Slow-mode shock candidate in the Jovian magnetosheath


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ABSTRACT

We discuss some interesting plasma observations in the Jovian magnetosheath by the onboard plasma instruments of the Cassini spacecraft during the 2000–2001 Jupiter flyby. We propose that the observations are consistent with a slow-mode shock transition. In the terrestrial magnetosheath, a number of observations have been made that are consistent with slow-mode waves or shocks. In addition, a number of observations have established that, at least occasionally, slow-mode structures form at the plasma sheet-lobe boundary in the terrestrial magnetotail, related to X lines associated with reconnection. There has been only one previously reported observation of a slow-mode shock-like transition in the Jovian plasma environment. This observation was made in the dayside magnetosheath. The observation we report here was made well downstream of the magnetosphere in Jupiter’s magnetosheath, at local time \( \sim 19:10 \). For our analysis we have used the data from the Cassini Plasma Spectrometer (CAPS) the Magnetospheric Imaging Instrument (MIMI) and the Magnetometer (MAG).

The bow shock crossings observed by Cassini ranged downstream to \( \sim 600 \) \( R_J \) from the planet & 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Planetary magnetosheaths, in general, and the terrestrial magnetosheath in particular are a rich source of wave modes and disturbances (see, e.g., Song and Russell, 1997 and references therein, and Siscoe et al., 2002). Dissipation across the bow shock increases the kinetic temperature of the inflowing solar wind plasma and scatters particle trajectories. Both these processes are sources of disturbances in the magnetosheath. In addition other frozen-in structures, for example interplanetary shocks or flux ropes carried in the solar wind (Eastwood et al., 2002) cause transient fluctuations on entering the magnetosheath region. After crossing the bow shock, the super-fast magneto-sonic solar wind is thermalized, the flow slows down and is diverted around the magnetosphere in the magnetosheath. Here there are systematic gradients in the field and plasma which cause magnetic field line draping and plasma compression prependicular to the field. Due to the high parallel velocity component relative to the shock front the flow may remain supersonic downstream as well. The magnetosheath flow has been described and discussed by, e.g., Southwood and Kivelson (1992), Song and Russell (1997) and Siscoe et al. (2002).

In the magnetohydrodynamic (MHD) approach to magne-tosheath plasma there are three propagating wave solutions of the linearized isotropic MHD equations. Different phase speeds belong to each wave mode (fast, intermediate, slow), therefore the obstacle will generate three wave modes in the MHD flow. Gas kinetic theory, or the simplified hydromagnetic theory, however, predicts only one standing wave front behind which the pressure variations are smooth as the gas flows around the obstacle, as in the early modelling by Spreiter et al. (1966). Some observations seem to contradict this latter statement of the gas kinetic approach, since there have been several reports of standing slow-mode structures in the magnetosheath (Crooker et al., 1979; Song et al., 1992). The formation of a plasma density depletion layer in front of the magnetopause was theoretically predicted by Zwan and Wolf (1976). In the vicinity of the sub-solar point of the magnetopause the magnetic field lines deflect around the nose of the magnetosphere as the plasma speed decreases, this causes perpendicular compression of the field. The pressure in the flow
the plasma beta is low and confirmed this theorem with hybrid simulations and concluded equal to the electron temperature. Hada and Kennel (1985) distribution is Maxwellian and the ion temperature is less than or such as the magnetosheath plasma – when the particle velocity tosheath is Landau damping. This occurs in high beta plasma – objection to the formation of slow-mode shocks in the magnetosheath. There have been no reported observations so far of slow-mode waves or shocks in the downstream magnetosheath of any of the planetary environments. At such distances downstream of the planet, the only slow-mode events observed were, as described above, associated in the magnetospheric tail with the plasma sheet-lobe boundary.

2. Instrumentation

In this study we used the measurements of the Cassini Plasma Spectrometer (CAPS) (Young et al., 2004) the Magnetospheric Imaging Instrument (MIMI) (Krimigis et al., 2004) and the Magnetometer (MAG) (Dougherty et al., 2004).

CAPS consists of 3 different plasma sensors, the Electron Spectrometer (ELS) (Linder et al., 1998), for electron plasma dynamics in the energy range 0.5 eV–28 keV; the Ion Mass Spectrometer (IMS) (McComas et al., 1998; Nordholt et al., 1998), for ion plasma dynamics and composition; and the Ion Beam Spectrometer (IBS) (Vilppola et al., 2001), for ion velocity distributions of narrow beam-like structures without mass separation in the energy range 1–50 keV). The ELS and IMS are mounted so that their fields-of-view are coplanar and coaxial as well. For our work the most important of the 3 plasma sensors of CAPS is the IBS, which is a high-resolution hemispherical section electrostatic analyser with 3 entrance apertures. Each aperture has an effective field-of-view (FOV) of 1.5 × 150° and the FOV of the central one is coplanar with the apertures of CAPS-ELS and CAPS-IMS. The apertures of CAPS-IBS are offset by 30° to create a triple “crossed-fan” array in order to achieve a 3-dimensional mapping of the incoming target ion distribution. However, during the Cassini Jupiter flyby this feature was not exploited because of the long integration time of the measurements. During the measurements CAPS-IBS collected the ions in 256 specially selected energy steps between ~95 and 200 eV with an energy resolution of ΔE/E=0.015. The CAPS instrument is set on a motor driven actuator, with a rotation axis parallel to the x-axis of the spacecraft so the instrument can perform a windshield-wiper like motion with a variable length interval in the ambient plasma flow. The central aperture of IBS looks towards the direction parallel with to y-axis of the spacecraft at zero actuator angle.

The Magnetospheric Imaging Instrument (MIMI) has three principal sensors, the Ion and Neutral Camera (INCA), the Charge Energy Mass Spectrometer (CHEMS) and the Low Energy Magnetospheric Imaging System (LEMMS). In this study we used the data of LEMMS, which is a two-end telescope to measure ions in the energy range 1–50 MeV and electrons between 15 keV and 1 MeV from the low energy end, while high-energy ions (1.6–160 MeV) and electrons (0.1–5 MeV) are detected from the high-energy end. LEMMS is designed to measure the three-dimensional distribution of high-energy ion and electron fluxes. The plane of measurement is the x–z plane in the spacecraft frame of reference. The sensor is mounted on a rotating platform, which completes a whole rotation during 86 s with a rotation axis parallel to the y-axis of Cassini. The platform was operational during the Jupiter encounter, however it stopped rotating later on February 2, 2005.

We also refer to the measurements of the Radio and Plasma Wave Science (RPWS) instrument (Blanc et al., 2002) in this work. The RPWS detects the electric and magnetic fields of plasma...
waves and radio signals. There is a Langmuir probe added to this experiment to measure the plasma density and temperature.

For the magnetic field we used 24 s resolution data from the MAG instrument in the RTN coordinate system. RTN coordinates are defined as follows: the \textbf{R} unit vector points from the Sun to the direction of the spacecraft, the \textbf{T} unit vector points to the \( \Omega \times \textbf{R} \) direction, where \( \Omega \) is parallel to the spin axis of the Sun and the \textbf{N} unit vector makes the right-hand system.

3. Analysis of slow-mode shocks

At a forward slow shock the basic requirements are that the magnetic field strength should decrease while the plasma velocity, density and temperature should show a steplike increase. At a reverse slow shock, the plasma velocity increases, while the magnetic field, as well as the plasma temperature and density should decrease. As we mentioned earlier observations of slow shocks either in the interplanetary medium or planetary plasma environments are very rare. The scarcity of observations has been explained theoretically by the relatively narrow variety of plasma conditions under which the slow-mode steepening rate would overcome the Landau damping (Baumjohann and Treumann, 1997). However rare, the occurrences of slow-mode shock detections make it reasonable to suppose that if the appropriate circumstances for the supporting plasma are fulfilled, the slow-mode steepening process can succeed in forming a propagating slow-mode shock front. The formation and steepening of the slow-mode wave are difficult to detect, due to the very likely transient nature of such a wave. Even if conditions for the slow mode are, statistically fulfilled, the occurrence, and even more so, the confirmed observation of the slow-mode wave shock tends to be fortuitous (see, e.g., Gloag, 2002).

The requirements for slow-mode shocks were summarized in the work of Seon et al., 1996. The restrictions for the phase speeds of the plasma flow upstream and downstream of a slow-mode shock are

\[
\frac{v_{\text{In}}}{c_{\text{Int}}} \leq 1, \quad \frac{v_{\text{In}}}{c_{\text{Sl}}} > 1 \quad \text{and} \quad \frac{v_{\text{Kn}}}{c_{\text{Sl}}} < 1 \quad (1. \ a, \ b, \ c)
\]

where \( c_{\text{out}} \) and \( c_{\text{in}} \) are the intermediate and slow-mode phase speeds in the medium, respectively, \( v_{\text{In}} \) is the normal and \( v_{\text{in}} \) the tangential component of the plasma flow speed and the subscripts 1 and 2 mark the upstream and downstream regions, respectively. If we consider perpendicular shock conditions then Eqs. [1.\ a, \ b, \ c] mean that the flow is sub-Alfvénic on both sides in the rest frame of the shock. Burlaga (1995) also mentioned the requirement that the magnetic field downstream should bend towards the shock normally.

The jump of the plasma parameters at the shock transition must obey the Rankine–Hugoniot relations (see for example in Tidman and Krall, 1971). Since for this case CAPS-IBS measured only the magnitude of the velocity, but not its vector components, we needed to make certain assumptions concerning the direction of the plasma flow in the region upstream of the slow-mode shock candidate as will be discussed later.

4. Observations and data analysis

During the Jupiter flyby in the beginning of 2001 the Cassini spacecraft flew on the dusk side of the magnetosphere along the Jovian bow shock. The closest approach to Jupiter was on December 30, 2000 at a distance of 138 Jovian radii \( (R_{J}=71 \ 492 \ \text{km}) \). During the flyby Cassini crossed the bow shock of Jupiter more than forty times (Szego et al., 2003). The Cassini Plasma Spectrometer and the onboard Magnetometer made almost continuous measurements of the ambient plasma flow and the magnetic field between the end of December, 2000 and the beginning of March, 2001. In this section we discuss a plasma event which we propose is a slow-mode shock candidate in the Jovian magnetosheath. It was detected on January 19, 2001 at \( \sim 12:30 \) UT. Prior to the event there was a Heliospheric Current Sheet (HCS) crossing on January 18.

For magnetosheath plasma the quasi-neutrality condition \( (n_e=n_p=n) \) is fulfilled, so for the calculation of the plasma beta we used the electron densities of CAPS-ELS. The rotation angles of the magnetic field were determined in the \( T–N \) plane of the RTN system using the 24 s resolution RTN data of the magnetometer. The bulk velocities, proton temperatures and densities were calculated from the plasma data measured by CAPS-ELS by fitting Gaussians for the incoming ion distributions. It is known that the velocity distribution is not a Maxwellian during and after the inbound bow shock transition, however in the Jovian magnetosheath it was a good approximation. The spectra was transformed into velocity space, so the maximum of the fit gave the most probable bulk velocity and the full-width at half-maximum (FWHM) gave the thermal velocity. We also derived values that are proportional to the number density by integrating the distribution function over the velocity space.

On the days investigated here the \( x \)-axis of the spacecraft pointed towards the Sun (within 1.3°), the orbit normal of Jupiter and the \( y \)-direction was inclined by \( \sim 8.5° \). The spacecraft attitude was not changed during DOY 019 between 10 and 20 UT when the slow-mode event was detected. The interval of the CAPS actuator motion was limited between 60° and 102° actuator angle. The actuator sweep is not synchronised with the 32 s long data acquisition period, and the actuator motion is very much slowed down near the turning points. From the actuating IBS sensor we can derive the flow direction of the plasma beam perpendicular to the orbit plane of Jupiter, whereas within the plane the flow direction of the beam can be derived from IMS ION data. The ION data gave a \( ±20° \) spread and the IBS results suggested that the flow was in the ecliptic plane. In the RTN frame of reference the flow direction we measured was \((0.93, 0.34, 0)\) with 15% error.

For any given 32 s long interval IBS scans only a part of the incoming plasma flow. We have analysed the IBS distribution functions by fitting a Gaussian to the spectra, and from that the bulk speed, the thermal speed and a relative density value were derived for each 32 s long data acquisition interval. As we do not have exact calibration for IBS, the derived density values are relative values. We have, however, absolute densities from ELS (Lewis et al., 2008), as well as electron temperature data. The IBS density, bulk speed and thermal speed values have a relatively large scatter due to the actuator motion; there is no way to compensate for that.

The time period of the studied plasma events is between 20:00 h UT on DOY 017 and 00:00 h UT on DOY 020. At 00:00 h UT on DOY 018 spacecraft position in JSE coordinates (the \( x \)-axis points from the planet to the Sun’s direction, \( y \) is defined by \( V_{\text{In}} \times x \) where \( V_{\text{In}} \) is the orbital normal of the planet and \( z \) is parallel to the planetary orbital upward normal) was \((-153.1, 235.8, -3.3)\) at a distance of \( \sim 281.2 \) Jovian radii from Jupiter. The velocity of the spacecraft was 11 km/s relative to the Sun. The plasma parameters derived from the IBS data together with the Magnetometer measurements are plotted in Fig. 1. The parameter values have been determined for the proton constituent of the plasma. The top panel contains the bulk flow velocity, the second panel is the proton temperature in eV, the third panel is proton density in arbitrary units and in the fourth panel there are the components of the magnetic field in RTN coordinates. Finally the bottom
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panel shows the rotation angles of the magnetic field in the $T-N$
plane.

At 02:17 UT on DOY 018 a Heliospheric Current Sheet (HCS)
crossing was observed while Cassini was in the magnetosheath.
The plasma density increased together with a bulk velocity and
magnetic field decreased. The magnetic field rotation at the HCS
transition was approximately $180^\circ$. Although we do not provide a
proof for this hypothesis, but we suggest that change in the
orientation of the Interplanetary Magnetic Field might have been
a possible cause of the initiation of a slow-mode front that was
observed later in the magnetosheath. It is known that the changes
in the IMF have well detectable effects in the magnetosphere
(Walker et al., 1999, 2001), but since there is no earlier reference
on slow-mode shocks in this context we do not pursue this
further in this paper.

Later on at 06:35 the spacecraft moved back into the solar
wind and then re-entered the magnetosheath at 23:34. Upstream
of the bow shock, the sonic and the Alfvénic number was 13.2 and
14.6, respectively. Downstream of the bow shock the events are
more complex. The bow shock (BS) crossing is clearly indicated
by the magnetometer data, the Radio and Plasma Wave
Science instrument and by change in the thermal velocity of the
plasma flow. However, the flow velocity dropped from its SW
value only for about 20 min, then it resumed to the solar wind
(SW) value. The magnetometer data allows for a possible second
BS crossing around 019:01:00 (doy:hh:min), but no wave
signature supports this. The strong plasma thermalisation
between 018:23:45 and 019:01:00 might support the picture

that during this period of time Cassini was in the close vicinity of
the shock front.

The density and temperature increase indicating the onset of
the slow-mode shock event was detected at 12:30 UT on DOY 019
approximately 38 h after the crossing of the HCS. The variations
of the plasma parameters started at $\sim$12:30 UT already with a
gradual increase in velocity and temperature, but the shock
transition itself occurred at $\sim$13:45 UT. As can be seen in Fig. 1, the
variation tendencies of the plasma parameters at the slow-mode
shock candidate show a correspondence with the characteristics
of a slow forward shock. There was also a significant structure
corresponding to this event in the RPWS data too. The plasma
parameters in more detail are plotted in Fig. 2.

The top panel shows the MIMI-LEMMS differential electron
fluxes for 3 different energy ranges. Below that there is the plasma
velocity in km/s units, the third panel is proton temperature in
eV s and the fourth shows electron number density derived from
ELS data. On the bottom panel the total value of the magnetic field
is plotted. It can be seen that there is clear anticorrelation
between the density and the magnetic field magnitude, which is a
property of slow-mode shock transitions. The plasma parameters
for the slow forward shock (at $\sim$12:30 UT) in the upstream
regions at $\sim$10:00 UT (upstream 1), $\sim$14:30 UT (downstream
1=upstream 2) and $\sim$15:30 (downstream 2) are summarized in
Table 1. The latter intervals correspond to a second jump of
plasma parameters, which occurred at $\sim$15:15 UT. Here the
magnetic field returned to its original value, that we measured
prior to the slow forward shock. It indicates that it is a reverse

Fig. 1. Plasma parameters calculated from the measurements of the CAPS-IBS and the MAG instruments onboard of Cassini between DOY 017T20:00 and 019T24:00 UT. The onset of the slow-mode shock event was detected at approximately 12:30 in the Jovian magnetosheath on DOY 019.
shock and that we observe a forward–reverse shock pair in this case.

According to the data presented in Table 1, the Mach numbers were $M_{S,u,1} \sim 6.3$ and $M_{A,u,1} \sim 2.4$ upstream, and $M_{S,d,1} \sim 6.8$ and $M_{A,d,1} \sim 10.3$ downstream of the slow forward shock candidate. The electron pressures calculated from the CAPS-ELS data are included in the value of the ion-acoustic speed – since the electrons have a significant contribution to the plasma kinetic pressure – but we note that the polytropic index used for the determination of the ion-acoustic speed is only evident for the proton constituent of the plasma. In its upstream region the conditions required for the slow-mode steepening – that is the proton temperature being less than the electron temperature and that $\beta < 1$ – are fulfilled.

The LEMMS electron intensities also show this tendency at some points, but the values are rather low. Due to the different look directions and energy range of the LEMMS sensor, the plasma structure was only partially detected. A second density jump (at 16:30 UT) though is well distinguishable also in the high-energy range and the tendency of anticorrelation with the magnetic field is observable too. We could consider this as a second event, though the IBS data do not really support this, so we do not pursue its investigation further in this paper and focus only on the main event (between 12:30 and 15:15 UT).

As was mentioned earlier, from the IBS measurements we can only derive the magnitude of the bulk velocity (and not its vector components), so we made some assumptions in order to estimate the plasma flow conditions upstream of the slow shock candidate. In the magnetosheath region towards the flanks the plasma flow is generally almost parallel to the boundary. So it is reasonable to assume that the direction of the flow is determined by the surface of the bow shock and the approximate shape of the magnetopause. Using the results of Joy and co-workers (2002) concerning the most probable locations of the bow shock during the Cassini Jupiter flyby we did a minimum variance analysis to determine the angle between the shock normal and the upstream magnetic field ($\theta_{Bn}$). For the DOY 018, bow shock crossing this angle was $\sim 65^\circ$.

At the slow-mode shock candidate we used the coplanarity theorem and the minimum variance method for the determination of $\theta_{Bn}$, which was approximately $73^\circ$. Therefore we estimate that the flow direction angle in the magnetosheath in the vicinity of the slow-mode shock candidate is between a $\theta_1 \sim 65^\circ$ and a $\theta_2 \sim 73^\circ$. If we consider $\theta_1$ then the normal component of the

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**Table 1**

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<th>Downstream 1= Upstream 2</th>
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Fig. 2. The variations of the plasma parameters at the slow-mode shock candidate.
plasma flow upstream of the shock is \( \sim 150 \text{ km/s} \) and for \( \theta_2 \) it is \( \sim 95 \text{ km/s} \). However, it is also necessary to take the speed of the shock into account. Since the shock propagates towards the bow shock, its speed would be negative in the reference frame of the shock. Taking the \( \theta_1 \) angle for the magnetosheath plasma flow direction and \( \theta_2 \) for the propagation direction of the slow shock candidate in the RTN coordinate system, the normal component of the plasma flow to the slow-mode front is \( \sim 45 \text{ km/s} \). This means that the normal component of the flow velocity is sub-Alfvénic even without considering the movement of the shock front. For the downstream region we found that the magnetic field bends towards the shock normal, which is also an important requirement for a slow-mode shock.

Fig. 3 shows the magnetic hodogram for the DOY 019 slow-mode shock candidate calculated for magnetic field vectors transformed into the minimum variance system. The direction of the magnetic field vector pointing into the minimum variance direction is perpendicular to the figure. The magnetic field vectors show a right-handed rotation on the shock transition. The rotation features were also observed at the slow-mode shocks found in Earth’s magnetotail (Seon et al., 1996). We also investigated whether the shock could be a tangential discontinuity, which can be done by examining the component of the magnetic field in the minimum variance direction. For the slow-mode candidates this is shown on the left-hand side plot of Fig. 3. Since \( B_y \) is not zero \((\sim 0.3 \text{ nT})\) — although the result is very much dependent on the selection of vectors — we excluded this possibility.

5. Conclusions

In this paper we analysed a set of plasma observations that are consistent with a slow-mode shock (forward–reverse pair) in the downstream magnetosheath of Jupiter. For our analysis we used the plasma and magnetic field data measured by the Cassini spacecraft on its way to Saturn during the 2000–2001 Jupiter flyby.

Slow-mode shocks are quite rare in the heliosphere and there are many debates concerning their origin and propagation characteristic. However, there were a few slow-mode shock detections already both in the solar wind and the plasma environment of Earth. Although the deep theoretical consideration of the propagation and steepening conditions of slow-mode shocks in planetary environments like Jupiter’s is not a subject of this study, we propose a possible mechanism for the formation of slow-mode shocks. We suggest that, since many types of shocks and disturbances can arise from wave–particle interactions, an extensive effect on the magnetopause can induce slow-mode waves that can steepen into shocks amongst favourable physical conditions. The source of this impact on the magnetopause is suggested to be the crossing of the Heliospheric Current Sheet (HCS), which was highly tilted to the solar magnetic equator during the Cassini Jupiter flyby in 2000–2001, when a heliospheric magnetic field reversal was in progress.

The studied data interval is between DOY 017T20:00 and DOY 019T24:00 the HCS crossing occurred while the Cassini spacecraft was in the Jovian magnetosheath. 38 h after the HCS crossing was detected, we observed a plasma disturbance at which the variation in the plasma parameters was in agreement with a slow forward shock. The magnetic field magnitude and the plasma density were anticorrelated during the shock transition, and the downstream magnetic field was inclined towards the shock normal, all of which are important requirements for slow-mode shocks. Since the CAPS-IBS sensor only measured the magnitude of the velocity we made assumptions for the flow direction in the magnetosheath, and concluded that upstream of the shock the plasma flow was sub-Alfvénic. Regarding the restrictions for the Landau damping we found that the plasma conditions were favourable for the slow-mode steepening in the case of the DOY 019 event. The possibility that the shock would be a tangential discontinuity was excluded.

We mark that tilted position of the HCS is suggested to have played an important role in this theoretical process and that the effects of a possible HCS-magnetosphere interaction may not be so significant during less active intervals of the solar cycle.

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References
