [Goedbloed and Poedts, 2004]

$$M_A = \frac{V_p}{V_A}, \quad V_A = 2.18 \times 10^{16} \sqrt{\frac{Z A}{B}} \frac{B}{A \sqrt{n}}, \quad (1)$$

with $n(\equiv n_e \simeq Z n_i)$ where $n_e$ is the electron density, $n_i$ the ion density and $Z$ the ion charge number (multiples of e) and with $A$ the ion mass number (multiples of $m_p$) and $B$ the magnetic field. The values of the electron number density $n_e$ are derived from the cut-off frequency of the electromagnetic waves using Galileo PWS data. The values for the magnetic field $B$ are taken in the lobe region, the average ion mass number $A$ is assumed to the 16 (the mixture of protons, oxygen and sulfur) and the ion charge $Z = +2$ as the average value for the Jovian magnetotail (as it was established by Geiss et al. [1992] for the low energy ions). Figure 7 shows the Alfvén speeds for the individual plasmoids in the three plasma sheet regions. The error of the Mach number estimation is up to $\sim 35\%$ and that of the flow velocity $\sim 30\%$. In the figure it is visible that most plasmoids are close to Alfvénic flows ($M_A \simeq 1$). Only a few events, mainly in the current sheet center reach super-Alfvénic speeds. This result also confirms the similarity of the Jovian substorm-like process with the terrestrial ones where plasmoids are moving of Alfvénic speed [Baumjohann et al., 1990].

4.2.5. Convection electric field during the plasmoid release

Plasmoids move in the central plasma sheet with a dominant velocity ($V$) component perpendicular to the instantaneous magnetic field. They are characterized by a dipolariza-
tion of the central plasma sheet and are associated with strong electric fields $E = -V \times B$. The average electric potential in the central plasma sheet during the plasmoid release can be estimated as: $E = -(\sqrt{V_x^2 + V_y^2}) \cdot B_\theta$. Using 29 events we studied the change of the degree of dipolarization of the plasmoids in the vicinity (up to 30 $R_J$ distance) of the $x$-line. The result shows that the dipolarization of the plasmoids decreases with the distance from $\sim 5.1 \pm 3.9$ nT at about 85 $R_J$ and $\sim 3 \pm 1.1$ nT at about 115 $R_J$. The large variations of the dipolarization degree make the conclusions on the decrease of the dipolarization statistically insignificant. Also the velocity changes slightly with distance to the $x$-line. Therefore we will use the average values in order derive a rough estimation of the convection electric field associated with the reconnection events. Assuming an average ion bulk velocity of $\sim 500$ km s$^{-1}$ and an average $\Delta B_\theta$ of $\sim 4$ nT this results in an average convection electric field of $\sim 2 \pm 1.25$ mV m$^{-1}$. This average value is comparable to values for the reconfiguration events at Earth and is around one order of magnitude higher than the ambient Jovian value of the convection electric field which is $\sim 0.25 \pm 0.13$ mV m$^{-1}$ (here we took the ion bulk flow velocity $\sim 250$ km s$^{-1}$ [Krupp et al., 2001] and an average $B_\theta \sim 1$ nT).

4.2.6. Estimations for two examples of plasmoids

Here we will show the estimation of the characteristic quantities for two plasmoids presented in Figure 4. The average ion bulk velocities during the event on DOY 161 are 330 km s$^{-1}$ for the protons, 300 km s$^{-1}$ for the oxygen and 380 km s$^{-1}$ for the sulfur. Therefore the average speed of the plasmoid will be 335 km s$^{-1}$. The plasmoid speed is approximately the Alfvén speed in this region, $\sim 332$ km s$^{-1}$, (here we took the cut-off frequency of 1200 Hz and the radial magnetic field component in the lobe region 6 nT).
The duration of the plasmoid is 34 min, therefore the length will be about 9.7 $R_J$. The convection electric field consequently if we take $\Delta B_\theta \sim 5.5$ nT will be $\sim 1.7$ mV m$^{-1}$. If we would define the start of the plasmoid at $\sim 12:01$, then the duration will be 48 min, average ion bulk velocity will be 306 km s$^{-1}$ and therefore the length of the plasmoid 12.6 $R_J$.

For the event on DOY 270, the protons, oxygen and sulfur have the average ion bulk velocities 250 km s$^{-1}$, 350 km s$^{-1}$ and 250 km s$^{-1}$, respectively. The average ion bulk velocity of all ions will be 283 km s$^{-1}$. For comparison the Alfvén speed here is $\sim 204$ km s$^{-1}$, where we took the cut-off frequency of 1300 Hz and the radial magnetic field component in the lobe is 4 nT. The length of the plasmoid is $\sim 10.6$ $R_J$ at duration of 44 min and the convection electric field is 1.2 mV m$^{-1}$ at $\Delta B_\theta \sim 4.5$ nT.

5. Summary

We showed a typical example of the Jovian reconfiguration event which associated with the release of plasma in form of particle bursts and plasmoids.

The statistics of particle bursts shows that the inward bursts are shorter in duration than the outward bursts therefore the outward mass-release process takes longer than the radially inward transport of emptied flux tubes. The correlation of the tailward flows with the northward magnetic field component and the earthward flows with the southward magnetic field component supplies evidence of a neutral line configuration forming in the Jovian magnetotail. The reconnection process certainly affects the major part of the Jovian magnetotail as the radially outward and inward ion bursts were observed in the current sheet center, the plasma sheet boundary layers and the lobe region.
Most bursts associated with bipolar magnetic signatures have similar bulk velocities for different ion species. We interpret these events as plasmoids. A summary of the basic parameters as burst duration, plasmoid speed, plasmoid duration, plasmoid length and convection electric field for the Jovian substorm-like processes in comparison to the Earth’s substorms is presented in the Table 1. The relatively small scale of the plasmoids ($\sim 9 R_J$) in Jupiter’s magnetotail has to be compared with the large-scale topology favoring reconnection (x-line at $\sim 80 R_J$) that persists for up to several planetary rotations during the reconfiguration events. The basic quantities, however, such as the speed of the bursty bulk flows and the convection electric field are in the same range as at Earth. Another similarity is that the convection electric field during plasmoid release is about an order of magnitude higher than the ambient value of the Jovian convection electric field. The ion bulk velocity of the Jovian plasmoids is close to Alfvénic speed.

Therefore the mass release processes in basic quantities and features are very similar in both magnetospheres and supports the reconnection configuration.

References


Goedbloed, H., and S. Poedts (2004), *Principles of Magnetohydrodynamics*, 587 pp., Cam-
bridge.


Richardson, I. G., S. W. H. Cowley, E. W. Hones, and S. J. Bame (1987), Plasmoid-associated energetic ion bursts in the deep geomagnetic tail - Properties of plasmoids...


**Acknowledgments.** We thank B. Kurth for the providing us the PWS data.
Table 1. Characteristic quantities of Jovian substorm-like processes in comparison with Earth’s substorms. For the terrestrial case the values for the bursty bulk flows are taken from Angelopoulos et al. [1994]; the plasmoid speed, duration and length are from [Ieda et al., 1998].

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burst duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inward</td>
<td>(\sim 1 \text{ hour})</td>
<td>(\sim 10 \text{ min})</td>
</tr>
<tr>
<td>outward</td>
<td>1.8 hour</td>
<td>(\sim 370 \text{ s}^{-1})</td>
</tr>
<tr>
<td>Plasmoid speed</td>
<td>(\sim 350-500 \text{ km s}^{-1})</td>
<td>(\sim 400-700 \text{ km s}^{-1})</td>
</tr>
<tr>
<td>Plasmoid duration</td>
<td>(\sim 10-20 \text{ min})</td>
<td>(\sim 1.5 \text{ min})</td>
</tr>
<tr>
<td>Plasmoid length</td>
<td>(\sim 9 R_J)</td>
<td>10 (R_E)</td>
</tr>
<tr>
<td>Convection electric field</td>
<td>(\sim 1-2 \text{ mV m}^{-1})</td>
<td>(\sim 2 \text{ mV m}^{-1})</td>
</tr>
</tbody>
</table>
Figure 1. Energetic particle and magnetic field observations on Galileo orbit G8 from DOY 159, 00:00 to DOY 163, 00:00 in 1997. 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 positive in the direction of Jupiter’s rotation, the south-north component positive southward) and its magnitude (sixth panel); continuous vertical lines outline “quiet”, pre-disturbed and disturbed periods. Yellow color indicates the plasmoid event. CSC is the current sheet center and PSBL is the plasma sheet boundary layer.

Figure 2. A sketch of the magnetic field configuration close to the x-point. The direction of the $B_\theta$ component jupiterward from the x-point is southward and in the tailward direction is northward.

Figure 3. Occurrence rate of the flow burst events versus event duration. Black bars show the total number of the burst events (outward, inward) and grey bars present the amount of radially outward directed events. The plot was constructed by binning the data into 30 min intervals.

Figure 4. Energetic particle and magnetic field observations on Galileo: orbit G8 DOY 161, from 10:43 to 13:23 in 1997 (left) and orbit G2 DOY 279, from 02:14 to 15:44 in 1996 (right). From top to bottom are displayed: first order ion anisotropies in the radial (black, positive is outward) and corotational direction (grey), scale from the left; and as star, plus and cycle symbols are denoted the average ion bulk velocities of the oxygen, protons and sulfur, scale from the right (first panel); the magnetic field components (second to fourth panels) in SIII coordinates and its magnitude (fifth panel); continuous vertical lines outline the start and the end of the plasmoids. Two dashed vertical lines show the other possibilities to define the start of the plasmoid.
Figure 5. Velocity distribution for plasmoid events. S, O and protons plotted versus each other in the different regions of the magnetotail, i.e. the current sheet center, the plasma sheet and the plasma sheet boundary layers regions (33 events). The speed for different species is almost the same, which means that the corresponding events have a bulk plasma flow.

Figure 6. The occurrence rate of plasmoids versus the ion bulk velocity measured in the plasmoid, 33 events (first panel); the occurrence rate of plasmoids versus the duration of the events, 23 events (second panel); and the occurrence rates of plasmoids versus the length of the events, where the panel was constructed by binning these events into 5-$R_J$-wide intervals, 23 events.

Figure 7. Alfvén Mach number $M_A = V_p/V_A$ of plasmoids in the three plasma sheet regions against the ion flow speed (14 events).
Quiet | Predisturbed | Disturbed | Quiet

Particle flux [cm⁻²s⁻¹(KeV)⁻¹]

Anisotropy 65-120 keV [°]

Magnetic Field [nT]

UT, JSE, [R_Jup], Loc. Time