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Statistical properties of mirror mode structures observed by Ulysses in the magnetosheath of Jupiter

G. Erdős

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Balogh

The Blackett Laboratory, Imperial College, London, England, United Kingdom

Abstract. During the outbound pass of the Jovian magnetosheath in February 1992, a large number of magnetic depressions, without a significant change in the direction of the magnetic field vector, were observed by the Ulysses magnetometer. These low-frequency fluctuations, identified earlier as mirror mode waves, lasted about 1 day. The largest amplitude fluctuations (with a decrease in the field magnitude by a factor 3, on average) were observed just after the spacecraft crossed the magnetopause. The amplitude of the waves decreased as Ulysses approached the bow shock. We report here the results of a systematic study on the statistical properties of these field depressions. We have found that there is a saturation in the level of low field at about 1.3 nT. The average duration of the depressions is about 40 s, corresponding to a spatial size of about 20 gyroradii of the plasma protons. The angle between the magnetic field vector and the minimum variance direction is almost perpendicular, the average of that angle for the 350 individual field depressions we have analyzed is 83°. Constraints on the theoretical models which these observations impose are discussed. Many characteristics of the field depressions suggest the importance of nonlinear effects. The longitudinal size of the weak field seems rather large, raising the question whether the particles have enough time to fill in that space during the development of the instability. This difficulty might be resolved if energetic particles are involved.

1. Introduction

Numerous experiments in space plasma have observed that under special circumstances, the magnitude of the magnetic field shows characteristic decreases while the direction of the field vector does not change significantly. The usual site of such observations is the magnetosheath of the Earth [*Tsurutani et al.*, 1982; *Hubert et al.*, 1989] and that of other planets, including Jupiter [*Balogh et al.*, 1992b; *Tsurutani et al.*, 1993b] and Saturn [*Tsurutani et al.*, 1982]. Similar magnetic field variations were reported in the magnetotail of the Earth [*Tsurutani et al.*, 1984], in the environment of Halley's comet [*Russell et al.*, 1987], and, recently, in the Ulysses observations, even in the interplanetary field [*Tsurutani et al.*, 1992; *Winterhalter et al.*, 1994], suggesting that this phenomenon may be a common occurence in space plasmas. The magnetic field depressions typically last several tens of seconds; thus the frequency associated with the waves is very low, in the range well below the gyrofrequency of plasma particles. When plasma measurements are available with an adequate time resolution, the plasma density is usually anticorrelated with the magnetic field magnitude, providing the basis for the identification of the instability as mirror mode [*Tsurutani et al.*, 1982].

The geometry of the field depressions is similar to that found in some laboratory experiments, in which high-density plasma is confined by an enhanced magnetic field. Although, due to collisions, the laboratory plasma is very different from space plasma, an analogy may be sought by raising the question of the development and stability of the mirror mode structures. Observational evidence that such mirror mode waves may exist in space have attracted many theoretical [*Hasegawa and Chen*, 1987; *Southwood and Kivelson*, 1993] and numerical [*Price et al.*, 1986; *Gary et al.*, 1993; *McKean et al.*, 1994] studies. It is well known [*Tajiri*, 1967; *Hasegawa*, 1969; *Hasegawa and Chen*, 1987] that the requirement for the mirror mode instability to grow is a high-β plasma ($\beta \gtrsim 1$) and a temperature anisotropy of plasma ions ($T_\perp/T_\parallel > 1$). However, temperature anisotropy, as a nonequilibrium state, may cause other instabilities to grow as well. Recently, *Gary* [1992] has suggested that in an anisotropic plasma, the ion cyclotron wave may grow faster than the mirror mode. The detailed explanation of the characteristic features of the mirror mode waves, and even their existence, is still under debate.

During the Ulysses flyby of Jupiter, enhanced low-frequency wave activity was observed when the spacecraft traversed the magnetosheath on the outbound pass

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[*Balogh et al.*, 1992b; *Tsurutani et al.*, 1993b]. These fluctuations, identified as mirror mode waves, lasted almost 1 day, which is the longest such wave train ever recorded. This data set thus gives a unique opportunity to study the characteristics of the instability. The purpose of this paper is to make a quantitative and statistical assessment of the various physical parameters which characterize the fluctuations of the magnetic field. In section 2 we describe the data analysis method and give the results in the form of distributions of physical parameters based on the analysis of 350 individual field depressions. In section 3 we discuss how the observations affect our present knowledge of mirror mode waves. In order to avoid the danger of subjectivity, we did not select individual events as being "typical," but used instead average values determined from the distributions. Some of our arguments concerning the discrepancy between observations and theories could have been demonstrated more easily by choosing extreme cases. However, using average values only, our conclusions have a stronger objective basis.

2. Observations

Magnetic field measurements on the Ulysses spacecraft were made by the dual-sensor magnetometer. We have used the highest time resolution data, 1 vector/s. The Ulysses instrument has been described in detail by *Balogh et al.* [1992a]. Here we would like to point out that the spacecraft-induced magnetic background at the sensor is only of order of 30 pT, and that the overall offsets are determined with the same accuracy. As a result, magnetic field vectors are measured with an accuracy significantly better than 0.1 nT, and the direction of the field can be reliably determined even when its magnitude is close to 1 nT.

The magnitude of the magnetic field measured during the outbound pass of Ulysses through the Jovian magnetosphere in Februray 1992 is shown in Figure 1. Arrows mark the magnetopause (MP) and bow shock (BS) crossings identified by the Ulysses plasma instrument [*Bame et al.*, 1992]. Magnetosheath crossings took place between 80 and 150 R_J. Not all boundary crossings are confirmed without doubt, but the observations nevertheless show that the spacecraft crossed at least intermittently from the magnetosheath to the magnetosphere or to interplanetary space during this period. It is clear from Figure 1 that the first magnetopause crossing on February 12 at 1345 UT coincided with the onset of enhanced magnetic field fluctuations.

2.1. Magnetic Field Fluctuations

The magnetic field observations in the magnetosheath of Jupiter are shown in more detail in Figure 2. The

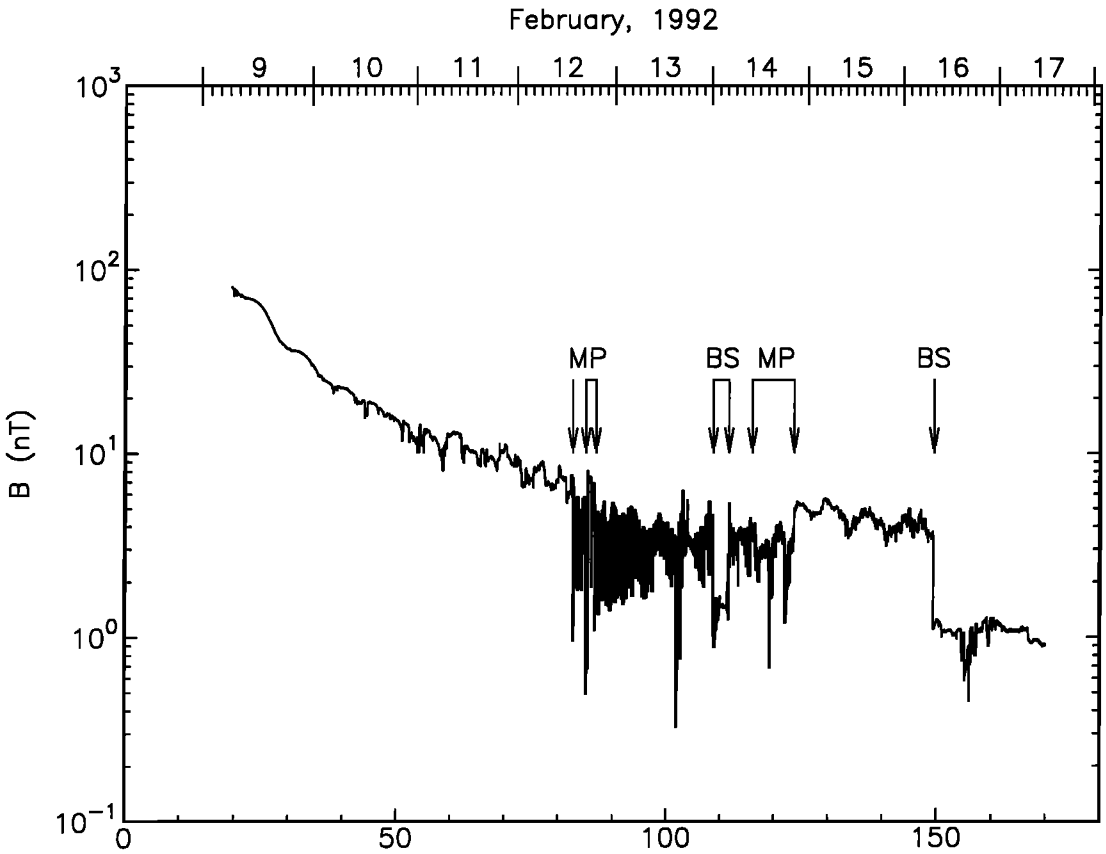

Figure 1. Magnetic field magnitude measured during the outbound trajectory of Ulysses at Jupiter. Arrows with labels MP and BS mark the time of the magnetopause and bow shock crossings, respectively. The horizontal scale gives the distance from Jupiter in units of Jovian radii.

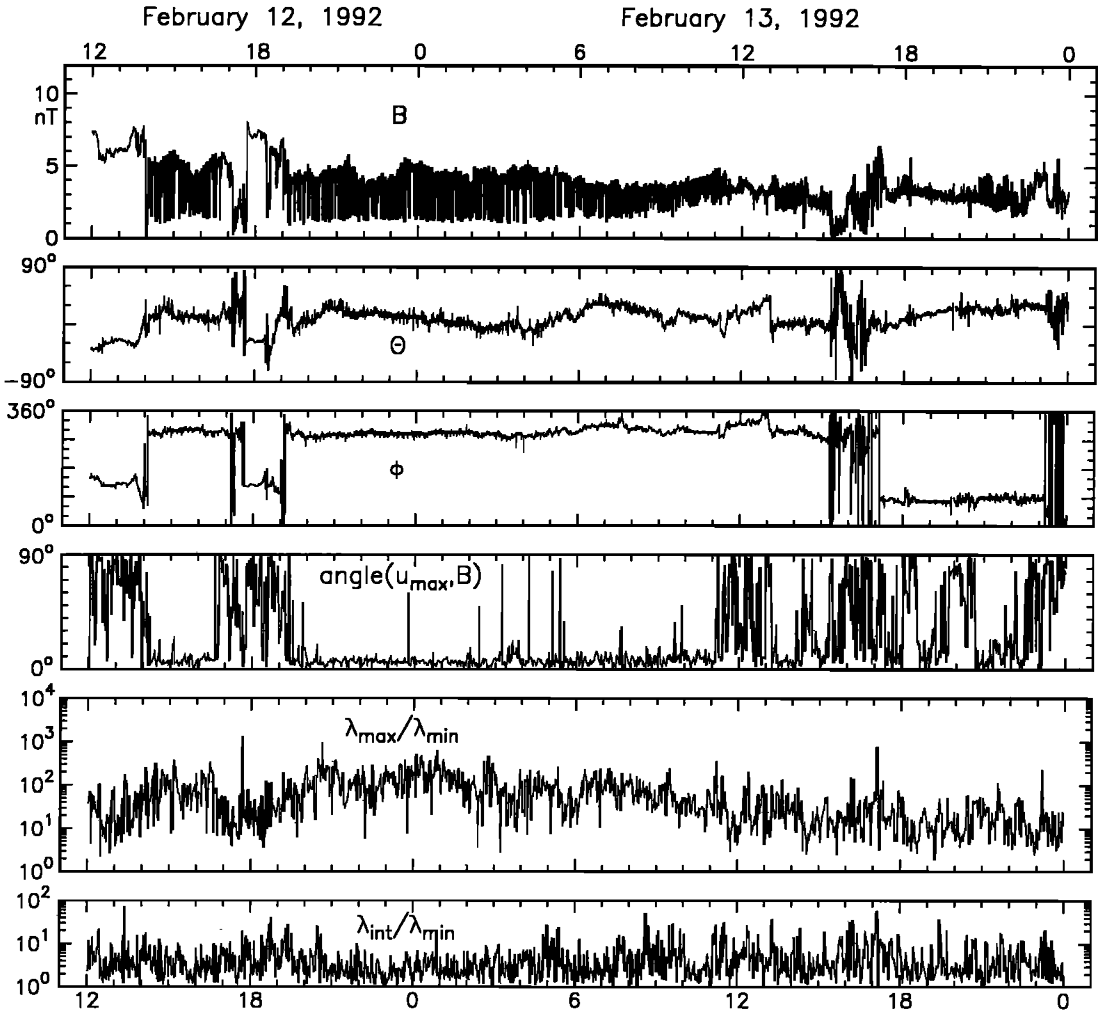

Figure 2. Magnetic field measured by Ulysses in the magnetosheath of Jupiter. The top three panels show the magnetic field vector in polar coordinates. The fourth panel shows the angle between the magnetic field vector and the direction of maximum variance. The bottom two panels show the ratios of the eigenvalues of the covariance matrix.

top three panels show 10-s averages of the magnetic field magnitude and direction from 1200 on February 12 to 2400 on February 13, 1992. This overview of the 1 $^1/_2$ - day interval is too long for the fluctuations in the magnetosheath, which took place on the scale of minutes, to be seen in detail, but it provides an overview of the intervals when the fluctuations took place and of their amplitudes. It is also clear in this figure that the fluctuations affected the magnitude of the field much more than its direction. The large-amplitude fluctuations in the field were first observed from 1400 UT on February 12, for about 2 $^1/_2$ hours. After 1900 UT the fluctuations were observed again, this time for almost a day. The time at which the fluctuations ended is less clear, as their amplitude decreased gradually after 0600 UT on February 13. The intervals during which the fluctuations were observed on February 12 coincided with the observations of hot and dense plasma [*Bame et al.,* 1992], suggesting that the magnetic field fluctuations occured in conditions of high-β plasma. The abrupt changes in the plasma parameters were identified as magnetopause crossings [*Bame et al.,* 1992], when Ulysses went back temporarily into the Jovian magnetosphere; at that time the magnetic fluctuations also disappeared.

A more detailed inspection of the magnetic field time profile (as shown in Figure 5 and discussed later) provides evidence that the fluctuations are not wavelike (with both increases and decreases in magnitude) but rather that there are sudden decreases from a slowly changing level. We note from Figure 2 that the minima of the field "dips" vary less during the first half of the observations, that is, until about 0400 on February 13. This feature will be examined in more detail later. The importance of the asymmetry in the field fluctuations in the sense that the field is more likely to decrease than to increase from a steady background level during the intervals of fluctuations will be emphasised in the discussion. At this point we note, however, one exception to this statement. From 2040 to 2220 UT on February 13, the field fluctuations consisted of increases above the background, rather than decreases, as during the rest of the observations. Such fluctuations were observed in the magnetosheath, shortly after the inbound bow shock crossing of the bow shock [*Tsurutani et al.*, 1993a]. The authors suggested that the instability was generated by $\approx$ 2–keV ion beams, reflected from the bow shock. This may well have been the case during the outbound pass as well, but this investigation is beyond the scope of this paper.

Minimum variance analysis of the magnetic field vectors was performed, using a 5–min long sliding window (with 1–min shifts) through the period covering the large-amplitude fluctuations. The bottom two panels in Figure 2 show the time evolution of the ratios of eigenvalues from the minimum variance analysis. The maximum to minimum eigenvalue ratio ($\lambda_{max}/\lambda_{min}$) is large, of order 100 during the intervals of enhanced fluctuations, while the intermediate to minimum ratio ($\lambda_{int}/\lambda_{min}$) is relatively small. This means that the variance ellipsoid is cigar-shaped, rather than pancake-like. The direction of the maximum variance vector ($\mathbf{u_{max}}$) is very closely aligned to the field vector ($\mathbf{B}$), as shown in the fourth panel (from the top) in Figure 2. The angle between these two vectors is less than 10° during the intervals of large-amplitude field fluctuations. In other words, it is the magnitude of the field which changes, rather than its direction. As a consequence, the angle Θ_{Bk} between the field vector and the minimum variance direction (known as the direction of wave propagation) is close to 90°. This statement is true even when the minimum variance direction cannot be determined precisely (i.e., when $\lambda_{int}/\lambda_{min} \approx 1$).

The nature of the field fluctuations can be further investigated by determining the distribution of the magnitude of the field vectors. Such a distribution is shown in Figure 3, covering the interval from 1410 UT on February 12 to 0300 UT on February 13, but excluding the interval without fluctuations from 1650 to 1920 UT on February 12. Later intervals were not included in this analysis because of the slow variations in the amplitude of the fluctuations, as seen in Figure 2. The distribution in Figure 3 has two relatively sharp peaks: the higher is for a value of the field of about 4.1 nT, the lower is for about 1.3 nT. This distribution suggests that during the period of large-amplitude fluctuations, the plasma had two "states," characterized by the high and low values of the magnetic field magnitude. As is apparent in Figure 3, the plasma is more frequently in the high field "state" during this interval.

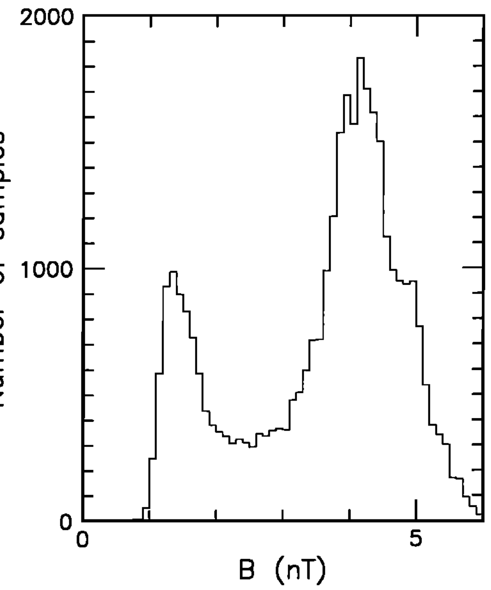

Figure 3. Distribution of the magnitude of the magnetic field vector in the magnetosheath during the interval 1410 UT February 12 to 0300 UT February 13, 1992, excluding the interval when Ulysses reentered the magnetosphere.

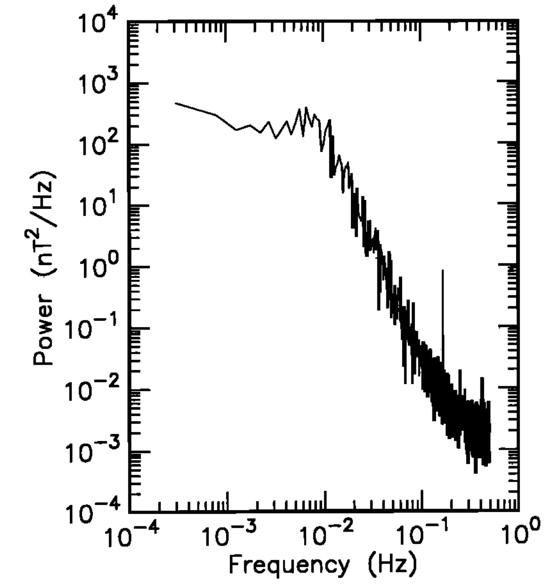

Figure 4. Power spectrum of the field magnitude from 0000 to 0216 UT February 13, 1992.

The power spectrum of the field magnitude was calculated during various time intervals to find out whether the fluctuations were periodic. For each spectrum, 8192 points of the highest time resolution data (i.e. 1 vector/s) were used. The power spectrum for the interval from 0000 to 0216 UT, February 13, is shown in Figure 4. Similar spectra were obtained for other intervals covering the field fluctuations. The spectrum shows, arguably, a very broad peak at around 10^{-2} Hz, but a more likely interpretation is that it shows a plateau extending from the lowest frequencies up to about 10^{-2} Hz. This latter interpretation is consistent with many individual field variations (decreases or increases) of about 100 s, distributed randomly in time. A Monte Carlo simulation of the magnetic field which consists of randomly distributed field "dips" has been performed and had a spectrum which reproduced well the observed spectra. The shape of the power spectrum thus suggests that the field fluctuations show little periodicity, and are more likely to consist of individual, uncorrelated field decreases. This question will be investigated further in this paper.

2.2. Characteristics of the Field Dips

Since the fluctuations of the field magnitude are at most weakly periodic, we cannot investigate them with conventional techniques commonly applied to wave structures, but rather we need to carry out a statistical analysis of the individual field dips. Partly because the

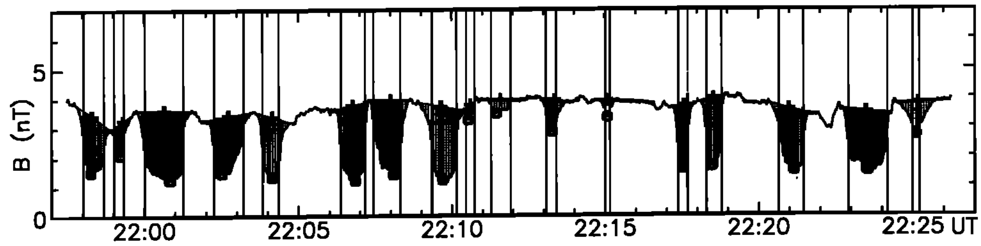

Figure 5. Sample of the observed magnetic field depressions, with indication on the analysis technique for determining their parameters. Vertical lines define the intervals of "low field state." The open circles and pluses mark the magnitude of the "low field" and "high field" states, respectively.

identification of a field drop may be subjective and also because of their very large number, a computer algorithm was developed for the survey and characterization of these structures. The identification of the field dips was based on the time derivative of the magnetic field. The slope of the function $B(t)$ was determined with a time resolution of 1 s. In order to avoid spurious large derivatives arising from statistical fluctuations or from errors in the measured field, the slope of $B(t)$ was not calculated from the nearest data points, but a linear fit was applied for each interval of 11 s. We note that this "smoothing" of the time derivative necessarily introduced a bias in the recognition of very short duration fluctuations. The next step in the data processing was to identify local minima and maxima of the time derivative. The local maxima were identified from periods when the slope exceeded a certain positive threshold. Similarly, the field minima were identified from searches through periods when the slope had a value less than a certain negative threshold. The algorithm used may fail to recognize the smallest field fluctuations if the thresholds are set too high. On the other hand, if the threshold is set too low, the algorithm may produce too many "identifications" at local extrema of the time derivative of the field which are not actually related to field dips. After trying several values for the thresholds, the best choice was found to be ± 0.03 nT/s. Even then, some manual interaction proved necessary to remove a few apparently spurious extrema. This left only a very few potentially controversial instances of field dips.

A typical sample of the field fluctuations is shown in Figure 5. The vertical lines mark the time of the steepest slopes, either negative or positive, as selected by the algorithm described above. We shall call the plasma as being in the "low field state" in between these vertical lines, and we define the duration of the field dips as the interval between these lines. The plasma is then in the "high field state" during the remaining time, that is, in the time intervals between consecutive dips. Turning to the height (change in the magnitude of the field) of the dips, the minimum value was taken to be the local minimum of the field magnitude. These points are marked with open circles in Figure 5. The determination of the level from which the field "dropped" is more complicated and involves a linear interpolation. Starting from the left vertical line bordering the drop, the local maximum of the field preceeding the drop was determined, using a 5-s-long moving average, in order to filter spurious fluctuations. The local maximum following the drop was determined in a similar fashion. The "high" state of the magnetic field was then determined as the centre value of the field, obtained from linear interpolation between the two maxima. These values are marked by plus signs in Figure 5. In the following we denote the field values at the points marked by pluses and open circles as B_{high} and B_{low}, respectively.

2.3. Statistical Analysis of the Field Dips

With the identification and parametrization of the individual magnetic field dips as described in the previous section, we were able to study the nature of the magnetic field instability statistically. We analyzed the first half of the observation period, that is, the interval from 1400 UT, February 12 to 0300 UT, February 13. During this interval 350 individual field dips were identified.

First, distributions of the durations of the "high" and "low" field states (i.e., the distributions of time intervals between vertical lines as in Figure 5) were determined. In the top panel of Figure 6 the histogram of the field dips is shown, as a function of duration, using 10-s

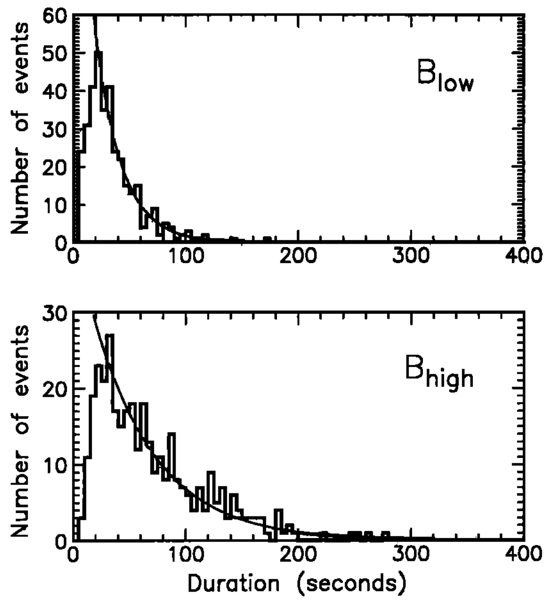

Figure 6. Distribution of the durations of the field "dips" (top panel) and "high field" intervals (bottom panel) for 350 field depressions observed from 1410 UT February 12 to 0300 UT February 13. Fits of exponential distribution to the data are shown by thin lines.

bins. After appropriate normalization, this figure can be interpreted as the probability density function of the duration of field dips. In a similar way, the lower panel in Figure 6 shows the distribution of the duration of the field in its "high" state. This distribution of the intervals of "high" field is much broader than that of the field dips. This is not surprising, given that the field is more often in its "high" state, as shown in Figure 3. Both distributions appear to peak at around 30 s; however, as described in the previous section, the smoothing of the time derivative of $B(t)$ introduced a bias against the recognition of short duration events. Therefore, the small number of field dips with duration from 0 up to about 20 s could be an artificial effect.

Beyond about 30 s both distributions in Figure 6 look exponential, that is, $p(t) = e^{-t/\tau}/\tau$. We may fit this curve to our observations, the only parameter of the function, τ can be easily calculated from the expectation value $< t >$ of the duration. The expectation value can be determined from the experimentally established probability distribution, that is, from the histograms in Figure 6 (with appropriate normalization applied). In this case we may take the cutoff at small t into account precisely. If we discard events with $t < t_0$ where $t_0 = 20$ s, the theoretical expectation value is modified to

$$< t > = \frac{\int_{t_0}^{\infty} t \frac{e^{-t/\tau}}{\tau} dt}{\int_{t_0}^{\infty} \frac{e^{-t/\tau}}{\tau} dt} \qquad (1)$$

This form serves as an equation for the parameter τ (by substituting the measured expectation value on the left-hand side). The theoretical curves thus obtained were multiplied with factors to match the total number of observed events, and shown in Figure 6. Inspecting the top panel, the good agreement between the theoretical curve and the observed points beyond the cutoff region confirms that the distribution of the duration of low field state is exponential. By an analogy to radioactive decays, this can be interpreted that the probability that in the next moment the field jumps back from low state to high state does not depend on how long the field is already in the low state (i.e., the low field state is not accumulated to give a higher probability). A similar conclusion may be drawn for the duration of high field state. This analysis gives evidence that the observed mirror mode structures are not ordinary waves with characteristic wavelength. However, we cannot exclude short timescale correlation, both for the high field state and the low field state, where the event selection algorithm has introduced a bias and prevented us to draw a firm conclusion.

Next, we determine the angle Θ_{Bk} between the minimum variance direction of the magnetic field and the direction of the average field. Each individual field drop was analyzed, with a time window which exceeded the nominal duration (low field state) by 30 s, in both directions. The result of the analysis is given in Figure 7. The top panel shows a histogram of the Θ_{Bk} distribution. The angle is very close to

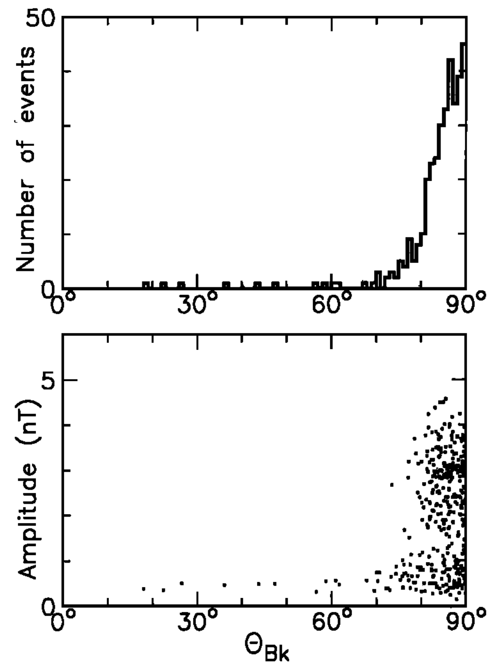

Figure 7. (top) Distribution of the Θ_{Bk} angle between the magnetic field vector and the minimum variance direction. (bottom) Scatter plot of Θ_{Bk} angle versus amplitude of depressions.

perpendicular, for the majority of the dips it is greater than 80°. The average of the Θ_{Bk} is 83.3°. The bottom panel of Figure 7 is a scatter plot of the amplitude of the dip, as defined by $B_{high}-B_{low}$, of the 350 field depressions versus Θ_{Bk}. This plot demonstrates that Θ_{Bk} depends weakly on the amplitude of the depressions, except for a few very small events. The observation that the minimum variance direction is nearly perpendicular to the field imposes a significant constraint on models that may be developed to understand the instability of the magnetic field.

Finally, we have analyzed the magnitude of the field dips. The two panels on top in Figure 8 refer to B_{high}, that is, the level from which the magnetic field dropped (see the definition of the plus signs in Figure 5). The bottom two panels are related to the lowest magnitude of the field (B_{low}) inside the dip (see the definition of the open circles in Figure 5). The left-hand panels of the figure show the distributions of these field values. The right hand panels give further details of the B_{high} and B_{low} distributions by resolving their dependence on the width (duration of the field dips), presented in a form of scatter plots. The B_{high} distribution shows that the value from which the field dropped fluctuates from event to event around 4.5 nT. According to the scatter plot on the right, this fluctuation does not show significant correlation with the width of the field dips. What is more interesting is the B_{low} distribution in the bottom panels in Figure 8. There is a very sharp peak in the distribution at around 1.3 nT, and a much broader peak at around 4 nT. The latter is due to narrow dips with durations hardly exceeding 40 s, as we can see in the scatter plot (bottom right-hand panel in Figure 8). For wide dips with long duration the minimum value of

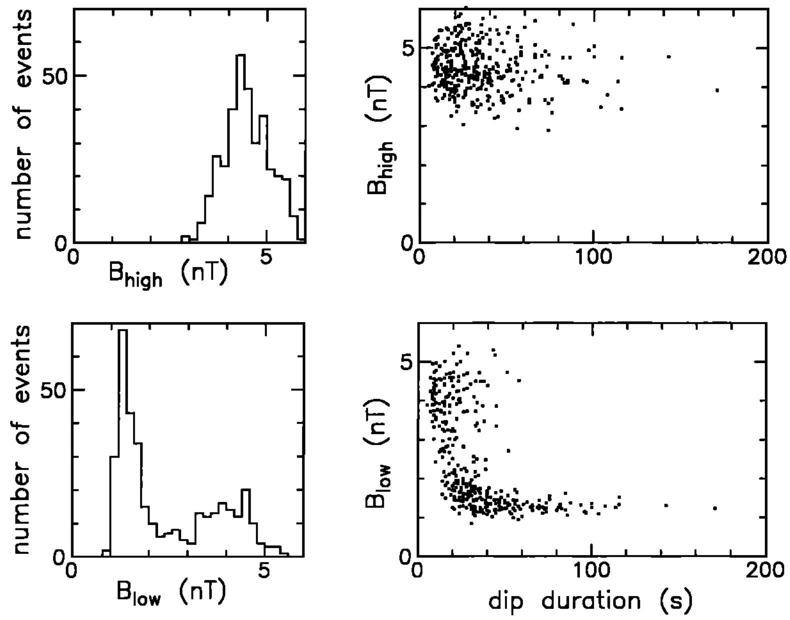

Figure 8. Distribution of the magnetic field magnitude in (upper left-hand panel) the "high" field state and in (lower left-hand panel) the "low" field state. The right-hand panels show scatter plots of the duration of the field dips versus (upper panel) "high" field magnitude and (lower planel) "low" field magnitude.

the field is fairly independent of the duration. In other words, the magnetic field does not drop further to a lower level even if the time of the low field state is long but the instability apparently becomes saturated at a field level around 1.3 nT. This tendency to saturation can be seen also in Figure 5.

Figure 9 shows the distribution of the field change itself, as defined by $B_{high}-B_{low}$. We have so far presented the results of the statistical study for the time period until 0300 UT, February 13. Here we extend the analysis for later time intervals as well (Figures 9b and 9c). The distribution in Figure 9a, covering the interval previously analyzed, has two major peaks. One is at around 0.5 nT, the other is at around 3 nT. The first peak, referring to small field dips is not necessarily a real one. Again, as discussed earlier, the number of small dips could be increasing with decreasing field change but, due to the event selection algorithm, we are unable to recognize them. The second peak is the important one, demonstrating that for large field dips, the most frequent field change is 3 nT. This value is remarkably high. Careful inspection of the peak at 3 nT shows that in reality, a sharp minimum at around 2.7 nT splits the peak. This local minimum seems significant, however, we do not intend to analyze the fine structure of the distribution in such detail. A more interesting feature of the observations is that the distribution has a broad minimum at about 1.5 nT. This means that the field dips are either large (about 3 nT) or small (about 0.5 nT) but that the intermediate field changes are rare. This statement is true only for the earlier times of observations. Later, as presented in Figures 9b and 9c (covering the time interval respectively from 0300 UT to 1200 UT and from 1200 UT to 2400 UT on February 13), the second peak has disappeared. Also, the value of the field drop is smaller, especially in the second half of February 13 (Figure 9c).

As to which parameter characterizes the magnitude of the field fluctuation best, it depends on the model to be developed. Besides the change in the magnitude the field, another reasonable measure is the ratio between the values of the field in the high state to its low state.

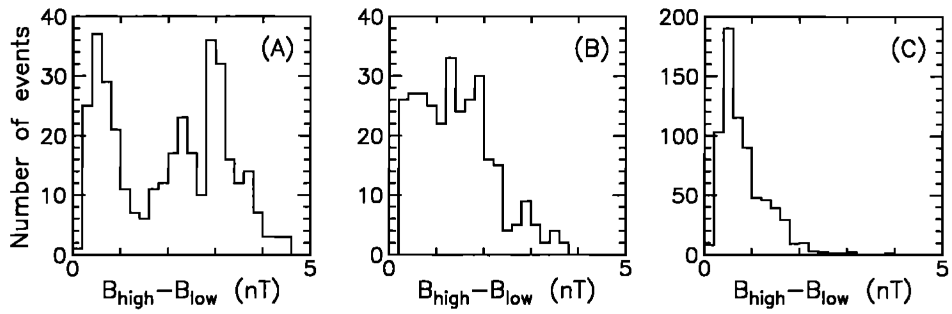

Figure 9. Distributions of the field change in the field dips in time intervals (a) 1400 UT February 12 to 0300 UT February 13; (b) 0300 UT to 1200 UT February 13; and (c) 1200 UT to 2400 UT February 13.

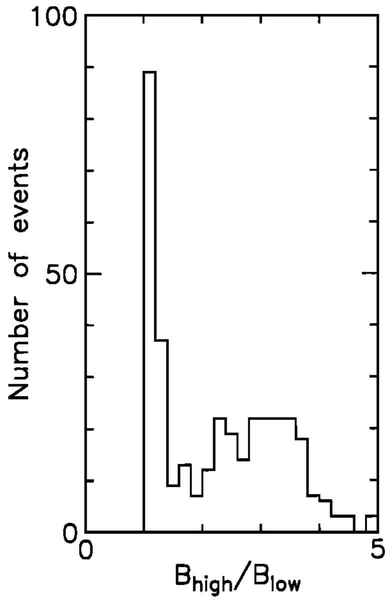

Figure 10. Distribution of the amplitude of field depressions (ratio of "high" field to "low" field) for the time interval 1410 UT February 12 to 0300 UT February 13.

The distribution, using this ratio as the parameter is shown in Figure 10, again for the time period from 1410 UT February 12 to 0300 UT February 13. The sharp peak slightly above $B_{high}/B_{low} = 1$ represents small field dips. The broad peak at around 3 is the one of interest, indicating that the most frequent large field drop corresponds to a factor of 3.

2.4. Summary of Observations

1. Fluctuations are restricted to the magnetosheath, with largest magnitude close to the magnetopause rather than to the bow shock.
2. The field is in high field state more frequently that in low field state.
3. The field magnitude between dips is flat.
4. The distribution of the duration of field dips is exponential, at least for longer events.
5. The angle between the magnetic field vector and the minimum variance direction (Θ_{Bk}) is close to perpendicular.
6. Field dips are large, a factor of 3 on average. The most frequent field changes are about 3 nT, intermediate (1.5 nT) dips are not frequent.
7. There is a saturation in the level of minimum magnetic field at about 1.3 nT.

3. Discussion

The very large number of magnetic field dips in the magnetosheath of Jupiter, observed by Ulysses during the outbound pass, provide an excellent opportunity for the statistical study of these fluctuations, which are believed to result from mirror mode instability. Unfortunately, the time resolution of the plasma detector on board was not high enough to demonstrate the most relevant signature of mirror mode structures, the time correlation between the field dips and the increase of the plasma pressure. Further, the instrument was not designed for the energy range of the Jovian plasma particles, and therefore did not measure the high energy tail of the spectrum. This gave an uncertainty in the determination of the plasma β and the temperature anisotropy of the plasma ions, which are the parameters involved in the criteria of the mirror mode instability to grow [*Hasegawa*, 1969]:

$$\beta_\perp \left(\frac{\beta_\perp}{\beta_\parallel} - 1 \right) - 1 > 0 \qquad (2)$$

Nevertheless, *Phillips et al.* [1993] demonstrated that plasma β was high (2-8) with positive temperature anisotropy; therefore the conditions were conducive to the growth of the mirror mode and ion cyclotron instabilities. Also, the signature of the magnetic field time profile resembles very much earlier observations of mirror mode structures in the magnetosheaths of Earth, Jupiter, and Saturn [*Tsurutani et al.*, 1982]; in the magnetotail of the Earth [*Tsurutani et al.*, 1984], and in the environment of comet Halley [*Russell et al.*, 1987]. Even without the use of plasma data, some of the instabilities other than mirror mode can be ruled out by analyzing the magnetic field data alone on the basis of the high measured value (close to perpendicular) of the angle between the magnetic field vector and minimum variance direction, in particular the ion cyclotron waves which should propagate parallel to field lines. All these arguments support the earlier identification of *Tsurutani et al.* [1993b] that the magnetic field fluctuations observed by Ulysses in the Jovian magnetosheath are mirror mode waves.

An interesting feature of the Ulysses observations is the timing of the wave amplitude. It is clear that the fluctuations are restricted to the magnetosheath of Jupiter, as we can see from the abrupt appearance and disappearance of the waves at the magnetopause crossings on February 12. However, the amplitude of the fluctuations decreases later as the spacecraft is traversing the magnetosheath toward the bow shock and, in fact, there is practically no wave activity close to the shock. One of the current interests in mirror mode waves is to find the source of the temperature anisotropy which is necessary to drive the instability. It had been proposed [*Thomsen et al.*, 1985] that the bow shock supplies the necessary free energy, by accelerating plasma ions and increasing their perpendicular momentum during the transmission downstream to the magnetosheath. For the Ulysses outbound magnotosheath crossing, *Tsurutani et al.* [1993b] argued that the instability continually grows as the plasma is convected downstream form the bow shock, resulting in a maximum wave activity at the magnetopause. However, the timescale of the convection seems much longer than any reasonable value for the instability to grow. We can suppose that the solar wind flow line, intersecting Ulysses close to the magnetopause, crossed the bow shock near the subsolar, "nose" point, which corresponds to a distance of about 200 R_J along the flow line. Taking into account that the amplitude of the fluctuations started to decrease when Ulysses was about half way in between the magnetopause and the bow shock, we may estimate the spatial scale length of the instability growth equal to about 100 R_J. The flow time in that distance is rather large, about 2×10^4 s. Therefore the growth rate should be very slow in order to match the observed spatial variation of the wave activity; we can estimate the resulting growth rate, normalized to the proton gyrofrequency as $\gamma/\omega_p \approx 10^{-3} \div 10^{-4}$.

An alternative explanation for the maximum wave activity at the magnetopause could be that mapping back the plasma flow to the bow shock, the shock was probably quasi-perpendicular, providing favorable conditions for the temperature anisotropy. At later times, as the spacecraft traversed the magnetosheath toward the bow shock, the flow line intersected the shock further and further away form the subsolar point which, assuming a Parker spiral magnetic field on average, suggests that the shock (at the flow line) became oblique rather than quasi-perpendicular. According to this scenario, one might expect the greatest wave activity downstream of the subsolar bow shock, which can be checked by looking at the inbound Ulysses data (note that the inbound and outbound bow shock crossings took place at Sun-Jupiter-spacecraft angles of about 25°and 95°, respectively). In fact, we have found magnetic field depressions which are possibly mirror mode waves, starting about 1 hour after the bow shock crossing, but much less in number than outbound. This can be explained, that contrary to expectation based on the theoretical Parker spiral angle, the bow shock was quasi-parallel on the inbound pass. Apart from geometrical considerations, we also have to bear in mind that the wave activity observed outbound changed on the timescale of a day, during which the interplanetary conditions might have changed considerably. The plasma density really increased as Ulysses approached the bow shock [*Phillips et al.*, 1993]; however, this increase is probably due to magnetohydrodynamic propagation effects in the magnetosheath rather than change of the interplanetary conditions. Note that the increase of the density implies an increase of plasma β, which would suggest an even larger mirror mode wave acivity closer to the bow shock, contrary to observations. Another, perhaps more relavant, change of plasma conditions in the magnetosheath is that close to the magnetopause, the composition measurements showed the presence of oxygen and sulphur ions [*Geiss et al.*, 1992], giving evidence that the plasma was mixed interplanetary and magnetospheric in origin. It seems difficult to explain why the wave amplitude is the largest close to the magnetopause rather than to the bow shock and the question needs further investigation. We would like to point out that it is not very obvious that the bow shock alone is responsible for the mirror mode fluctuations.

When comparing the observations with theoretical models, one of the important parameters is the size of the field dips in terms of gyroradii of plasma ions. The typical duration of the field dips is about 40 s (see Figure 6). If these structures are mirror mode waves, they do not propagate with respect to the plasma, therefore the component of plasma velocity vector perpendicular to the field line should be considered only when converting time to distance. The plasma velocity vector (more reliably determined from electron rather than ion data) was fairly constant in the magnetosheath, both the magnitude and the direction [*Phillips et al.*, 1993], similarly to the direction of the magnetic field (see Figure 2). The angle between the field line and plasma flow was close to perpendicular, about 70°, imposing little correction to the flow speed, which was about 360 km/s [*Bame et al.*, 1992]. Adopting these values, the average width of the magnetic field dips is $w =$ 13,000 km. A temperature of the plasma protons of 5×10^5 K, which showed little variation in the magnetosheath, was measured by *Phillips et al.* [1993]. We have determined the distribution of the spatial size (width) of the magnetic field depressions, expressed in units of the gyroradius (r_G) of plasma protons (taking the actually measured minimum field inside the dips in event to event). Such a distribution of the depression size for the time interval from 1410 February 12 to 0300 February 13 is shown in Figure 11. For this time interval, the average width of the mirror mode structures is $w = 20\ r_G$. This value is uncomfortably large when comparing with the theory of mirror mode waves, which predicts a width of the order of a few r_G only [*Price et al.*, 1986]. Earlier observations have reported even larger values (up to about 100 r_G) in some cases [*Tsurutani et al.*, 1992]. However, for the Ulysses observations, the plasma temperature was underestimated, up to by a factor of about 10, due to a considerable suprathermal population, not measured up to its the full energy extent [*Phillips et al.*, 1993]. This means that the gyroradius of plasma protons on average might be a factor 3 larger if one includes the suprathermal particles. Applying this correction to Figure 11, the peak of the distribution (the most probable depression size) and the average value would shift close to that expected from theory, but the tail

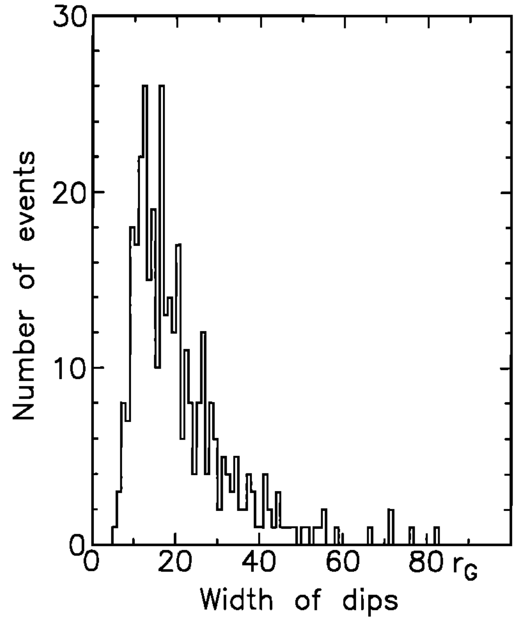

Figure 11. Distribution of the width of magnetic field depressions, expressed in terms of gyro radii of plasma protons for the time interval 1410 UT February 12 to 0300 UT February 13.

of the distribution towards large depression sizes still needs to be explained.

The angle between the magnetic field vector and the minimum variance direction is very close to perpendicular, for the average of the 350 events we have analyzed it is $\Theta_{Bk} = 83°$. Similar values have been reported earlier as well [*Tsurutani et al.*, 1992, 1993b]. However, numerical simulations predict about 60°–70°[*Price et al.*, 1986]. It is not clear if the observed large value is still consistent with theoretical expectations. One explanation could be that the Θ_{Bk} angle is shifted to close to perpendicular in the nonlinear phase of the development of the instability only. The bottom panel of Figure 7 does not support this idea, since that angle looks large also for small amplitude events, apart from a very few depressions (which may not be proper mirror mode fluctuations). Here we would like to point out the difficulties we face when explaining the observed field fluctuations in terms of mirror mode waves. The fact that the minimum variance direction is almost perpendicular to the field suggests that the size of the weak field region should be much larger in the direction along the field line than across it. We can estimate the length of the structures by $L = w\tan(\Theta_{Bk}) \approx$100,000 km. This value seems rather large. The problem is that the weak field region should be filled in by a larger number of plasma particles in order to maintain the pressure balance. These particles have to travel along the field line about a 100,000 km distance during the growth phase of the instability. Particles with zero pitch angle travel the fastest into the low field region, but even those need about 1500 s to complete the journey (equivalent to about 30 gyro periods). Thus the growth time γ^{-1} of the instability should substantially exceed 1500 s or, expressed in another way, the growth rate, normalized to the proton gyrofrequency, should be less than $\gamma/\omega_p \approx 0.005$.

The growth rate above is an upper limit, the growth of the instability needs particles which not only penetrate into the weak field region but bounce inside the field depression, between the two high field ends of the field lines during the development phase. Similar condition is present implicitly in kinetic theories of mirror mode waves by assuming that $\gamma/k_\parallel v_\parallel \ll 1$ [*Hasegawa*, 1969]. Here we would like to point out that due to the large longitudinal size of the field depressions, the condition is not readily satisfied, unless the growth rate is very small. This might be the case, because those particles having insufficient parallel velocity to bounce inside the weak field trap stabilize the plasma and reduce the growth rate of the instability, as shown by *Southwood and Kivelson* [1993]. Since the number of such, so-called resonant particles increases with increasing growth rate, they might serve as a break to prevent the instability to grow faster. However, if the growth of the instability is really so slow, then this makes the question whether any other instability than the mirror mode can grow faster important to consider. In particular, as has been suggested by *Gary* [1992], the ion cyclotron instability may successfully compete with the mirror mode in an anisotropic plasma. However, our observations are inconsistent with ion cyclotron waves.

The characteristics of the observations do not suggest that the plasma is marginally unstable. The distribution of the values of field dips, as shown in Figure 9a, has a significant minimum at around 1.5 nT, showing that the intermediate-sized field dips are rare. This would be unlikely to happen if the growth of the instability is very slow. The lack of the intermediate field changes suggests a more rapid, and perhaps highly nonlinear, development, which would result in the "bistable" behavior of the plasma shown by the observations. The distribution of the magnetic field values, shown in Figure 3, gives further evidence that the plasma is either in high field or in low field state, rather than in any state between these two. We can expect a nonlinear development of the mirror mode waves on the basis of the time dependence of the plasma β during the growth of the instability. In the kinetic treatment, the growth rate of the mirror mode instability is [*Tajiri*, 1967; *Southwood and Kivelson*, 1993]:

$$\gamma = \sqrt{2/\pi}k_\parallel v_\parallel \left\{ \left(\frac{\beta_\perp}{\beta_\parallel} - 1\right) - 1/\beta_\perp \right\} \tag{3}$$

According to our observations, the field magnitude drops by a factor 3 on average, as shown in Figure 10. This field drop corresponds to an order of magnitude drop in the magnetic field energy density. Furthermore, the plasma pressure should also increase in order to maintain the balance, resulting in an increase of β even further. This implies that the growth rate (equation (3)) should increase as the instability develops. However, this may not happen if the temperature anisotropy decreases in time. In fact, this may happen due to adiabatic focusing of particles when the field magnitude decreases.

The adiabatic focusing appears to be an important effect, especially since the average field drop is very large, a factor of 3. Assuming the conservation of the first adiabatic invariant, this implies a decrease of the perpendicular temperature by a factor of 3 as well. Meanwhile, the parallel temperature should increase if the energy of particles is conserved; however, this is not the case for the "resonant" particles (see work by *Soutwood and Kivelson* [1993] for details). At any rate, even if we neglect the possible increase of the parallel temperature, the temperature anisotropy should decrease by a factor of 3 at least during the development of the instability. Since the mirror mode instability requires an anisotropy greater than 1 to grow (equation (2)), the starting value of the temperature anisotropy should be at least 3. This rather large value at the start of the mirror mode instability is a problem as far as the competition of the ion cyclotron instability is concerned. Although a small He^{++} population in the plasma effectively reduces the growth rate of the ion cyclotron mode [*Price et al.*, 1986], for reasonable values of the He^{++} contamination the temperature anisotropy should be less than about 2, otherwise the cyclotron waves would grow faster [*Gary et al.*, 1993]. As for the mirror mode waves to grow the temperature anisotropy is expected to be between 1 and 2, the existence of field drops by a factor of 3 is a surprise, and therefore a mechanism which breaks down the conservation of the first adiabatic invariant should perhaps be considered. A very fast growth time of the instability which is comparable or less than the gyro period of protons would help here, but, in that case, the problem as to how the particles could fill in the low field region in a short time is even more difficult than discussed in previous paragraphs.

The shape of the magnetic field time profile (Figure 5) clearly indicates that the magnetic field tends to drop in many places, but there is no sign of the opposite deviation from the average level. Similar characteristics of the magnetic field have been observed practically in all fluctuations identified as mirror mode waves earlier [*Tsurutani et al.*, 1982, 1984, 1992, *Russell et al.*, 1987]. The theory of mirror mode waves suggests that both the weakening and the enhancements of the field magnitude should happen. Although the asymmetry of the observations in this respect has not been emphasised in earlier reports, it is worthwhile to discuss its possible cause. When comparing theories with observations on mirror mode structures, we have to bear in mind that theories usually treat the problem in linear approximation while measurements suggest the importance of nonlinear effects, and what we actually observe is the saturated final new state of the plasma. We may continue our earlier discussion on the consequences of the adiabatic invariance here. It is true that the increase of the field should increase the temperature anisotropy of plasma ions, and therefore unlike for a decrease in the field (field dips), this would help maintain the instability criteria. However, the plasma β is expected to decrease dramatically which, according to (2), could quench the growth of any field increase.

Most of the earlier papers on the observations of magnetic depressions have argued that the observations support the theory of mirror mode waves, although, in some cases, the measured parameters were on the margin of acceptable values (or even beyond). We have very good statistics in the magnetosheath of Jupiter, therefore any discrepancy between observations and theories must be considered seriously. In the discussion we wanted to emphasise those findings which are not readily explainable in the framework of present theories. One obvious reason for disagreement could be that our observations, especially the large amplitude of the waves, suggests the importance of nonlinear effects, not incorporated in most of the models. Beyond that, however, we find it also puzzling that the size of the dips along the magnetic field seems rather large, requiring rather a long time for the particles to fill in the weak field region. This difficulty might be solved if we assume that the particles with temperature anisotropy are energetic. This was suggested for the event observed in the magnetotail of the Earth [*Tsurutani et al.*, 1984]. Also, in the case of Halley's comet, the pickup particles are expected to control the development of the mirror mode waves [*Russell et al.*, 1987]. For the Ulysses outbound crossing of the Jovian magnetosheath, the spectrum of the plasma protons also showed a suprathermal tail [*Phillips et al.*, 1993].

The obvious complexity of the development of the mirror-type instability requires further work to match theoretical expectations with the results presented in this paper. A possible way forward is to implement nonlinear analytical and numerical models, to include the effects of alpha particles and suprathermal particles, and to explore their effects on competing growth rates for different instabilities. This would allow the role (if any) of more energetic ions, possibly of Jovian origin, to be considered. The constraints provided by the large number of instances of the instability observed in the Jovian magnetosheath, their relative location with respect to the magnetopause and bow shock, and their apparent saturation need to be addressed in any numerical modelling.

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A. Balogh, The Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, England, United Kingdom. (e-mail: a.balogh@ic.ac.uk)
G. Erdős, KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest, P. O. Box 49, Hungary. (e-mail: erdos@rmki.kfki.hu)

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