



Mirror mode structures in the Jovian magnetosheath

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[1] Mirror mode waves are commonly observed in planetary magnetosheaths. Their magnetic signatures are often periodic but occasionally appear as intermittent increases of field magnitude (peaks) or as intermittent decreases (dips). We define quantitative mirror structure identification criteria and statistically analyze the distributions of the various forms. A survey of all the relevant magnetometer data in the Jovian magnetosheath reveals that mirror mode structures are present 61.5% of the time. Two-thirds of the events include waves that are either quasi-periodic or aperiodic, while 19% contain dips and 14% contain peaks. The amplitude and period of quasi-periodic and periodic structures appear to increase as the residence time of the flowing plasma within the sheath increases. Peaks are primarily observed on the dayside in the high β plasmas of the middle magnetosheath. Dips are observed mostly in low β plasma near the magnetopause and on the flanks. A phenomenological model for the evolution of mirror structures that accounts for these observations has been developed. We propose that the mirror structures form near the bow shock and undergo an initial growth phase during which their amplitude increases linearly. Structures that dwell in anisotropic, high β plasma may saturate nonlinearly as described by *Kivelson and Southwood* [1996]. We interpret field magnitude peaks as the signatures of such nonlinear saturation. Finally, we ascribe the dip signatures to the process of stochastic decay of mirror structures as flow away from the subsolar point carries the structures into lower β plasma.

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1. Introduction

[2] Mirror mode structures are commonly observed in naturally occurring, high β (ratio of plasma to magnetic pressure) plasmas. They have been identified in numerous planetary magnetosheaths [*Kaufmann et al.*, 1970; *Tsurutani et al.*, 1982; *Russell et al.*, 1989; *Balogh et al.*, 1992a, 1992b; *Erdős and Balogh*, 1996; *Bavassano Cattaneo et al.*, 1998; *Richardson*, 2002], planetary magnetospheres [*Russell et al.*, 1998] cometary magnetic environments [*Yeroshenko et al.*, 1986; *Russell et al.*, 1987], and interplanetary space [*Tsurutani et al.*, 1992; *Winterhalter et al.*, 1994]. High β ($\beta \geq 1$), thermally anisotropic ($T_{\perp}/T_{\parallel} > [1 + 1/\beta_{\perp}]$) plasmas are unstable to the growth of mirror structures [*Tajiri*, 1967; *Hasegawa*, 1969; *Hasegawa and Chen*, 1987; *Southwood and Kivelson*, 1993]. Other instabilities, most notably ion cyclotron waves, may also grow under these conditions [*Gary*, 1992]. High β , anisotropic plasmas are frequently found downstream of shocks or in regions where

the ion pickup process provides a source of plasma anisotropy [*Southwood and Kivelson*, 1993].

[3] Mirror modes are compressional structures, nonpropagating in the rest frame of the plasma [*Tajiri*, 1967]. In the rest frame of a uniform plasma, theory predicts nonoscillatory structures that are purely growing or decaying in time depending on the local plasma conditions [*Johnson and Cheng*, 1996]. The observed field and plasma pressure variations associated with these structures appear to oscillate either quasi-periodically or aperiodically in time because they are rapidly convected past the observing spacecraft. When high time resolution plasma data are available the structures are observed to be in pressure balance with anticorrelated magnetic and plasma pressure fluctuations [*Tsurutani et al.*, 1982].

[4] In this paper we examine mirror mode structures observed in the Jovian magnetosheath using magnetic field data from all of the spacecraft that have sampled this environment (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini, and Galileo). In particular, we look at the differences in the mirror structures observed near the bow shock and magnetopause, structures observed at different local times, and under differing plasma conditions. Previous authors have reported their analyses based on a single spacecraft flyby over a limited range of local times and plasma conditions [*Tsurutani et al.*, 1982; *Erdős and Balogh*, 1996; *André et al.*, 2002]. The magnetosheath

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boundary locations vary over wide distances in response to changing solar wind dynamic pressure [Slavin *et al.*, 1986; Huddleston *et al.*, 1998], IMF orientations [Kivelson and Southwood, 2003; Walker *et al.*, 2005], and magnetospheric thermal pressure [Joy *et al.*, 2002]. Here we generalize earlier work to cover a wide range of local times and solar wind conditions that affect magnetosheath properties.

[5] In describing the forms of the mirror mode waves identified in our survey, we categorize the structures in relation to the following different field signatures. Dips are regions where intermittently the magnetic pressure suddenly drops from a relatively high, slowly varying background value to a much lower and less regular value for a brief time. Peaks are regions where intermittently the magnetic field strength rises suddenly from a slowly varying low background level (opposite of dips), and other regions are those where there is no clearly defined high or low field background state.

[6] In many of the “other” intervals, the signatures appear to vary nearly sinusoidally but sometimes they are aperiodic. Previous analyses of mirror structures in the terrestrial and outer planet magnetosheaths have identified similar classes of magnetic variations [Leckband *et al.*, 1995; Erdős and Balogh, 1996; Bavassano Cattaneo *et al.*, 1998; Lucek *et al.*, 1999b; Génot *et al.*, 2001; Tétrallyay and Erdős, 2005] although the terminology has varied somewhat among authors.

[7] Several authors have put forth models that describe the evolution of mirror mode structures as they traverse the magnetosheath. Bavassano Cattaneo *et al.* [1998] developed a model based primarily on Voyager observations made on the dayside of Saturn. In this model (BC model), quasi-periodic mirror structures form near the bow shock. These structures increase in amplitude and decrease in apparent frequency as residence time in the magnetosheath increases. As the magnetopause is approached, the wave form changes. Initially, the waves evolve into large amplitude, aperiodic structures. Finally, in the plasma depletion layer near the magnetopause, the form further evolves into large amplitude field depressions (dips). Tétrallyay and Erdős [2002] report that in the terrestrial magnetosheath, mirror structure amplitudes grow with sheath residence time but there is no observed change in the apparent wave period (TE model). Here we develop a new model that incorporates our observations and relate our findings to these two models.

2. Identification and Classification of Mirror Modes

[8] Plasma data at Jupiter with sufficient time resolution to resolve 20–120 s duration mirror structures, such as those typically found in the Jovian magnetosheath [Erdős and Balogh, 1996], are not generally available. Thus the expected anticorrelation in the field and plasma pressure fluctuations associated with mirror structures cannot be used as a mirror mode identification criterion. Furthermore, plasma temperature anisotropy data are not available so the conditions for mirror mode stability cannot be verified. Given these limitations, we identify mirror mode structures using only magnetic field data, recognizing that the struc-

tures that we refer to as mirror modes could represent other types of plasma/field perturbations [Stasiewicz *et al.*, 2003].

[9] In our analysis of the properties of mirror modes in the magnetosheath we make use of magnetometer measurements from Pioneer 10 and 11 [Smith *et al.*, 1975], Voyager 1 and 2 [Behannon *et al.*, 1977], Ulysses [Balogh *et al.*, 1992a, 1992b], Galileo [Kivelson *et al.*, 1992], and Cassini [Dougherty *et al.*, 2004]. The Galileo measurements are the only ones that cover a wide range of postnoon, predusk local times. Unfortunately, only low time resolution magnetic field data were acquired when the spacecraft was in the magnetosheath. In order to achieve some consistency in comparison of data from Galileo and the other spacecraft used in the study, the high time resolution vector magnetic field data from the Pioneer (4/3 s), Voyager (1.92 s), and Cassini (16 Hz) spacecraft were averaged to 24-s samples. Ulysses magnetic field data, publicly available as 1-min averages, were also included in our analysis. The low sample rate of the complete data set limits our ability to use some of the standard techniques for identifying mirror structures in the data set, as will be discussed later.

[10] In magnetic field data, mirror structures appear as large amplitude perturbations in the field strength that are generally linearly polarized with a maximum variance direction that is closely field aligned [Lucek *et al.*, 1999a; Génot *et al.*, 2001]. We use these properties to identify mirror structures in the field data. The first step in our procedure is to determine the background field level. When mirror peaks or dips are present, the background field is not well described by its mean or median values. In these regions, the background field is more appropriately described by upper (dips) or lower (peaks) quartiles. In order to determine the background level, we compute the difference between observed field strengths and the field magnitude quartiles determined using sliding 20-minute windows with single time increment (24 s) shifts. Thus

$$a_i = B_i - B_i^{75} \quad b_i = B_i^{25} - B_i \quad (1)$$

where the subscript i indicates individual samples, B is the field magnitude, and the 75 and 25 superscripts indicate upper and lower quartiles respectively. Negative values of a (above) and b (below) are eliminated and the remaining values are averaged by using the same sliding window. If the ratio of a to b is greater than 3 ($a/b > 3$) the background field is well described by the upper quartile. If the inverse is true ($a/b < 1/3$), then the lower quartile tracks the background field. If neither condition is met, the median field strength is considered to be the background field level. The selection of the critical ratio 3 was arbitrary. It was selected by inspection of the data to establish that it selected intervals of different types of waves that appeared evident by inspection. The selection results are insensitive to the choice of the critical ratio 3. Values between 2.5 and 3.5 work nearly as well. The choice of 20 min sliding windows for the statistics is also arbitrary. It was chosen to satisfy the requirements that the window be long enough to track mirror structures of 4–5 min duration, short enough to track slow changes in the background field strength and orientation, and to be an integral number of 24 s data points.

[11] After the background field level is established, the amplitude of the field perturbations (δB) is determined. If

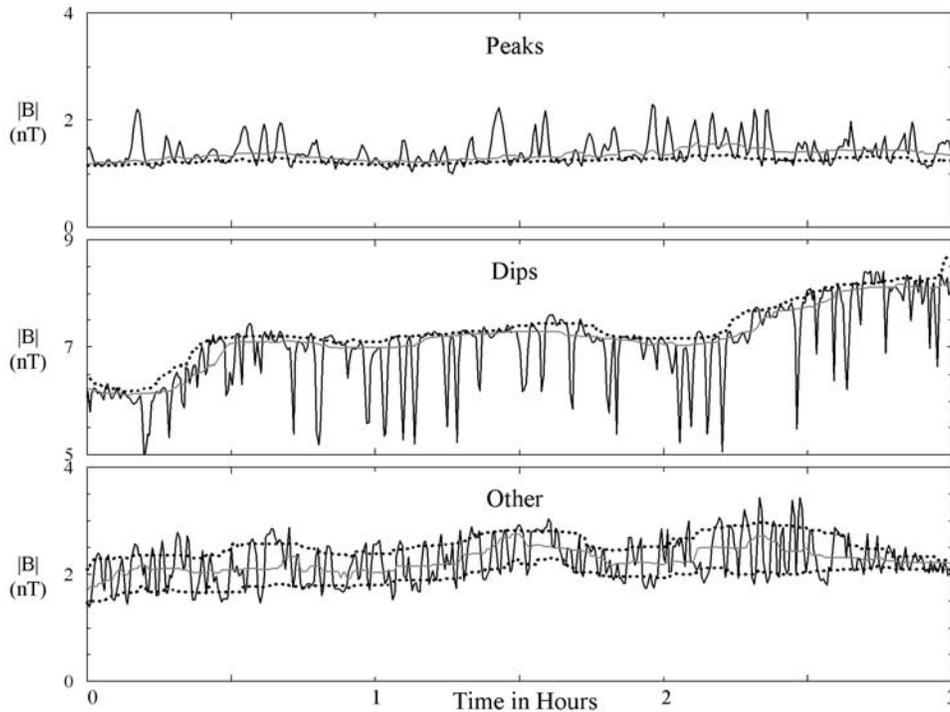


Figure 1. Each panel shows 3 hours of Galileo magnetometer field magnitude data (solid black line), appropriate quartiles (dotted), and the median value (solid gray) computed using 20 min sliding windows with single sample shifts. The panels show examples of “peaks” (top), “dips” (middle), and “other” (bottom) structures.

the background level corresponds to one of the quartiles, δB is determined by subtracting the observed field from the background (or vice versa); otherwise the difference between field upper and lower quartiles is used. We require that the magnitude of the field perturbation be at least 1 nT or be at least one quarter of the field magnitude ($\delta B \geq 1$ nT or $\delta B/B \geq 0.25$) to be considered a candidate mirror structure. Given that Jovian magnetosheath field strengths are generally 2–8 nT, this corresponds to a change of field pressure of $\sim 25\%$ ($1 - [B - \delta B]^2/B^2$).

[12] Once field compressions are determined to have amplitudes large enough to be considered as mirror mode candidates, their field-alignment must be verified. A commonly used test [Erdős and Balogh, 1996; Bavassano Cattaneo et al., 1998; Lucek et al., 1999a; Tátrallyay and Erdős, 2002] of this condition applies the minimum variance technique of Sonnerup and Cahill [1967] to establish the maximum variance direction, and the angle between this direction and the field direction. Previous work has required that the angle thus determined should be less than $\sim 30^\circ$ for mirror structures [Bavassano Cattaneo et al., 1998; Tátrallyay and Erdős, 2002]. Unfortunately, the minimum variance technique does not work well with the low time resolution data used in this study. Instead, we require that the variations of the field direction lie within a $\pi/4$ steradian solid angle (45° cone angle) of the background field direction.

[13] In this study, compressional perturbations that meet the above specified amplitude and directional requirements are considered to be mirror mode structures. Mirror modes whose background field state is defined by the upper

quartile are identified as dips. Those where the background is defined by the lower quartile are peaks, and the remainder are “other.” Figure 1 shows examples of the magnetic signatures each of three types of mirror mode structures, as well as the upper and/or lower quartiles computed as described above. The plot shows that the quartiles (dotted lines) define the background field level during periods of peaks and dips better than the median (gray line), and the separation of the quartiles provides a slight underestimate of the amplitude of the “other” structures.

[14] The mirror mode structures identified by these criteria in the low time resolution data of this study do not necessarily match the qualitative structural identifications made by previous authors. For instance, Erdős and Balogh [1996] report mirror dips in the Ulysses magnetometer data during the magnetosheath portion of the interval between 1400 UT 12 February until 0300 UT on 13 February 1992. Our quantitative criteria identify 83% of the interval as dips, but the remainder as quasi-periodic. André et al. [2002] report dips between 0600–0800 UT on 8 January 2001 where our criteria identify dips only at the beginning and end of this interval, with the central section identified as quasi-periodic. Our use of low resolution data also impacts the identification of some high frequency structures. Erdős and Balogh [1996] report observing peaks in the one second magnetic field data between 2040 and 2220 UT on 13 February but did not analyze them. We have examined that interval using the one-minute averaged data that are publicly available and fluctuations are mostly lost to the averaging process. Our criteria identify only two 5 min

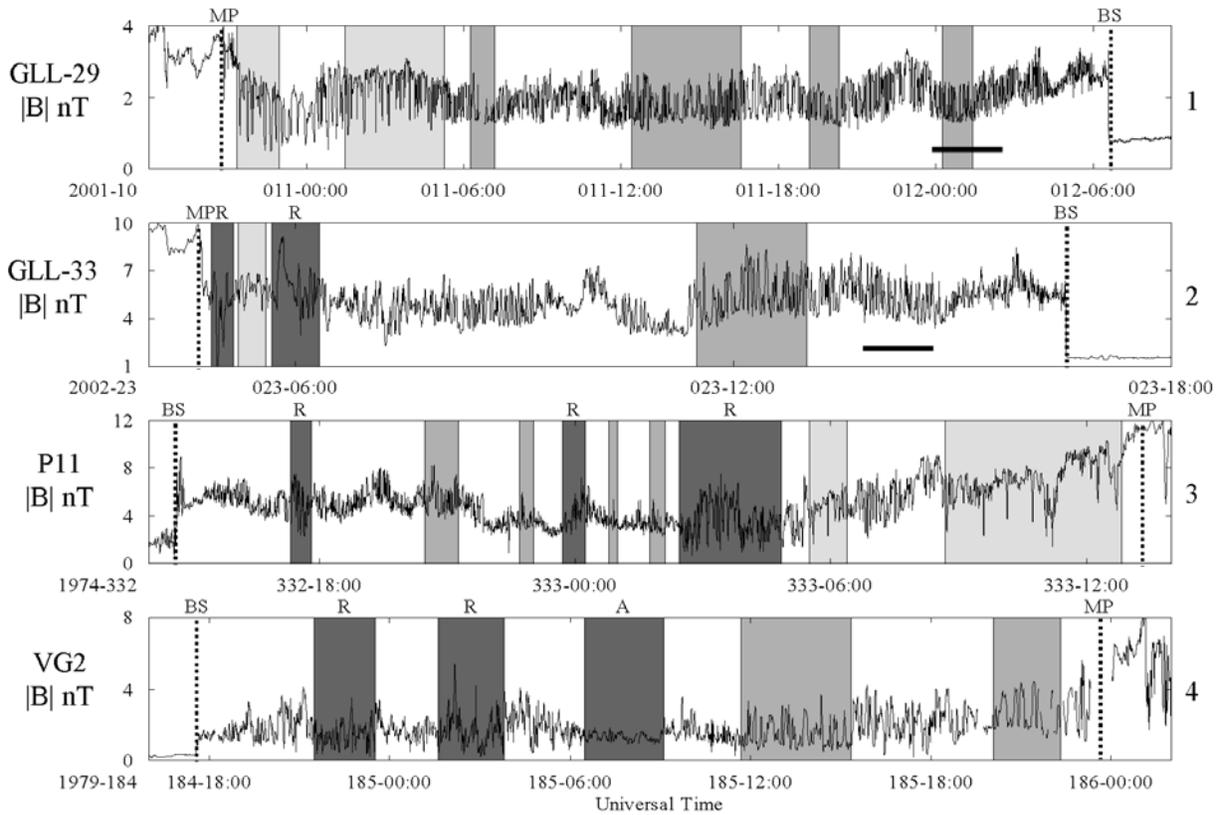


Figure 2. Magnetic field strength (nT) observed during dayside passes through the magnetosheath. Each panel is from a different pass: (1) Galileo outbound orbit 29, 1630 local time (LT); (2) Galileo outbound orbit 33, 1310 LT; (3) Pioneer 11 inbound, 0910 LT; (4) Voyager 2 inbound, 1015 LT. Time intervals with dips are shaded in light gray, peaks in medium gray, with unshaded regions being “other” mirror structures. Dark gray shading indicates time intervals that do not meet our mirror mode identification criteria, either because the fluctuations are rotating (labeled R) or because they fail to meet the amplitude criterion (labeled A). Dotted vertical lines mark the bow shock (BS) and magnetopause (MP) crossings (all panels) and heavy horizontal lines mark intervals of amplitude saturation (panels 1 and 2).

segments of this interval as peaks with the remainder identified as quasi-periodic structures.

3. Analysis

[15] In this section we examine properties of mirror mode waves identified in the magnetosheath of Jupiter, focusing on the nature of the waves, the spatial distribution of waves of different types within the magnetosheath and the background field and plasma conditions in which they are found. Magnetosheath intervals for the Galileo spacecraft were determined by a combination of independent and joint analyses of the plasma wave [Gurnett *et al.*, 1992] and magnetometer data sets. Boundary crossing times for the earlier spacecraft were obtained from the literature (Pioneer 10 and 11 [Intriligator and Wolfe, 1976], Voyager 1 and 2 [Lepping *et al.*, 1981], Ulysses [Bame *et al.*, 1992], Cassini [Kurth *et al.*, 2002; Szego *et al.*, 2003]). Compressional wave power in the Jovian magnetosheath is generally much greater than in the surrounding plasmas of the magnetosphere and the solar wind. More than 80% of the magnetosheath observations at Jupiter contain waves that meet our amplitude requirement for mirror modes. Some compres-

sional fluctuations fail to satisfy the identification criterion on the variance of the field orientation. This reduces the fraction of time in the magnetosheath for which mirror mode waves are present to 61.5%. Two-thirds of the mirror structures are identified as quasi-periodic or aperiodic, while 19% are dips and 14% are peaks.

3.1. Distribution Relative to the Bow Shock and the Magnetopause

[16] In analyzing the properties of the mirror mode structures present in the Jovian magnetosheath, we examined the ways in which they change with distance from the bow shock. Earlier studies have come to differing conclusions on the evolution of the mirror mode waves. Figure 2 shows the field magnitude (nT) observed during four dayside passes through the Jovian magnetosheath. Near the bow shock (BS) the field perturbations typically have smaller amplitudes and shorter periods than they do as time from the shock crossing increases. On average, one can link increasing time to increasing distance, although shock motion may make this a poor assumption in individual cases. Between the shock and the magnetopause, the fluctuations appear to increase in amplitude and decrease in

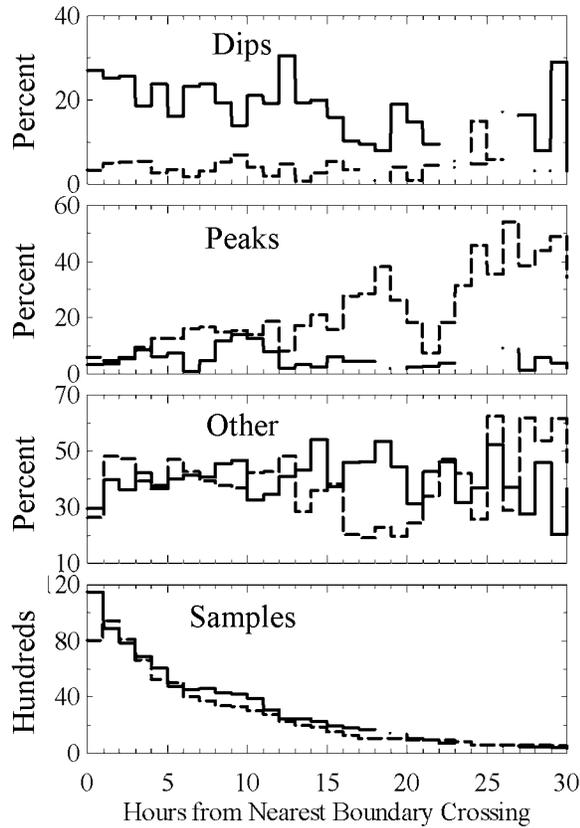


Figure 3. Distribution of dips, peaks, and “other” mirror structures relative to the time of the nearest bow shock (dashed) or magnetopause (solid) crossing. Gaps indicate bins with no observed peak or dip mirror structures. The bottom panel shows the number of observations (in hundreds) in each bin.

frequency. In some passes (panels 1, 2) the amplitude of the perturbations appears to saturate (remain fixed for a few hours) while in other passes (3, 4) no amplitude saturation is observed. Peaks (medium gray shaded regions) are observed in all of these passes. Time intervals that contain fluctuations that do not meet our mirror mode identification criteria are shaded dark gray. The failed criterion is noted above the shading (A for amplitude or R for rotational).

[17] We do not quantitatively analyze mirror mode amplitude variations in this study. Previous work indicates that absolute fluctuation amplitudes cannot be fully resolved in our low-resolution data [Erdős and Balogh, 1996]. We have qualitatively analyzed the relative amplitude (δB) of the mirror mode structures in each of the 29 complete traversals of the magnetosheath (from the solar wind to magnetosphere or vice versa). Increases in amplitude from the bow shock (BS) toward the magnetopause (MP) were visually identified in 17 cases. No statement can be made about amplitude changes in ten of the crossings because the mirror structures are intermittent and two have amplitudes near the bow shock that are equal or greater in amplitude than the structures observed near the MP. Of the 12 crossings that do not fit the previous models, all but two occur more than 5 hours away from local noon. The two traversals near local noon that do not match the previous models expectation of

amplitude growth occur in passes where the magnetosheath appears to be highly disturbed. These passes have intermittent mirror mode waves separated by periods containing both large field rotations and compressions. The events where the mirror amplitudes near the BS were equal to or larger than the amplitudes near the MP (Pioneer 10 outbound, Cassini) both occurred near the terminator. The Pioneer 10 field data have small amplitude fluctuations at both the MP and BS, with several regions in the middle magnetosheath having larger compressions. Cassini observed large amplitude fluctuations ($\delta B \sim 0.8$ nT, $B \sim 2$ nT) immediately following the BS crossing on the dusk flank of the bow shock at approximately 1630 UT on 3 January 2001, which persisted for about a day, after which the mirror mode amplitude diminished, and remained relatively small ($\delta B \sim 0.2$ – 0.5 nT; $B \sim 1.2$ – 1.5 nT) for several days. As Cassini approached the MP, the mirror mode amplitude increased to values equal to or greater than those observed near the shock ($\delta B \sim 0.8$ – 1.0 nT).

[18] The *Bavassano Cattaneo et al.* [1998] and *Tátrallyay and Erdős* [2005] observations that dips (light gray shaded regions) are found near the magnetopause is consistent with the results of this study. Dips are observed within three hours of the MP crossing in two thirds (80 of 121) of the crossings analyzed. This association is found for both inbound and outbound magnetosheath traversals at all local times examined and for all seven spacecraft. Mirror modes are observed within 3 hours of the bow shock crossing in only 52.4% (54 of 103) of the available events. Of the intervals that contained mirror modes, “other” forms were observed 96% of the time, peaks 17%, and dips 13%. (Note that a single 3 hour interval may contain all three mirror structure forms.) Shock crossings that did not have mirror structures in close temporal proximity primarily occur on the flanks. Of the 28 shock crossings that occurred within four hours of local noon, mirror structures were identified within 3 hours in 82% (23 of 28) of the crossings.

[19] In order to establish whether the various mirror structures are associated with proximity to the magnetosheath boundaries, we compute the time separation between the individual magnetic field samples and the nearest boundary crossing. Time is used as a proxy for distance without correcting for spacecraft velocity. Large, rapid boundary motions are likely to be as important as spacecraft velocity in converting time to distance from the magnetopause or bow shock. Data were collected into 1-hour bins relative to the nearest boundary crossing time and normalized by the total number of observations within each bin. The top panel of Figure 3 shows the percent of the bins that contain dips versus the time to the nearest boundary crossing. The solid (dashed) line shows the time offset from the magnetopause (bow shock) crossing time. The fraction of dips falls as the time from the magnetopause increases. Throughout the magnetosheath, dips are found more often than peaks for observations closer in time to the magnetopause than the bow shock. The next panel down in Figure 3 shows the relationship between the occurrence of peaks and the nearest boundary crossing by using the same line style convention as in the top panel. Peaks are found only a small percentage of the time when the spacecraft is within a few hours of either the magnetopause or the bow shock. As the time from the bow shock increases, the fraction of the data

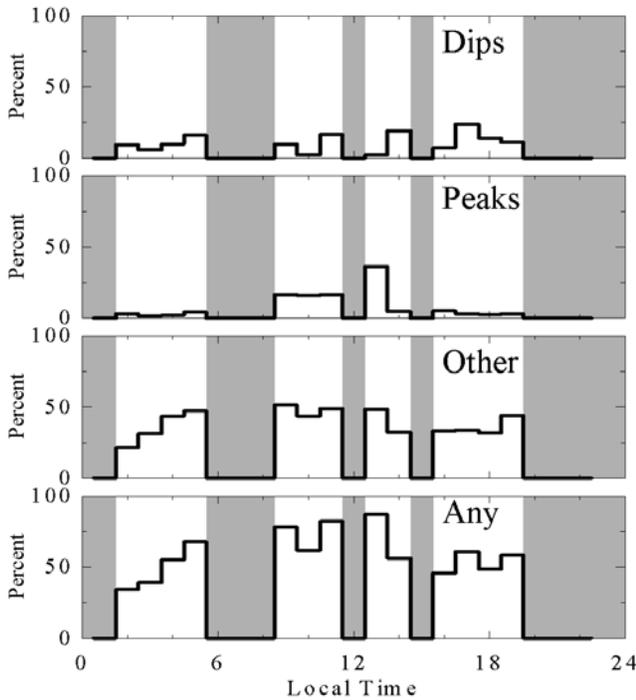


Figure 4. Occurrence distribution of MM structures versus local time. Shading indicates regions of no data coverage. Values indicate the percentage of the observations within each bin containing MM waves of a given form.

that contains peaks within each bin increases. Throughout the interval plotted, peaks are always found more frequently than dips when observations are nearer (in time) to the bow shock than magnetopause. Peaks are primarily “middle-magnetosheath” structures at Jupiter. Quasi-periodic structures are found throughout the magnetosheath and their occurrence frequency seems to be unrelated to proximity to either the bow shock of the magnetopause or the absence thereof.

[20] Mirror mode structures are found in close temporal proximity to the bow shock at all local times for which observations are available. Solar wind with nominal Parker spiral IMF field orientation at Jupiter forms a quasi-perpendicular shock in the subsolar region creating the temperature anisotropy required for mirror mode growth. Unsurprisingly, mirror mode structures are observed near 82% of the shock crossings within four hours of local noon, and a similar fraction of the entire magnetosheath near local noon is found to have mirror modes. However, the appearance of mirror mode waves close to the bow shock at all local times implies that mirror modes structures do not form exclusively near the subsolar bow shock. *Tátrallyay and Erdős* [2005] report that in the terrestrial magnetosheath, pressure anisotropy associated with field line draping at the magnetopause may be important source of mirror modes. Alternatively, the IMF orientation occasionally gives rise to quasi-perpendicular shock jump conditions along the flanks of the magnetosphere, thus providing the anisotropy required for mirror mode growth. Indeed, *Achilleos et al.* [2004] report that Cassini passed through a quasi-perpendicular bow shock on day 18, 2001 in the postdusk magnetosheath. We observe

mirror modes near 34% of the bow shocks on the flanks of the Jovian system and mirror structures are found in 40–60% of the flank magnetosheath observations. This result is consistent with a combination of mirror mode transport from the high probability subsolar region plus a lower rate of local production.

3.2. Local Time Distribution

[21] Mirror structures are observed at all local times for which magnetometer data are available. Figure 4 shows the percentage of observations in each 1-hour local time bin that contain dips, peaks, other (quasi-periodic) or any of the identified forms of mirror structure. Mirror structures are most frequently observed near the subsolar point and gradually diminish in occurrence frequency as the local time departs from noon. Peaks are observed at all local times examined but they are most commonly observed near local noon. Similarly, dips are observed at all local times; however, on the flanks of the magnetosphere, dips comprise a larger fraction of the total observed mirror structures than they do near local noon. The “other” MM form is the most commonly observed form at all local times.

3.3. Background Field and Plasma Conditions

[22] The instability condition for mirror mode waves is most readily satisfied for high values of plasma β . Ideally, one would examine both plasma and field properties throughout the magnetosheath, but the magnetic field itself can serve as a proxy if one assumes that the plasma pressure is roughly constant. In this section we first consider how the form of mirror mode waves changes with the magnitude of the background field, and then examine some passes for which Galileo plasma data were available.

[23] On Galileo’s G29 outbound pass near 1630 LT, (Figure 2, panel 1) all mirror structural forms were clearly observed. Figure 5 shows the distribution of the field magnitude (0.1 nT bins) for each of the three types of waveforms we have identified. When dips were observed, the field strength remained near 2.5 nT; the field minima within the dips were variable with small event clusters near 0.5 nT and 1.0 nT. Peaks were observed when the background field strength was lower (~ 1.4 nT); the field maxima were distributed around 2.3 nT. “Other,” mostly quasi-sinusoidal mirror structures range from 1.6 nT to 2.3 nT with little clustering. The distributions are similar to those found by *Bavassano Cattaneo et al.* [1998] for both dips and quasi-sinusoidal regions. The *Erdős and Balogh* [1996] distribution result for dips showed two separate and distinct maxima in the distribution; one associated with the field minima and the other with the higher background field. The mirror structures analyzed by *Erdős and Balogh* [1996] appear to have saturated in amplitude such that the δB associated with field dips remained nearly constant for an extended time interval. When there is amplitude saturation, the separation between the field minima and maxima is constant and clear peaks are observed in the distribution of B . The field distributions plotted in Figure 5 (top two panels) do not have clear peaks at the field extrema because amplitude saturation occurs in only a small fraction of the interval as indicated by the solid black line.

[24] Galileo plasma moments in the magnetosheath (ion density, ion temperature, and velocity) are available at

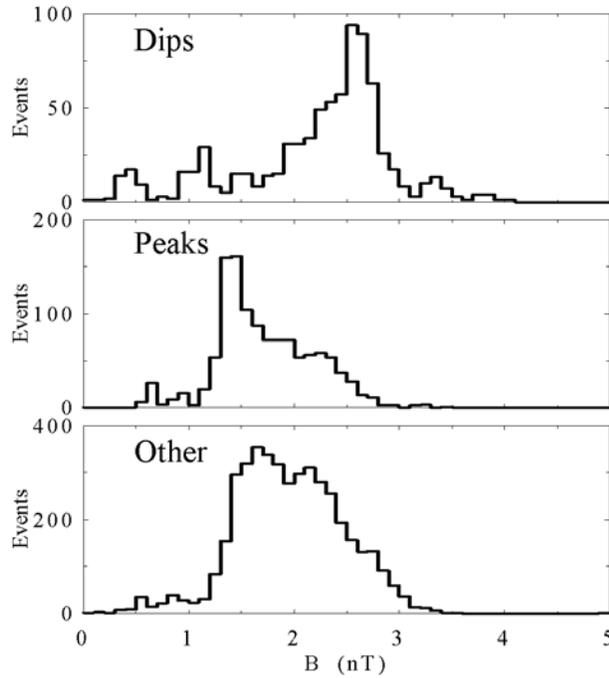


Figure 5. Distribution of B (nT) for different types of wave structures.

low time resolution (~ 5 min) for only a few select time intervals. Similar Voyager plasma parameters are available for some sheath passes at a bit higher sampling rate (96 s). When only ion temperature data are available, we compute β by neglecting the electron contribution and assuming 4% He^{++} at 3.5 times the proton temperature

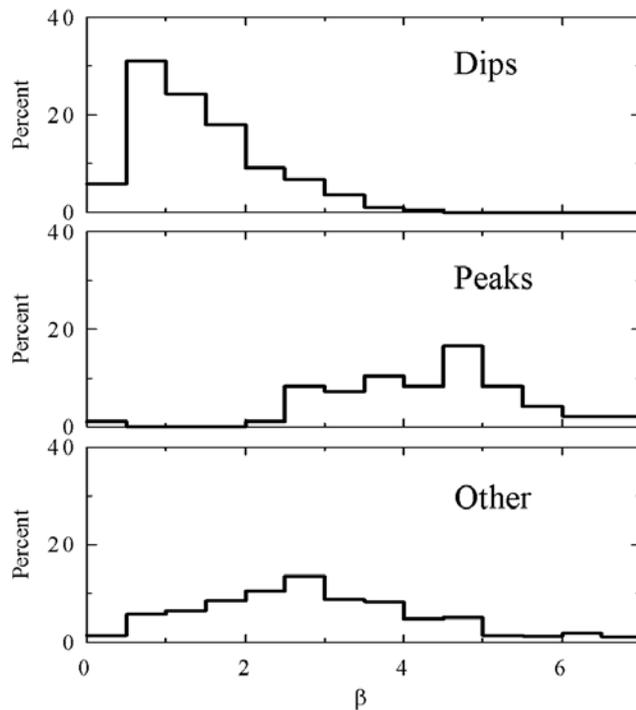


Figure 6. Occurrence distribution of MM structures versus plasma Beta (β).

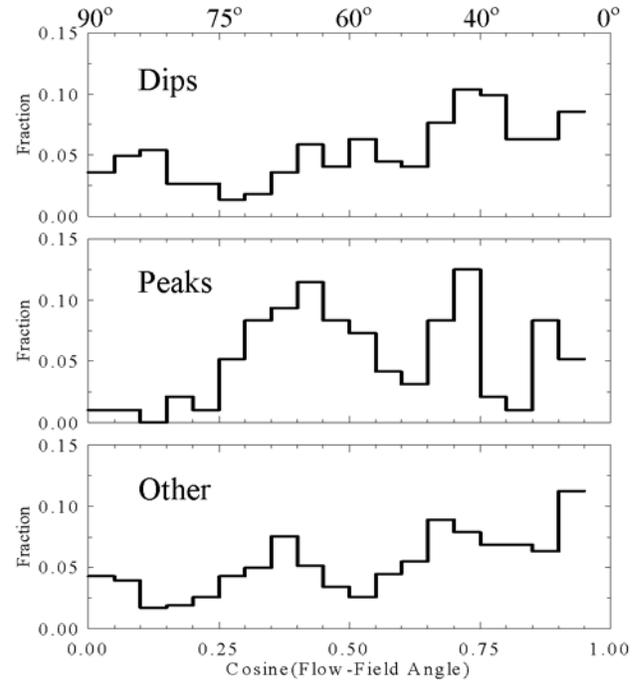


Figure 7. Occurrence distribution of MM structures versus the cosine of the angle between the plasma velocity vector and the background magnetic field orientation.

($\beta = 2\mu_0 n_p k(1.14T_p)/B^2$). Neglecting the electrons leads to a systematic underestimate of β . Typically $T_i \gg T_e$, in which case our approximate pressure estimate is good, but the error could be larger if the temperatures are comparable. Figure 6 shows the percentage of the observations within each 0.5 β -bin that contain the identified mirror structure type. Dips are primarily observed in relatively low (<3) β plasma; peaks are observed when β is higher (3–6). *Pantellini* [1998] showed that dips form preferentially when β is relatively small (≥ 1) and peaks form when the anisotropy and β are relatively high ($R = \frac{T_i}{T_e} \lesssim 0.5$, $\beta_{\parallel} \gtrsim 10$). Other mirror structures are observed over a wide range of β values with the distribution peaking at β values of about three. Regions where our criteria do not identify mirror modes (none) are independent of the value of β in the range shown. Noting that at fixed density, high β implies low B , these results are consistent with the distributions shown in Figure 5. The full range of β values observed ($0.3E-7$ – $1.4E2$) in the data set is much larger than shown in Figure 6. However, the events at large β that are not shown are rare and do not impact the distribution shapes shown, except to extend the high β tails, particularly on the “none” distribution.

[25] We have analyzed the distribution of the various MM structural forms relative to the angle between the plasma flow vector and the background field orientation. MM structures are presumably aligned with the background field, regardless of the structural form. The local angle between the magnetic field and plasma flow vector defines the orientation of the MM structures as they are convected past the observing spacecraft. Figure 7 shows the distributions for dips, peaks, and other quasi-periodic structures. Each of the forms is observed over a wide range of flow-field angles and there is significant overlap in the occur-

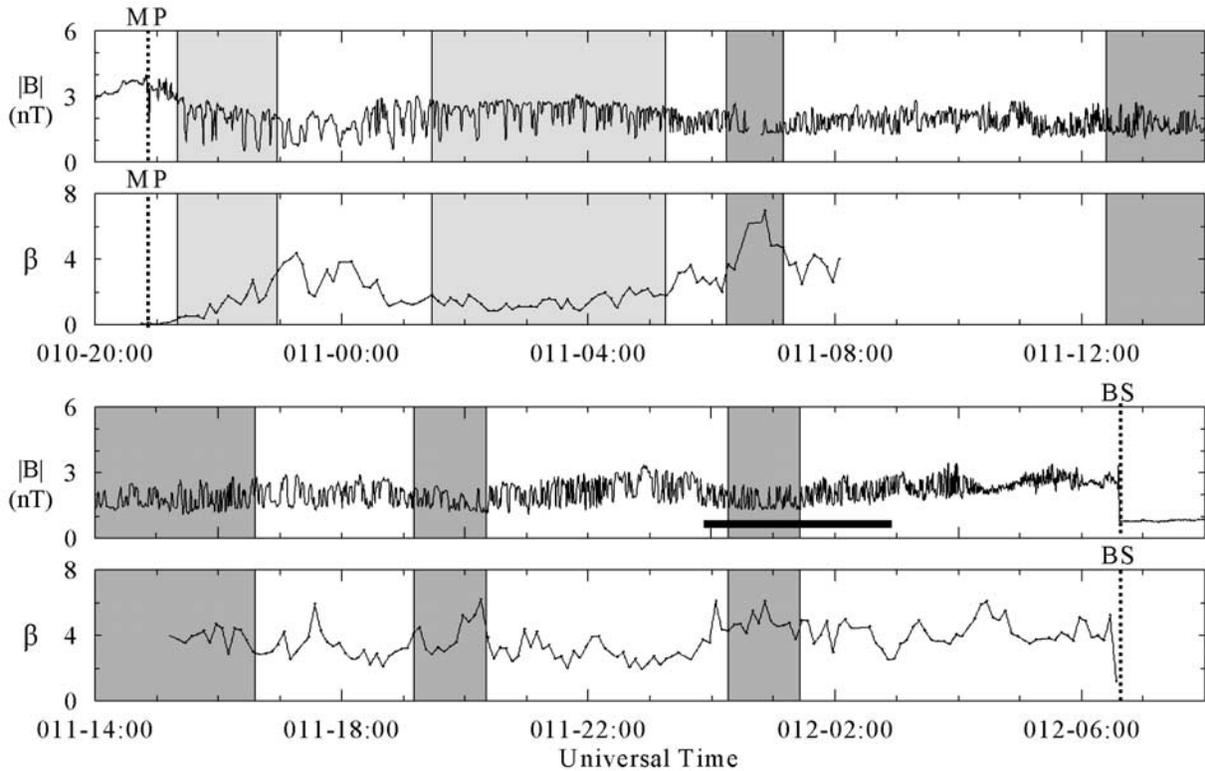


Figure 8. Galileo magnetic field and plasma β observations from the outbound pass of the 29th orbit. The shading convention used here is the same as in Figure 2. The heavy black line indicates an interval of amplitude saturation. The vertical dotted lines mark the bow shock and magnetopause crossing times.

rence distributions of the various forms. This implies that the different structural forms are not merely an artifact of the observation geometry. The distribution functions of both dips and the quasi-periodic forms have mean and most probable values near 45° . The distribution of peaks is skewed towards slightly larger flow field angles (mean = 55° , mode = 60°). This result is consistent with the observation that dips and quasi-periodic forms are found throughout the magnetosheath where a wide range of flow-field angles are possible. In the middle magnetosheath near local noon where peaks are found, the field and flow are not as closely aligned.

[26] Figure 8 shows the magnetic field data plotted in Figure 2, panel 1 on an expanded timescale, along with the plasma β , in order to provide specific examples of the control of the waveforms by the plasma conditions. Shading conventions again indicate mirror mode structural forms and magnetospheric boundaries. Dips are identified in the data beginning shortly after the outbound magnetopause crossing at 2052 [Kurth *et al.*, 2002] when β is low (1–3). From 10 January 2318 UT until 11 January 0128 UT, β is relatively high (2–4) and dips are no longer observed. When β falls back into the 1–2 range (11 January 0127–0551 UT) dips are identified again. Between 11 January (010) 0614 and 0710 UT, β rises into the 4–7 range and peaks are observed. Several intervals with peaks are observed on 11 and 12 January 2001 when β rises into the 3–6 range. Plasma β is mostly in the 2–4 range for the remainder of 11 January 2001 and quasi-periodic mirror structures are observed. Quasi-periodic structures are also identified on 12 January from 0016 until the bow shock crossing at approximately

0635 UT. The structures appear to grow in amplitude away from the shock until the amplitude saturates (indicated by the solid black bar in the lower set of panels).

3.4. Summary of Observations

[27] Peaks are the least common of the three identified structural forms of mirror modes, they are associated with plasma $\beta > 3$, they are usually found only within a few hours of local noon, and they are mostly found in the middle magnetosheath.

[28] Dips are commonly found in close proximity to the magnetopause, they are associated with plasma β between 1 and 3, and they comprise a greater fraction of the total observed mirror structures on the flanks of the magnetosphere than near local noon.

[29] Other, by definition, are either quasi-periodic or aperiodic mirror structures, they are most common of the three structural forms at all local times, they are observed over the full range of plasma β sampled (1 to >6), in intervals near shock crossings, this is usually the only type of structure observed, and amplitude (δB) is typically small near the bow shock and grows for the first few hours following the crossings.

[30] All amplitudes both increase and decrease during a typical magnetosheath pass, and amplitudes can saturate (remain fixed) for long periods of time.

4. Discussion

[31] The low-frequency compressive magnetic fluctuations analyzed in the previous section are consistent with

the expected magnetic signatures of mirror modes. The field perturbations are generally field aligned and are always within 30° of the background field direction. Even though we systematically underestimate the thermal pressure by ignoring electron contributions, the observed values of β are greater than 1 for nearly all of the fluctuations we identify as mirror mode waves. However, our hypothesis that these are mirror mode structures cannot be confirmed without plasma data. Temperature anisotropy measurements are needed to test whether the plasma is marginally stable to mirror growth and high rate plasma data are needed to confirm constancy of total pressure and convective transport of the structures. Despite the limitations imposed by the unavailability of high time resolution plasma data we believe that we have correctly identified mirror mode structures in the magnetic field data from all of the Jovian magnetosheath passes. Furthermore, we believe that our identification criteria are overrestrictive, eliminating some structures that may well be mirror modes rather than risk including non-mirror mode compressions in our statistical analysis.

[32] In order to significantly improve the local time coverage of the magnetosheath, we included all relevant Galileo data, despite its poor time resolution. Use of Galileo data has not been without cost. For the sake of consistency among cuts at differing local times, we had to average all the data down to Galileo's 24 s/sample resolution. Previous mirror mode studies [Erdős and Balogh, 1996; Bavassano Cattaneo et al., 1998] have shown that duration of individual structures can be less than 24 s; therefore we cannot analyze the amplitude and frequency distributions of mirror structures with our data set. We do find that in general, mirror mode amplitudes appear to be larger near the magnetopause than near the bow shock as reported by the authors cited above with the following caveat: for any given magnetosheath crossing, the detailed time sequence of observed mirror mode amplitudes is unpredictable. Visual inspection of our data shows that the amplitude can grow, shrink, or remain constant for long time intervals.

[33] In low-resolution data, short duration changes of large amplitude and longer duration changes of smaller amplitude cannot be distinguished. Erdős and Balogh [1996] analyzed the mirror modes observed in Ulysses 1 s resolution magnetometer data and were able to provide estimates of the duration, separation, and amplitude distributions of mirror structures in the Jovian magnetosheath. Erdős and Balogh [1996] derived their statistics from the nearly continuous mirror mode wave train that occurred 12 February 1992 1400 UT and 13 February 0300 UT. They identified mirror dips throughout the interval. Our analysis identifies 83% of the interval as containing dips, with the remainder being quasi-periodic and thus categorized as “other” mirror mode structures. Erdős and Balogh [1996] found that the field decreases have an average duration of ~ 30 s with an exponential fall-off in occurrence frequency for periods greater than 20 s. The separation between what we would call “dips” also falls off exponentially for separations greater than 20 s, with an average duration of about a minute. The authors computed the width of the dip structures in proton gyroradii (R_g) and found that the distribution peaked near $15 R_g$ and fell off exponentially but argued that the proton temperature used in the computation was likely an overestimate. Correcting the tempera-

ture could reduce the width of dips by a factor of about three. Bavassano Cattaneo et al. [1998] reported similar widths ($10\text{--}30 R_g$) for both quasi-periodic and dip structures in the Saturn magnetosheath. We do not believe that the removal of the quasi-periodic structures would substantially impact the distributions of the durations and widths of dips reported by Erdős and Balogh [1996]. However, eliminating the short duration separations between “dips” in the quasi-periodic intervals would lengthen the average separation time between dips in their analyses.

[34] Plasma β clearly plays an important role in determining both the presence and type of mirror structures that develop in the Jovian magnetosheath. Figure 9 shows contours of plasma β and flow streamlines in the equatorial plane at $Z = 0$ derived from the Ogino et al. [1998] MHD simulation of Jupiter. The run was carried out with a small southward interplanetary magnetic field and nominal [Joy et al., 2002] dynamic pressure conditions ($B = B_z = -0.42$ nT, $P_{\text{dyn}} = 0.90$ nPa, $V_{\text{sw}} = 300$ km/s). Bright (white) contoured areas indicate regions of high β and dark regions are relatively low β . In this plot, Jupiter is at $X = Y = 0$. The heavy black curve marks the bow shock location, and the innermost flow streamline marks the approximate magnetopause location. The colored lines show the approximate locations of Galileo's 29th and 33rd (Figure 2) orbits, the outbound Ulysses pass projected into the equatorial plane, and the Voyager 1 (1 March 1979) and Pioneer 11 (28–29 November 1974) inbound passes. The Voyager and Pioneer passes are mirrored about $Y = 0$ for display in this quadrant. The color-coding on the trajectories shows the approximate locations where mirror structures were observed. Pink indicates dips, cyan is used for peaks, yellow is “other” mirror mode structures, and gray indicates no mirror structures were observed. All trajectories have been linearly stretched so that the observed magnetopause and bow shock crossings match the locations in the simulation result. Flow streamlines are color-coded to indicate the magnetosheath residence time of the plasma flowing along each streamline.

[35] In the simulation, symmetric regions of high β plasma form slightly away from the subsolar bow shock. In Figure 9, the maximum β region in the magnetosheath is found at approximately 1315 local time. When the simulation is run using different upstream conditions, particularly those including a finite B_y (azimuthal) component of the IMF, the region of maximum β moves slightly toward or away from the subsolar point. With the exception of the details in the subsolar region ($\sim 1100\text{--}1300$ LT) region, all of the simulation results examined show similar flow patterns and β distributions in the magnetosheath in the plane about which the simulation displays approximate north-south symmetry [Walker et al., 2005]. As the plasma flows from the bow shock toward the magnetopause in the subsolar region, plasma β diminishes as the magnetic field piles up. As a spacecraft passes through the magnetosheath from the bow shock toward the magnetopause at local times away from the subsolar region (G29 in Figure 9.) the flow streamlines it encounters originate closer and closer to local noon and their lengths (within the magnetosheath) increase. The streamlines encountered close to the magnetopause have crossed the bow shock near the subsolar point. The plasma flowing on these streamlines has been in a low β state for a significant fraction of the magnetosheath transit.

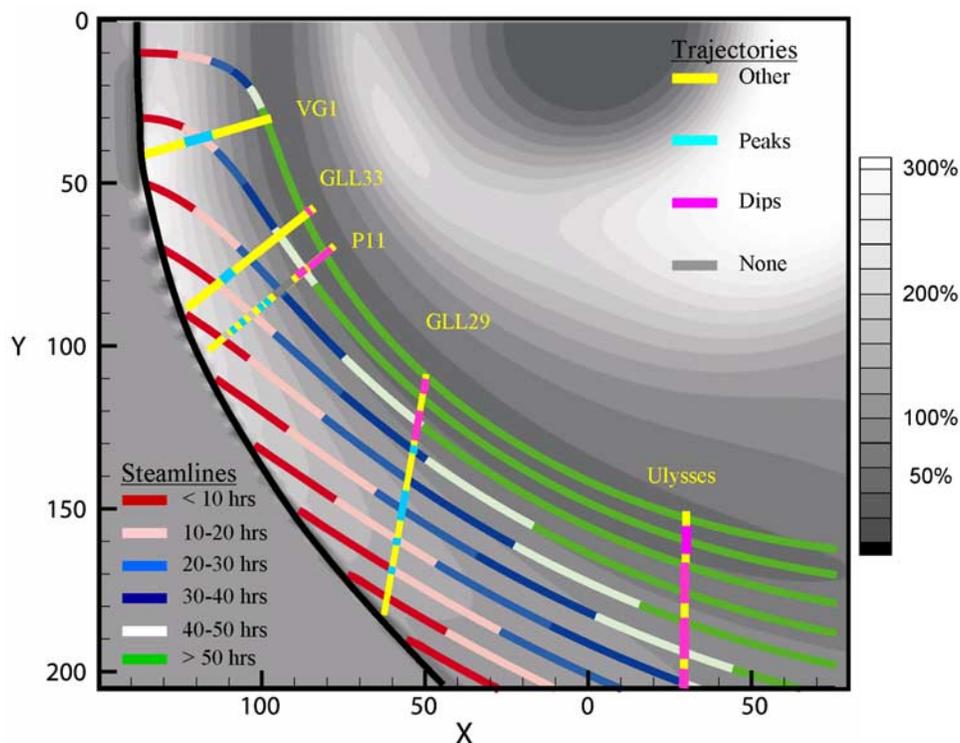


Figure 9. Plasma β (grayscale contours as percent of solar wind value) and flow streamlines from an *Ogino et al.* [1998] Jupiter simulation. Flow streamlines are color coded to indicate the time elapsed as the plasma flows to any magnetosheath location following the bow shock crossing. Spacecraft trajectories cut across the streamlines and are color coded to indicate the type of mirror structures observed. Voyager and Pioneer trajectories are mirrored about the Sun line. Note that the simulated magnetosphere is in an expanded state.

[36] If we assume that the MHD simulation provides a reasonable model of the magnetosheath plasma flow and β configuration, then we can use the result to try to understand the conditions that allow mirror structures to form and later appear as dips and peaks. *Tátrallyay and Erdős* [2005] have reported that field line draping at the magnetopause is an important source for mirror modes in the terrestrial magnetosheath. This mechanism may contribute some mirror structures near the Jovian magnetopause but cannot explain the observation that the magnetosheath is nearly filled with mirror structures. Structures formed near the magnetopause are trapped near the magnetopause by the flow (see Figure 9). Mirror structures found near the bow shock in all of the passes shown in Figure 9 are quasi-periodic (yellow). The proximity to the bow shock suggests that it is the source of temperature anisotropy required to initiate mirror mode growth. In addition, the initial form of mirror modes appears to be quasi-periodic. Peaks are seldom observed on the flanks (Figure 4). Figure 9 shows that the regions where peaks are observed (cyan) occur on streamlines that have passed through regions of relatively high β after crossing the bow shock and have just entered regions of lower β . Under steady-state conditions, the highest β region is found in the middle magnetosheath on the dayside. Dips, on the other hand, are observed after the plasma carrying the mirror structures has traveled extensively through a relatively low β region. On the dayside, this condition is seldom met except near the magnetopause. The fraction of the magnetopause

sheath that contains streamlines that meet this criterion increases as the flanks are approached.

[37] Our observations, as well as those of *Bavassano Cattaneo et al.* [1998] and *Erdős and Balogh* [1996] show that near the bow shock mirror structures are primarily small amplitude and quasi-periodic. As the time from the shock crossing increases, the mirror structures grow in amplitude but remain quasi-periodic. These observations are consistent with a model of mirror structure formation near the bow shock followed by a linear growth phase; however, other interpretations are possible [*Tátrallyay and Erdős*, 2002; *Tátrallyay and Erdős*, 2005]. The linear theory of mirror mode growth has been extensively studied since the pioneering work of *Tajiri* [1967] and *Hasegawa* [1969]. *Leckband et al.* [1995] observed quasi-periodic mirror structures in the Earth's magnetosheath with ion distribution functions in the form predicted by the linear theory of *Southwood and Kivelson* [1993].

[38] *Tsurutani et al.* [1993] reported observing large amplitude magnetic pulses approximately one hour downstream of the Jovian bow shock (quasi-parallel) on the inbound pass of the Ulysses flyby. Our classification criteria would likely identify these structures as mirror mode peaks while the authors argue that these structures are similar to short large-amplitude magnetic structures (SLAMS) observed downstream of quasi-parallel bow shocks at Earth [*Thomsen et al.*, 1990] and at comet Giacobini-Zinner [*Tsurutani et al.*, 1990]. SLAMS are circularly polarized

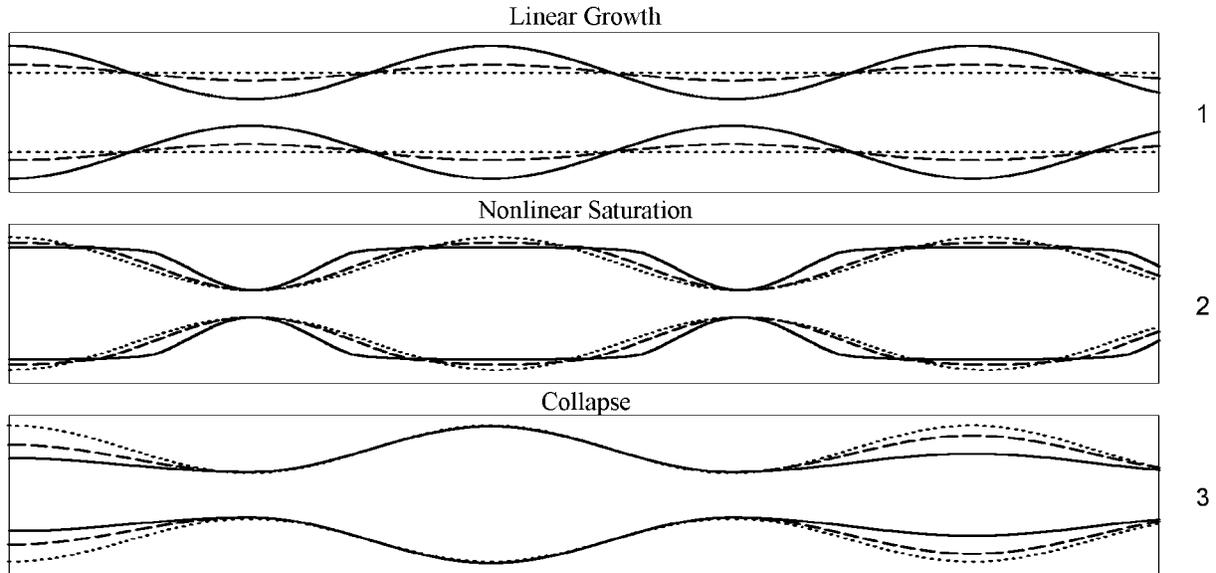


Figure 10. These three panels show our model of the evolution of MM waves in the Jovian magnetosheath. All panels show a time evolution of field lines beginning with the dotted trace, proceeding to the dashed trace and ending with the solid trace and have substantial vertical exaggeration. Panel 1 shows onset and linear growth of mirror modes. A quasi-periodic waveform oriented along the background field direction grows in amplitude while preserving its wavelength. Panel 2 shows the effects on the waveform as non-linear saturation proceeds. The perturbation amplitude diminishes slightly as the trapped particles cool while losing energy to the increased curvature of the field. The magnetic bottle structures elongate without changing their wavelength. Panel 3 shows the relaxation of MM bubbles from a quasi-periodic structure back towards a uniform field with individual bubbles decaying stochastically. Dips are observed in the “solid line state” where some of the bubbles remain while most have collapsed or mostly collapsed.

magnetosonic plane waves. *Schwartz et al.* [1992] proposed that SLAMS form in the foreshock region of quasi-parallel shock and are then convected into the magnetosheath. We have analyzed numerous individual “peaks” within the Voyager (1 and 2) and Pioneer (10 and 11) datasets where high time magnetic field data are available for minimum variance analysis. All of the peaks we have analyzed are linearly or nearly linearly polarized which is consistent with the expectation for mirror modes and not SLAMS. In addition, under nominal IMF conditions at Jupiter, the dayside bow shock is quasi-perpendicular not quasi-parallel. While a small fraction of the events that we have identified as mirror mode peaks may indeed be SLAMS, we believe that they do not significantly impact our statistics or their interpretation.

[39] *Leckband et al.* [1995] observed isolated large amplitude structures in the AMPTE-UKS data that our criteria would identify as peaks during intervals of exceptionally large β (~ 30). The AMPTE ion distribution functions during these intervals were consistent with those predicted by nonlinear saturation theory of *Kivelson and Southwood* [1996] and the observed β was consistent with the *Pantellini* [1998] result. Particles trapped in the field minimum of a mirror mode structure deliver momentum to the field at their mirror points. This momentum transfer deforms the shape of the magnetic bottle so that it changes from a sinusoidal structure to a sausage-like structure. Loss of trapped particle energy reduces the pressure of the trapped

particles and consequently the minimum field increases (Figure 10, panel 2). *Kivelson and Southwood* [1996] conclude that stability occurs by the combination of the field decrease between the magnetic mirrors and the motion of magnetic mirrors away from the minimum in the trapped particle well.

[40] Our model of the growth and evolution of mirror structures in the Jovian magnetosheath is summarized in Figure 10. We describe mirror mode waves as quasi-periodic structures that form along the background field in isolated flux tubes (see the wire frame model of *Constantinescu* [2002] and discussion therein). Linear growth increases the amplitude (δB) of the structures while preserving the waveform (panel 1). In the Constantinescu model [*Constantinescu*, 2002], linear growth occurs if either $\beta_{o\perp}$ (background component of β normal to the background field direction) increases or if the anisotropy of the plasma (A_o) increases. However, for a given value of A_o the bottle wavelength to radius ratio (L/R) becomes nearly insensitive to increasing $\beta_{o\perp}$ [*Constantinescu et al.*, 2003] and linear growth cannot proceed. If A_o is taken as 1.5, then the critical value of $\beta_{o\perp} \approx 4$. If the plasma along a streamline remains unstable to mirror growth long enough and the plasma β and anisotropy are sufficiently high [*Pantellini*, 1998], nonlinear growth saturation may occur. During this phase, the individual mirror bottles elongate into sausage-like structures that are observed as mirror mode peaks (panel 2). As the plasma cools and its anisotropy

diminishes, the mirror structures begin to collapse under magnetic tension. If this process is stochastic, then individual structures decay at different rates. Since the particles that are responsible for the existence of the magnetic bottles are trapped within individual bottles, there is no communication between bottles. Therefore stochastic relaxation is a plausible mechanism for the collapse of mirror mode structures (panel 3). Inflated bottles (those that collapse later) appear as dips while the collapsed bottles become indistinguishable from the background field.

[41] This model is consistent with our observations of the spatial distribution of mirror mode structures and the simulated distribution of plasma β . Near the bow shock, we commonly observe quasi-periodic mirror mode structures but seldom observe either peaks or dips. Mirror mode wave trains that extend from near the bow shock into the middle magnetosheath tend to have amplitudes that increase away from the bow shock. These observations suggest that mirror mode structures form near the shock and grow as they move through the sheath. Linear growth increases the field perturbation amplitude while preserving the quasi-periodic waveform. Changes in longitudinal wavelength resulting from plasma acceleration or deceleration, and changes in the transverse wavelength related to evolving plasma parameters (anisotropy, β_{\perp}) in the linear regime, do not change the quasi-sinusoidal nature of the mirror mode waveform [Constantinescu *et al.*, 2003]. Peaks are found primarily in the middle magnetosheath on the dayside where plasma β remains high for tens of hours along typical flow streamlines (Figure 9). Under these conditions, mirror structures may undergo nonlinear growth saturation. During this process, individual magnetic bubbles elongate along the background field direction into sausage-like structures. In a space-filling geometry, the sausage-like structures fill the volume with a significantly higher fraction of low field than high field. As the structures are convected past the observing spacecraft, the field appears to “peak” in the high field regions while mostly remaining in a low field state. While truly space filling geometries are not supported by the Bessel function form of the Constantinescu model [Constantinescu, 2002], the most closely packed spacing is achieved by truncating the Bessel function at the first zero crossing. Finally, as plasma β approaches unity, the instability criterion is no longer met and the mirror structures begin to decay away. Lower β plasmas are commonly found near the magnetopause and on the flanks of the magnetosheath where dips are most commonly observed. As individual bottles collapse, the bottles that have not yet collapsed are observed as dips in the magnetic field.

5. Conclusions

[42] We observe compressive magnetic field fluctuations that are consistent with mirror structures throughout the magnetosheath of Jupiter. These structures appear to form near the bow shock and evolve with the plasma that carries them. Our observations are generally consistent with the evolution model put forth by *Bavassano Cattaneo et al.* [1998]. The BC model has quasi-periodic mirror structures forming near the bow shock. The structures increase in amplitude and transverse wavelength as they move away

from the shock. As the plasma β decreases and becomes mirror stable, the field enhancements decay leaving only field reductions or dips.

[43] The BC model does not explain the formation of the peak structures we observe in the dayside middle magnetosheath. *Bavassano Cattaneo et al.* [1998] correctly interpret the *Kivelson and Southwood* [1996] model that “predicts that the fully evolved mirror modes do not have a sinusoidal spatial structure, but consist mainly of holes.” A spatial structure consisting mostly of holes can produce a time series that appears to have peaks rising up from a low “background” level (Figure 9). The *Bavassano Cattaneo et al.* [1998] model is based on a very limited set of pre-Cassini Saturn observations and our identification criteria at Saturn only find during two short time intervals included in that study: Voyager 2 day 237, 0415–0425 UT and Pioneer 11 day 243, 1941–2002 UT. These intervals may have been too short to be included in the BC model. The BC model of evolution of mirror structures explains the bulk of the Saturn observations, as well as most of those at Jupiter.

[44] We have extended the BC model to include the formation of mirror mode peaks through the process of nonlinear saturation as described by *Kivelson and Southwood* [1996] but we have not explained why mirror structures in the form of peaks are seldom reported in the magnetosheaths of planets other than Jupiter. It is possible that the presence of peaks results from a particularly favorable variation of plasma β and temperature anisotropy with distance along the streamlines. Figure 6 shows that the peaks appear most often in regions where β values are of order five. Another possibility is that the wave growth in the nonlinear regime is extremely slow and that fully developed structures are only found in plasmas that have had many hours to develop these structures. Figure 3 shows that peaks are preferred when the nearest magnetosheath boundary is the bow shock, but that observing spacecraft is 5–30 hours away from crossing this boundary. The simulation result shown in Figure 9 is consistent with this observation. Only at Jupiter are magnetosheath dwell times commonly on the order of tens of hours. Lastly, most of the studies of mirror modes in the terrestrial magnetosheath have focused on the more common mirror dips and quasi-sinusoidal forms. It may well be the case that peaks represent about the same fraction (~10%) of the total terrestrial magnetosheath mirror modes but that authors other than *Leckband et al.* [1995] and *Lucek et al.* [1999b] have focused their analyses on the more common forms. None of these explanations is particularly satisfying. Even slow plasma processes typically develop much faster than the 1000+ ion gyroperiods we observe, plasma β commonly is as large as five in other planetary magnetosheaths without peaks being routinely reported.

[45] The Cassini Saturn observations may provide additional insight into the processes that form mirror mode structures and control their evolution in the magnetosheaths of the outer planets. Cassini has a high time resolution magnetometer and can acquire fairly high time resolution plasma measurements when the spacecraft is properly oriented. Finally, orbit of Cassini will take it through the magnetosheath at a large range of local times, radial distances, and presumably solar wind conditions which will provide opportunities for this and other models to be tested.

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