Jovian plasma sheet morphology: particle and field observations by the Galileo spacecraft

L.S. Waldrop\textsuperscript{a,*,1}, T.A. Fritz\textsuperscript{b}, M.G. Kivelson\textsuperscript{c}, K. Khurana\textsuperscript{c}, N. Krupp\textsuperscript{d}, A. Lagg\textsuperscript{d}

\textsuperscript{a}Coordinated Science Laboratory, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 1308 West Main Street, Urbana, IL 61801, USA

\textsuperscript{b}Department of Astronomy and Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA

\textsuperscript{c}Institute of Geophysics and Planetary Physics, University of California at Los Angeles, 6843 Slichter Hall, Los Angeles, CA 90095, USA

\textsuperscript{d}Max Planck Institute for Aeronomy, Max Planck—Str. 2, D37191 Katlenburg-Lindau, Germany

Received 7 October 2002; received in revised form 16 November 2004; accepted 17 November 2004

Available online 8 February 2005

Abstract

We present results from an investigation of the plasma sheet encounter signatures observed in the Jovian magnetosphere by the Energetic Particles Detector (EPD) and Magnetometer (MAG) onboard the Galileo spacecraft. Maxima in ion flux were used to identify over 500 spacecraft encounters with the plasma sheet between radial distances from Jupiter from 20 to 140\textit{R}_J during the first 25 orbits (4 years of data). Typical signatures of plasma sheet encounters show a characteristic periodicity of either 5 or 10 hours that is attributed to an oscillation in the relative distance between the spacecraft and the plasma sheet that arises from the combination of planetary rotation and offset magnetic and rotational axes. However, the energetic particle and field data also display much variability, including instances of intense fluxes having little to no periodicity that persist for several Jovian rotation periods. Abrupt changes in the mean distance between the plasma sheet and the spacecraft are suggested to account for some of the transitions between typical flux periodicities associated with plasma sheet encounters. Additional changes in the plasma sheet thickness and/or amplitude of the plasma sheet displacement from the location of the spacecraft are required to explain the cases where the periodicity breaks down but fluxes remain high. These changes in plasma sheet characteristics do not display an obvious periodicity; however, the observations suggest that dawn/dusk asymmetries in both the structure of the plasma sheet and the frequency of anomalous plasma sheet encounters are present. Evidence of a thin, well-ordered plasma sheet is found out to 110\textit{R}_J in the dawn and midnight local time sectors, while the dusk magnetosphere is characterized by a thicker, more disordered plasma sheet and has a potentially more pronounced response to an impulsive trigger. Temporal variations associated with changing solar wind conditions are suggested to account for the anomalous plasma sheet encounters there.

\textcopyright 2004 Elsevier Ltd. All rights reserved.

Keywords: Jovian magnetosphere; Plasma sheet configuration; Magnetoospheric structure and dynamics

1. Introduction

A dominant signature in the particle and field observations made by all of the Jupiter flyby missions is the 10-hour periodicity associated with the planet’s rotation. This periodicity has long been interpreted as evidence for the confinement of energetic plasma into a thin disk near the magnetic equator, known as the magnetodisk or plasma sheet, which separates two regions of nearly radial but anti-parallel magnetic field known as the magnetic lobes. The plasma sheet forms between 10 and 20\textit{R}_J and extends far into the distant magnetotail. To a spacecraft located near the rotational equator, the sheet flaps up and down every Jovian rotation due to the 9.6° offset between the spin and magnetic axes. The periodic encounters with the plasma...
sheet are characterized by enhancements in the energetic particle intensities and a reversal of the magnetic field direction through the current sheet, while the magnetic lobes are associated with a plateau in magnetic field strength and a decrease in magnetic fluctuations. Though the nature of the flapping is not well understood, the observed periodicity in both current sheet and plasma sheet boundary crossings, or equivalently, the organization of the sheet encounters with respect to longitude $\lambda_{III}$ in System III (SIII) coordinates, has been used to infer the configuration of the sheet (Carbary, 1980; Goertz, 1981; Khurana and Kivelson, 1989; Khurana, 1992). Previous studies of its configuration indicate that magnetic perturbations propagate outward from the jovigraphic equator as a surface wave (Northrop et al., 1974; Eviatar and Ershkovich, 1976; Kivelson et al., 1978) which may be modified by hinging beyond a certain distance due to solar wind dynamic pressure (Goertz, 1981; Behannon et al., 1981; Khurana and Kivelson, 1989; Khurana, 1992).

While the 10-h periodicity has been well documented, variations in the pattern of oscillations of particle intensities have also been reported (Vasyliunas et al., 1997). Changes in the oscillation pattern from having one maximum per planetary rotation to having two maxima can be attributed to changes in spacecraft latitude in some cases. However, data from the Galileo Plasma Analyzer (PLS) (Frank et al., 1992) indicate that other transitions between one- and two-crossing intervals are unrelated to the position of Galileo in its orbit (Vasyliunas et al., 1997). These changes therefore are likely to represent temporal variations in the mean displacement of the plasma sheet, its surface wave amplitude, or its thickness.

The extended duration of the Galileo mission also provides the opportunity to investigate global dynamics and long-term periodicities superimposed over the characteristic 10-h oscillation. Studies have revealed a 3–5 day quasi-periodic modulation associated with the amplitude of energetic particle intensities (Woch et al., 1998) and burst-like signatures in energetic particle intensities and radial anisotropies (Krupp et al., 1998) that are simultaneous with intensifications of auroral radio emissions and excursions from the plasma sheet environment as determined using the continuum radiation cutoff frequency (Louarn et al., 1998). Vasyliunas et al. (1997) also reported variations in the intensities of $\sim$keV electrons at a slightly longer period of 5–7 days. These observations suggest that the Jovian magnetotail is subject to large-scale reconfigurations at a 3–5 day frequency that is indicative of an intrinsic time constant of the Jovian system. The dynamic reconfigurations have been interpreted as transitions between two states: one characterized by a thick plasma sheet having high particle intensities and corotating plasma (most common) and the other with lower particle intensities, a much thinner magnetodisk, and a plasma flow pattern stretched downstream (corresponding to the periodic particle burst periods) (Woch et al., 1998, 1999; Krupp et al., 1998).

In this paper, we report on Galileo Energetic Particles Detector (EPD) and Magnetometer (MAG) observations of variations in plasma sheet characteristics, particularly its thickness and/or oscillation amplitude, using data obtained beyond 20 $R_J$ during the first 25 orbits of Galileo’s extensive and systematic survey of the Jovian magnetotail. The paper is organized as follows: Section 2 describes the Galileo EPD and MAG instrument characteristics. In Section 3, we present signatures of typical plasma sheet encounters as well as potential observational evidence for temporal variation in the plasma sheet geometry. A discussion of the observations is given in Section 4.

2. Instrumentation and data analysis

The EPD (Williams et al., 1992) onboard the Galileo spacecraft consists of two bi-directional solid state detector telescopes. The Composition Measurement System (CMS) employs a time-of-flight telescope on one end to provide elemental energy spectra above 10 keV/nucl for helium through iron, and a typical $\Delta E$ versus $E$ telescope on the other end to measure ion composition for energies greater than 200 keV/nucl. The Low Energy Magnetospheric Measurement System (LEMMS) consists of two detector heads and uses magnetic deflection to separate electrons from ions, providing energy spectra ranging from 15 keV to 11 MeV for electrons and 20 keV to 55 MeV for ions in 32 rate channels. Both the CMS and the LEMMS telescopes are mounted on a platform which rotates through 228$^\circ$ stopping at eight viewing positions. During the intervals considered in this study, the EPD instrument was in a low-resolution scanning mode. Sampling during each spacecraft rotation was resolved into four sectors, and data from several sectors were binned to ensure approximately equal angular resolution. Thus, 16 different directions ($\theta, \phi$) in three dimensions have been defined, and a full set of data points is obtained in approximately 11.5 min for most of the data set.

Measurements of the vector magnetic field were made by the MAG onboard Galileo (Kivelson et al., 1992) and are presented here with 24 s resolution. The instrument consists of two sets of ring core triaxial fluxgate sensors mounted on a boom. Each set is composed of three orthogonal sensors, one which is aligned close to the spin axis of the satellite and two which lie in the spacecraft spin plane.
3. Observations

EPD observations of energetic ions beyond 20$R_J$ were used together with MAG observations of the magnetic field configuration to determine the characteristics of the Jovian plasma sheet. Data from seven of the eleven primary orbits (G1, G2, E6, G7, G8, C9, and C10) and from five of the extended Europa mission orbits (E16, E18, C20, C23, and I24) are available. During these intervals, the spacecraft ranged from 20:30 to 04:45 in local time, $\pm 6R_J$ off of the Jovian rotational equatorial plane, and extended 142$R_J$ into the local midnight tail region; however, Galileo spent most of this time in the distant ($>70R_J$) magnetotail between the post-midnight and pre-dawn sectors. During most of the period investigated, the distinct 10-h period in counting rate maxima associated with Jupiter’s rotation was observed simultaneously (to within instrument resolution) for all energetic particle channels studied. By interpreting these maxima as spacecraft encounters with the plasma sheet, over 500 plasma sheet crossings can be identified, ranging over all local times and radial distances sampled beyond 30$R_J$.

The oscillation pattern in the count rates associated with plasma sheet encounters frequently varied from having a maximum every 5 h to a single- or double-peaked maximum every 10 h. The EPD also observed periods of high energetic particle counts with little or no periodicity for long durations ($>3$–4 jovian rotation periods). It is this last type of signature that will be presented in the most detail in this paper. Particle counts for three total ion channels (42–65, 65–120, and 120–280 keV) and magnetic field measurements will be presented for this type of flux signature, as well as for examples of the three typical oscillation patterns observed by the EPD for comparison.

3.1. Five-hour periodicity

Fig. 1 presents a typical example of particle and field signatures of encounters with the Jovian plasma sheet occurring twice every Jovian rotation. In this example, the signature persists for more than 7 days as Galileo traverses inbound from 69 to 31$R_J$ on the E6 orbit (~04:00 local time) but maintains a near constant distance between 2.66 and 1.95$R_J$ above Jupiter’s rotational equator. Panel A displays omni-directional (spin-averaged) counting rates of 42–65 keV total ions as a function of both System III longitude ($l_{III}$) and UT time in a spectrogram-type format. So that the spacecraft encounters with the plasma sheet are more apparent in the spectrogram, counting rates in each $l_{III}$ bin during each 9 h 55 m rotation period are divided by the maximum rate in that cycle; thus, light areas delineate the longitude of plasma sheet encounters as a function of time, while the dark gray intervals correspond to the low density region that surrounds the plasma sheet. Black areas represent data gaps. For completeness, Panel B gives the normalization factor (in counts/second) used to generate the spectrogram in Panel A. Panels C–E show 24 h of the data plotted in Panels A and B, expanded for clarity. UT time, radial distance from Jupiter in $R_J$, and local time are listed along the bottom of the figure for reference. This signature occurs during the inbound E6 orbit in the predawn sector between 69 and 31$R_J$ from the planet.
encounters separated by a System III longitude of $\Delta\lambda_{III} \approx 180^\circ$. As expected, ion flux maxima closely correspond to minima in the magnetic field. The fluxes also display very sharp onsets and dropoffs, indicative of either a thin or fast moving sheet. Panel D displays the characteristic reversal of the radial component of the magnetic field during plasma sheet encounters. The nearly square wave pattern around the $B_r = 0$ axis as well as the organization of the plasma sheet encounters in System III longitude indicates that the periodic displacement of the plasma sheet with respect to the spacecraft is symmetric around the location of the spacecraft throughout this interval.

Another common feature in the Galileo data set is a small ($\approx 30\%$) decrease in magnetic field strength that typically occurs between the plateaus and reversals in magnetic field (i.e., near the edge of the plasma sheet). These small decreases in magnetic field strength are coincident with increases in particle flux. Examples of this feature can be seen at 07:15 UT and 13:00 UT on DOY 086 in Fig. 1. The diamagnetic effect of the energetic particles depresses the field strength, and this feature in the data could be a signature of a spacecraft encounter with a detached filamentary structure or a rapidly flapping plasma sheet.

### 3.2. Ten-hour periodicity (single maximum)

Fig. 2 presents an example of a signature for a typical encounter with the plasma sheet occurring once every 10 h. During this period, the spacecraft ranges from 38.4 to 73.1 $R_J$ from Jupiter outbound on the G2 orbit (near midnight local time), and its distance from the Jovian rotational equator remains fairly steady, decreasing from $-1.3$ to $-1.0 R_J$. The spectrogram in Panel A indicates a transition between plasma sheet encounters separated by $\Delta\lambda_{III}\approx 180^\circ$ and single encounters occurring over a broad range of magnetic longitudes. This evolution from one crossing type to another occurs in less than 2 Jovian rotation periods and lasts for $\approx 6$ Jovian rotations ($\approx 2.5$ days). Panels C–E present 24 h of the single plasma sheet encounter signature in detail. Flux maxima that occur once per planetary rotation are often much more broad than those having 5-h periodicity, as seen in Panel C. The maxima in the counting rates display much variability superimposed over the 10-h periodicity, which again may be accounted for by multiple encounters with a flapping plasma sheet. The magnetic field strength (in Panels D–E) plateaus during intervals of low particle counting rate, consistent with a spacecraft excursion into the southern magnetic lobe (where $B_r < 0$), and field direction reversals indicate that the spacecraft periodically crosses the neutral sheet and enters the northern magnetic hemisphere as well. However, depressed and fluctuating field strength, as well as high energetic particle counting rates, indicate that the spacecraft does not exit the plasma sheet and enter the magnetic lobe in this hemisphere. This asymmetric sampling of the magnetic lobes implies that the mean location of the periodic displacement of the plasma sheet with respect to the spacecraft is northward of the spacecraft itself.

![Fig. 2. Plasma parameters for typical plasma sheet encounters occurring once every 10 h. Format follows Fig. 1. This signature occurs during the outbound G2 orbit in the predawn sector between 38 and 73$R_J$ from the planet.](image)

![Fig. 3. Plasma parameters for typical plasma sheet encounters having a double peaked signature every 10 h. Format follows Fig. 1. This signature occurs during the inbound C10 orbit in the predawn sector between 81 and 70$R_J$ from the planet.](image)
3.3. Ten-hour periodicity (double peaked maximum)

Fig. 3 displays an example of plasma sheet encounter signatures having two closely separated flux maxima every 10 h. This example is taken from the inbound C10 orbit (~01:00 local time), as Galileo ranges from ~81 to 70R_J from the planet and maintains at a constant distance of 2.3R_J above the rotational equator. In Panels C–E, 24 h of this signature are displayed. As in the previous example, low particle count rates coincide with a plateau in magnetic field strength and a decrease in magnetic fluctuations, consistent with a spacecraft excursion into the southern magnetic lobe. Also, magnetic field reversals indicate that the spacecraft crosses the neutral sheet periodically twice every planetary rotation period. However, in the northern hemisphere (B_r > 0), the decrease in particle flux is less pronounced than that in the southern lobe region, and despite magnetic field strengths in this region comparable to those in the opposite hemisphere, magnetic fluctuations remain present throughout the entire B_r > 0 interval. These signatures again are consistent with an asymmetric sampling of the southern and northern magnetic lobes, suggesting a northward mean displacement of the plasma sheet with respect to the spacecraft.

Furthermore, the largest magnetic fluctuations, including one on DOY 300 near 23:00 UT when Galileo was located in the southern magnetic hemisphere, coincide with enhancements of energetic particle counting rates superimposed over the 10-h variation. These particle and field signatures again are indicative of multiple encounters with the sheet or a filamentary structure of plasma that induces diamagnetic field strength depressions.

3.4. No periodicity

Another type of plasma sheet encounter signature observed by EPD is that of high fluxes having little or no periodicity for several Jovian rotations. Figs. 4–6 present three examples of this signature, which will be referred to as Examples A, B, and C, respectively.

Example A is observed between 1997 DOY 132 12:00 UT and DOY 136 06:00 UT, when the satellite is located at approximately 23:00 local time and traverses from 31 to 68R_J from Jupiter at 1.2R_J below the rotational equator on the G8 orbit. Panel 4A indicates that Galileo is near the center of the oscillation of the plasma sheet displacement (encounters are initially separated by ΔLIII ~180°), until a sharp decrease in ion flux at DOY 132 13:30 UT disrupts the organization of the data in SIII coordinates. Within 2 Jovian rotation periods of the dropout, the particle flux loses its dependence on magnetic longitude and remains at values associated with the center of the plasma sheet for up to 6 Jovian rotations (~2.5 days).

Fig. 4. Plasma parameters for Example A of an EPD signature of intense particle flux having little or no periodicity. Format follows Fig. 1. In this example, uniformly high count rates are associated with an oscillating magnetic field and depressed field strengths. This example occurs while Galileo was outbound on the G8 orbit near local midnight and ~40–60R_J from Jupiter.

Fig. 5. Plasma parameters for Example B of an EPD signature of intense particle flux having little or no periodicity. Format follows Fig. 1. Particle fluxes increase to high values for several days after a sharp dropout in the flux near 08:00 UT on DOY 229. The magnetic field during this time is highly disordered and prior to a return to quiet conditions, it becomes almost mono-directional for ~2 days. This example occurs on the inbound G1 orbit near local pre-dawn and ~120–100R_J from the planet.

Panels 4C–E show a 6-day interval spanning this transition and subsequent anomalous encounter signature in detail. The magnetic field data (Panel D)
crossing of the neutral sheet by the spacecraft. The magnetic field direction suggestive of the periodic particle counting rates despite the continued oscillation loss of the 5-h periodicity characterizing the initial around DOY 133 at 06:15 UT, is accompanied by a symmetric oscillation which is maintained throughout for 3 Jovian rotations before returning to a more

displacement of the plasma sheet with respect to the spacecraft persists 12:00 UT (DOY 133). This change in the average plasma component of the magnetic field (Panel D) 00:00 and plasma sheet is best seen as an asymmetry in the radial component, and that the particle flux dropout is preceded by an interval of enhanced magnetic fluctuations that lasts for ~1.5 Jovian rotation periods. The dropout itself occurs as the spacecraft is located in the southern hemisphere, though not far enough from the center of the plasma sheet into the magnetic lobe that magnetic fluctuations subside. Magnetic field signatures of subsequent crossings of the neutral/plasma sheet indicate that following the flux dropout, the mean displacement of the plasma sheet with respect to the spacecraft moves below the spacecraft on a timescale ~6 h. Evidence for this sudden reconfiguration of the plasma sheet is best seen as an asymmetry in the radial component of the magnetic field (Panel D) 00:00 and 12:00 UT (DOY 133). This change in the average plasma sheet displacement with respect to the spacecraft persists for 3 Jovian rotations before returning to a more symmetric oscillation which is maintained throughout the remaining duration of the interval.

However, this return to symmetry, which occurs around DOY 133 at 06:15 UT, is accompanied by a loss of the 5-h periodicity characterizing the initial particle counting rates despite the continued oscillation of the magnetic field direction suggestive of the periodic crossing of the neutral sheet by the spacecraft. The magnitude of the particle flux itself is consistent with values up to and beyond 90–100% of those associated with the center of the plasma sheet, while Panel E shows that the oscillation amplitude of the magnetic field components during the period of high flux is significantly less than their amplitude during the periodic plasma sheet encounters in the hours before this signature was seen. The particle fluxes gradually decay over ~2.5 days, more than 6 Jovian rotation periods, until both the particle and field signatures return to typical behavior and display the characteristic periodicity associated with planetary rotation.

Fig. 5 shows Example B of this type of energetic particle signature. During this interval, the spacecraft is located in the pre-dawn region (~4:15 local time), moving inbound from 114 to 105 R_J on the G1 orbit between ~4.6 R_J from the rotational equator. The organization of the particle counting rate maxima in System III longitude (Panel A) indicates that the spacecraft initially is offset from the mean displacement of the plasma sheet since one broad flux maximum occurs every 10 h for the first day of data shown in the figure. Asymmetries in the radial field component in Panel D indicate that the mean plasma sheet displacement is offset above the location of the spacecraft, an observation that is consistent with the spacecraft’s location significantly below the rotational equator.

Near 12:00 UT on DOY 227, the periodicity in both the particle flux and magnetic field direction breaks down, fluxes increase to values associated with the center of the plasma sheet, and the B_y component of the magnetic field increases significantly, as shown in Panel D. The magnetic field is highly disordered and reverses direction on time scales much smaller than the typical planetary rotation period throughout this interval, which lasts until DOY 232 ~00:00 UT. During this time, a dropout in the particle flux occurs near 12:00 UT on DOY 229, though following the flux dropout, the particle intensities return to high values and display little periodicity. After DOY 232, the flux exhibits a 10-h oscillation pattern superimposed on a gradual decay, while the magnetic field direction becomes nearly constant, corresponding to the nominal field direction of the southern magnetic hemisphere. During this interval of more than 40 h, the spacecraft neither crosses the neutral sheet into the northern magnetic hemisphere nor exits the plasma sheet into the southern magnetic lobe. By DOY 235, the plasma sheet encounter signatures become typical once again, with one plasma sheet encounter occurring every 10 h.

Example C is shown in Fig. 6. This signature occurs during the C10 orbit (00:30 local time), while Galileo is near apojove at ~85–91 R_J from Jupiter and ~2.25 R_J above the rotational equator. Fairly typical 10-h periodicities are seen in the EPD measurements before DOY 285, centered on λ_{III} ~180°, and the magnetic field

![Figure 6](image-url)

Fig. 6. Plasma parameters for Example C of an EPD signature of intense particle flux having little or no periodicity. Format follows Fig. 1. Asymmetries in the magnetic field indicate that the mean location of the plasma sheet with respect to the spacecraft is displaced southward before the magnetic field becomes highly variable and the ion flux loses its characteristic 10-h periodicity for more than 2 Jovian rotations. When the plasma signatures return to normal, the plasma sheet has been displaced northwards of the satellite. This example occurred near apojove of the C10 orbit, near local midnight and ~99 R_J from Jupiter.
signatures indicate that the spacecraft is located above the center of oscillation of the plasma sheet displacement and encounters only the northern magnetic lobe. At 15:00 (DOY 285), the spacecraft makes a final normal encounter with the plasma sheet, moving from the northern magnetic hemisphere to the southern, yet instead of exiting the plasma sheet into the southern lobe, the particle and field data indicate that it re-enters the northern hemisphere where $B_r$ is positive (see Panel D). From DOY 285 at 17:00 UT to DOY 286 at 20:00 UT (21 h), ion counting rates (Panel C) remain high and do not display the periodicity associated with Jupiter’s rotation. During this time, the magnetic field is highly irregular, particularly the azimuthal component, which displays a large increase in variability comparable to the variability shown during earlier plasma sheet encounters. Particle fluxes and magnetic fluctuations return to values associated with the lobes at DOY 286 21:00, after which time both the particle and field data display the 10-h periodicity signatures of encounters with the plasma sheet that has its center of oscillation displaced southwards from the satellite, now near $\lambda_{HI} \sim 90^\circ$ as seen in Panel A.

These three examples of EPD signatures having little or no periodicity for extended durations each show unique magnetic field signatures. It is difficult to establish observational characteristics that apply to every example, even when all cases observed by the EPD are considered, and no two cases are exactly alike. Table 1 summarizes the EPD observations of this kind of plasma sheet encounter signature, giving the orbit, duration, and radial distance and local time ranges for each event. The duration of the signatures is commonly 3 or 4 rotation periods, although some last up to 20–25 Jupiter rotations (7–10 days). Furthermore, the magnetic field signatures of some of the events are similar to the three examples presented in the text. For those that apply, a general classification of the magnetic field configuration during the event are given in the table. A classification of “A” corresponds to a magnetic field that is depressed during the event, but continues to oscillate indicating that the spacecraft crosses the neutral sheet (as seen in Example A) but not the plasma sheet/lobe boundary. Events that have magnetic field signatures similar to Example B, where the $B_y$ component is large and/or the radial component shows a constant value for several Jovian rotations would receive the classification of “B” (no other events apply). Finally, a classification of “C” corresponds to a transition of the center of oscillation of the plasma sheet displacement from above or below the spacecraft, as seen in Example C. The three events presented in the text are indicated with asterisks.

### 3.5. Spatial distribution of crossing types

Fig. 7 displays the spatial distribution of all energetic particle periodicity signatures that EPD observed. Organization of the signatures along the Galileo trajectory in Jupiter’s rotational equator is shown in the top panel, while organization with respect to the distance off of the rotational equator is shown in the bottom panel, in which the z-axis has been expanded for clarity. Intervals where EPD observed typical plasma sheet encounter signatures are indicated by varying shades of blue: the darkest shade corresponds to

<table>
<thead>
<tr>
<th>Orbit</th>
<th>UT Time</th>
<th>Radial distance (in $R_J$)</th>
<th>Local time</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1996 228(00:00)–234(00:00)</td>
<td>114.2–104.7</td>
<td>04:09–04:25</td>
<td>B*</td>
</tr>
<tr>
<td>G8</td>
<td>1997 133(00:00)–136(00:00)</td>
<td>46.4–63.1</td>
<td>22:45–23:33</td>
<td>A*</td>
</tr>
<tr>
<td>G8</td>
<td>1997 155(05:00)–156(12:00)</td>
<td>99.9–99.3</td>
<td>01:28–01:34</td>
<td>C</td>
</tr>
<tr>
<td>C9</td>
<td>1997 181(04:00)–182(12:00)</td>
<td>33.4–43.8</td>
<td>20:24–21:05</td>
<td>n/a (irregular)</td>
</tr>
<tr>
<td>C9</td>
<td>1997 189(15:00)–191(19:00)</td>
<td>84.9–94.0</td>
<td>22:42–22:56</td>
<td>n/a (irregular)</td>
</tr>
<tr>
<td>C9</td>
<td>1997 208(19:00)–209(21:30)</td>
<td>135.9–137.2</td>
<td>23:54–00:00</td>
<td>C</td>
</tr>
<tr>
<td>C9</td>
<td>1997 211(09:00)–213(01:30)</td>
<td>138.8–140.2</td>
<td>00:00–00:05</td>
<td>C</td>
</tr>
<tr>
<td>C10</td>
<td>1997 285(00:00)–287(12:00)</td>
<td>98.7–98.8</td>
<td>00:29–00:40</td>
<td>C*</td>
</tr>
<tr>
<td>E16</td>
<td>1998 232(15:00)–233(22:00)</td>
<td>123.7–124.2</td>
<td>23:42–23:48</td>
<td>n/a (limited data)</td>
</tr>
<tr>
<td>E16</td>
<td>1998 244(11:00)–245(03:00)</td>
<td>118.8–117.8</td>
<td>00:16–00:18</td>
<td>C</td>
</tr>
<tr>
<td>E18</td>
<td>1998 331(22:00)–337(00:00)</td>
<td>55.4–82.0</td>
<td>21:00–21:48</td>
<td>A</td>
</tr>
<tr>
<td>E18</td>
<td>1998 340(00:00)–345(06:00)</td>
<td>94.1–109.7</td>
<td>22:08–22:30</td>
<td>A</td>
</tr>
<tr>
<td>E18</td>
<td>1998 349(00:00)–352(00:00)</td>
<td>117.7–122.5</td>
<td>22:42–22:51</td>
<td>n/a (irregular)</td>
</tr>
<tr>
<td>E18</td>
<td>1998 353(00:00)–354(06:00)</td>
<td>123.7–125.0</td>
<td>22:54–22:57</td>
<td>n/a (irregular)</td>
</tr>
<tr>
<td>E18</td>
<td>1998 363(12:00)–365(00:00)</td>
<td>128.8–128.3</td>
<td>23:21–23:25</td>
<td>n/a (irregular)</td>
</tr>
<tr>
<td>C21</td>
<td>1999 129(11:00)–130(17:00)</td>
<td>56.0–63.1</td>
<td>19:41–19:57</td>
<td>C</td>
</tr>
<tr>
<td>C21</td>
<td>1999 133(00:00)–135(04:00)</td>
<td>74.6–82.2</td>
<td>20:19–20:34</td>
<td>n/a (irregular)</td>
</tr>
</tbody>
</table>

Spacecraft ephemeris information and the general classification of the magnetic field configuration during the event are given (see text for details). The three examples presented in the text are indicated with stars.
intervals of 10-h periodicity (single maximum), the intermediate shade represent intervals of double-peaked encounter signatures for which the time separating the two maxima ranges from 0 to 5 h, and the lightest shade of blue corresponds to intervals of 5-h periodicity. Plasma sheet encounter signatures having little or no periodicity for extended durations are represented by yellow, orange, red, green shades, with the different classifications marked separately as shown. The events depicted in Figs. 4–6 are marked on the diagram as A, B, and C. Intervals of erratic spacecraft encounters with the plasma sheet that neither qualify as events presented in Section 4 nor display typical 5 or 10-h oscillation are left blank, where only the spacecraft trajectory, plotted as a thin black line, is shown. Gaps in the spacecraft trajectory correspond to data gaps throughout the 4-year interval.

Asymmetries between the dawn and dusk local time sectors are apparent in the spatial distributions of both periodic plasma sheet encounter signatures as well as the instances when EPD encountered the plasma sheet for longer durations with little or no periodicity. Well-defined periodicity is observed beyond 110\(R_J\) and is more common in the dawn and midnight local time sectors than in the dusk sector, where a noticeable lack of identifiable periodicity prevails. Five-hour periodicity is more commonly observed at smaller radial distances from Jupiter, while double- and single-peaked 10-h periodic signatures are more frequent in the outer magnetosphere and at the largest distances off of the rotational equator. Sudden transitions on timescales less than a single planetary rotation between the plasma sheet encounter signatures of varying periodicity are also observed.

The spatial distribution of the atypical plasma sheet encounters having little to no periodicity also displays a distinct dawn/dusk asymmetry. Only one event, that corresponding to Example B, occurs in the predawn/dawn local time sector. Type C events, in which the center of oscillation of the plasma sheet displacement moves above or below the spacecraft, occur predominately in the local midnight sector, while the rest of the anomalous plasma sheet encounter signatures occur only in the region between local dusk and local midnight. Neither type A, type C, nor irregular type signatures (as classified in Table 1) show an obvious dependence on distance off the rotational equator.

4. Discussion

Clear evidence of a well-defined periodicity in the energetic particle and magnetic field signatures of Jovian plasma sheet encounters has been observed out to distances beyond \(\sim110R_J\) between the midnight and dawn local time sectors, but such clear periodicity is observed only within \(\sim45R_J\) in the dusk sector. The energetic particle signatures of encounters with the magnetodisc display much variability, often changing between two maxima every 10 h, either equally spaced every 5 h or closely spaced and double-peaked, and one broad maximum per rotation period.

Fig. 8 schematically shows the interpretation of these 5-, 10- and intermediate-hour periodicities as encounters with a plasma sheet of varying configuration or mean...
displacement from the location of the spacecraft. On the left are 24 h of omni-directional energy spectra for all ion channels. Each panel displays an example of plasma sheet crossing signatures observed by the EPD, and the separation between the maxima in a given 10-h period decreases from 5 h in the first panel (1) until the two flux peaks have merged into one broad maximum in the 10-h rotation period in the panel labeled (3). On the top right is a schematic, adapted from Vasyliunas et al. (1997), showing solid lines that correspond to the spacecraft trajectory through various latitudes of an idealized plasma sheet configuration that would give rise to the signatures in Panels (1)–(3) on the left. The decreasing separation between the two flux maxima in a given 10-h period is associated with an increase in the mean distance between the plasma sheet and the spacecraft itself. The 5-h periodicity signature in Panel (1) of Fig. 8 corresponds to a trajectory near the center of oscillation of the relative plasma sheet displacement, such that both sides of the plasma sheet are sampled symmetrically. If the sheet’s thickness is smaller than the amplitude of its periodic displacement, then the spacecraft will encounter both magnetic lobes, also symmetrically. The particle signature of a single flux maximum every 10 h (Panel 3) is interpreted as a mean plasma sheet displacement with respect to the spacecraft large enough that the spacecraft samples the plasma sheet asymmetrically and may or may not cross the neutral sheet and/or enter the opposite magnetic lobe before exiting the sheet again on the same side. For this last signature, if the spacecraft only encounters the plasma sheet/lobe boundary on one side of the sheet, the opposite boundary may have a configuration different from the schematic depiction in Fig. 8.

This association of changes in the observed plasma sheet encounter periodicity with changes in the average relative distance between the spacecraft and the plasma sheet is also supported by Vasyliunas et al. (1997). Such changes could be due to changes in the spacecraft trajectory itself, and this explanation is given for the Voyager observations of the disappearance of the two-maxima pattern between 80 and 100R_J (Vasyliunas et al., 1997). However, sudden transitions in EPD encounter signatures on timescales smaller than either a planetary rotation or the evolution of spacecraft trajectory, as seen in detail in Fig. 3 and more generally in Fig. 8, for example, imply that the average location of the plasma sheet may move by the spacecraft. The anomalous energetic particle signature reported in Example C is best interpreted as a sudden displacement.

Fig. 8. Schematic showing the interpretation of various plasma sheet encounter signatures as changes in sheet configuration and mean location with respect to the spacecraft. (at left) Examples of the types of signatures discussed in this paper displayed as omni-directional ion energy spectra. (at right) Schematic illustrating the effect of vertical displacement of the plasma sheet relative to the spacecraft trajectory. Labeled lines are spacecraft trajectories that would give rise to the signatures on the left. The top right illustrates signatures resulting from an encounter with a plasma sheet having an oscillation amplitude larger than its thickness, while the bottom right shows those resulting from a sheet having a greater thickness than oscillation amplitude. Adapted from Vasyliunas et al. (1997).
of the mean location of the plasma sheet from below to above the spacecraft, a transition which occurs in less than 28 h. Such displacements can occur suddenly, within a few planetary rotation periods, and the spatial distribution of these dynamical events indicates that they occur more often near local midnight beyond 80$R_J$. Similar dynamical signatures in plasma sheet configuration are also reported by Frank et al. (2002), who indicate that the inferred change in plasma sheet geometry may arise from a small change (~1%) in the direction of the incident solar wind. Fluctuations in solar wind ram pressure also could alter the mean position of the plasma sheet by changing its amount of bending towards the ecliptic plane (Vasyliunas et al., 1997). A periodicity in the transitions between the variations in plasma sheet crossing signatures of ~3–5 days duration and ~5–7 days recurrence of a particular signature type was reported by Vasyliunas et al. (1997) based on low-energy plasma observations of the G2 orbit. The authors interpreted these changes as having a temporal origin, and in at least one instance, only a change in the mean position of the plasma sheet can account for their observations.

Under this interpretation, the radial dependence of the distribution of periodic signatures shown in Fig. 7 indicates that at larger radial distances, the mean location of the relative plasma sheet displacement is more likely to lie farther from the location of the spacecraft. Such an interpretation suggests that the “quiet-time” Jovian plasma sheet is aligned with the magnetic dipole equator at small radial distances, where it flaps symmetrically twice every planetary rotation around the rotational equator. At larger radial distances, the mean location of the plasma sheet more often experiences displacements from the rotational equator, possibly indicative of a solar wind influence on its global configuration. However, the lack of identifiable periodicity in the dusk sector of the magnetosphere indicates that the plasma sheet is more disordered and irregular in that region and that axisymmetric models of plasma sheet configuration are not sufficient to describe its location in a global sense.

Thus, traversals through a plasma sheet whose distance from the spacecraft oscillates with an amplitude large relative to its thickness can explain many of the plasma sheet encounter signatures observed by Galileo, including the anomalous signatures typified by Example C. However, many of the other anomalous plasma sheet signatures listed in Table 1 require an additional change in the sheet thickness relative to the amplitude of oscillation. Such encounters are shown schematically in the bottom right of Fig. 8. If the spacecraft is displaced from the center of oscillation, the same signature shown in Panel (3) on the left could result; however, the signatures in Panels (1), (2a), and (2b) are not possible in this model configuration. Panel (4) on the left is an example of this anomalous flux signature. In this interpretation, this signature could arise in the EPD data only if the thickness of the plasma sheet is at least as large as the amplitude of its relative oscillation with respect to the spacecraft. The magnetic field could continue to oscillate as the neutral sheet flapped over the satellite, but the fluxes and overall field strength would correspond to that of a plasma sheet environment.

This interpretation does explain the overall morphology of several of the events seen by the EPD, including Example A, but does not fully account for the plasma signature observed in Example B. In this case, the magnetic field does not resemble that of a plasma sheet environment and therefore does not support the interpretation of an encounter with a plasma sheet having an inflated thickness relative to its oscillation amplitude. No other event observed by Galileo shares the same characteristics as this example and, unfortunately, the spacecraft does not sample this region of the magnetosphere again on subsequent orbits. As a result, distinguishing between a spatial or temporal origin of the signature is not possible. However, the existence of a boundary layer in this region between the plasma sheet and the dawn magnetopause has been reported based on similar Voyager and Pioneer observations of a breakdown in periodicity coincident with fairly steady particle intensity, radially outward plasma flows, and an irregular magnetic field configuration (Schardt and Goertz, 1981; Krimigis et al., 1981). It is possible that this unique event in the EPD data reflects an encounter with this boundary layer.

The increased frequency of anomalous encounters that are interpreted as a change in sheet thickness relative to its oscillating distance from the spacecraft, as well as the lack of identifiable periodicity in the more typical plasma sheet encounter signatures, suggest that Jupiter’s dusk magnetosphere is characterized on average by a thicker and more disordered plasma sheet. The erratic periodicity of encounters implies that this region is particularly sensitive to changes in the global magnetospheric configuration and responds with sudden changes in either plasma sheet thickness, amplitude of sheet motion with respect to the spacecraft, or its mean distance from the spacecraft. A survey of the magnetic field configuration throughout Jupiter’s magnetosphere indicates that the magnetic field curvature in the dusk sector is smaller than in the dawn, evidence which supports an enhancement in plasma sheet thickness in the dusk region (Kivelson and Khurana, 2002). These observations may be related to dawn/dusk asymmetries that have been observed with regard to many other magnetospheric parameters as well, including energetic ion anisotropies (Krupp et al., 2001) and global MHD model parameters (Ogino et al., 1998).

Table 1 indicates that type A and irregular type events, while more prevalent in the dusk sector, are not
associated with any clear periodicity. The lack of correlation with previously reported time scales indicate that these events are possibly not associated with the intrinsic time constant of the system and may arise from more impulsive origins. Two potential sources for impulsive control over plasma sheet configuration are the solar wind and volcanic activity on Io. Little is known regarding the modulation of plasma transport and hence plasma sheet thickness by the highly variable volcanic outbursts on Io, but such an effect remains an interesting possibility. More studied is the effect of solar wind pressure pulses on the Jovian system. Goertz (1981) attributed a change in the observed plasma sheet hinging distance from 40 to 60\(R_J\) during the Voyager 1 flyby to changes in the solar wind ram pressure. Such modulation of the hinging distance would certainly affect the amplitude of plasma sheet oscillation with respect to the rotational equator. Changes in solar wind pressure are expected to affect the plasma sheet thickness as well. Southwood and Kivelson (2001) investigated the theoretical effects of a solar wind pressure pulse and predicted that the plasma sheet thickness could increase up to 2.5 times its quiet-time value. Further observational evidence for the influence of solar wind pressure on the Jovian magnetosphere was obtained during the recent Cassini flyby of Jupiter. Simultaneous measurements by Galileo and Cassini showed that interplanetary shocks triggered major magnetospheric compression and large scale reconfiguration, likely influencing the thickness of the plasma sheet (Gurnett et al., 2002). It should be noted that, although a coordinate system associated with Jupiter's orbital rather than rotational motion would be more suited to an investigation of the potential role of the solar wind in triggering the events presented in this paper, the 3.13° offset between the two equatorial planes amounts to a 1% effect, which has a negligible influence over the dawn/dusk asymmetry observed.

A final consideration is that, if the anomalous events are truly associated with solar activity, the observed asymmetry may be attributed to the combination of the spacecraft orbit precession and the increase in solar activity throughout the 4 years of observations. When Galileo arrived at Jupiter in late 1995, solar activity was at a minimum, and as the orbital apoapses precessed towards the dusk sector, the solar activity increased as well, reaching a peak in early 2000 (Abdel-Hady, 2002). Thus the increase in event frequency in time may be due more to the increase in solar activity than to the delineation of a spatial asymmetry in the Jovian magnetosphere. However, given the clear asymmetries observed in “quiet-time” plasma sheet conditions between the dawn and dusk sectors, this interpretation is unlikely.

Regardless of the origin, which is at best speculative at this point, there seems to exist evidence for temporal variations in the plasma sheet configuration in the outer Jovian magnetosphere. This variation often can be interpreted as the sudden displacement of the mean position of the plasma sheet, but indications of enhancements in the sheet thickness relative to the amplitude of its oscillation with respect to the spacecraft are also observed. These enhancements are observed most often in the post-dusk local time sector of the magnetosphere, which is characterized on average by a thicker, more disordered plasma sheet.

Acknowledgments

This research was supported under Subcontract 825485 from the Johns Hopkins University Laboratory under prime NASA/JPL Contract No. 1214877. The authors gratefully acknowledge the careful evaluation of this manuscript by J. Woeh and another referee.

References


