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Magnetosheath and heliosheath mirror mode structures, interplanetary magnetic decreases, and linear magnetic decreases: Differences and distinguishing features

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[1] There has been considerable confusion in the literature about what mirror mode (MM), magnetic decrease (MD), and linear magnetic decrease (LMD) structures are and are not. We will reexamine past spacecraft observations to demonstrate the observational similarities and differences between these magnetic and plasma structures. MM structures in planetary magnetosheaths, cometary sheaths, and the heliosheath have the following characteristics: (1) the structures have little or no changes in the magnetic field direction across the magnetic dips; (2) the structures have quasiperiodic spacings, varying from ~20 proton gyroradii (r_p) in the Earth's magnetosheath to ~57 r_p in the heliosheath; and (3) the magnetic dips have smooth edges. Magnetosheath MM structures are generated by the mirror instability where $\beta_\perp/\beta_\| > 1 + 1/\beta_\perp$ (β is the plasma thermal pressure divided by the magnetic pressure). In general, the sources of free energy for the mirror instability are reasonably well understood: shock compression, field line draping, and, in the cases of comets and the heliosheath, also ion pickup. The observational properties of interplanetary MDs are as follows: (1) there is a broad range of magnetic field angular changes across them; (2) their thicknesses can range from as little as 2–3 r_p to thousands of r_p, with no "characteristic" size; and (3) they typically are bounded by discontinuities. The mechanism(s) for interplanetary MD generation is (are) currently unresolved, although at least five different mechanisms have been proposed in the literature. Tsurutani et al. (2009a) have argued against mirror instability for those MDs generated within interplanetary corotating interaction regions. Interplanetary LMDs are by definition a subset of MDs with small angular changes across them (θ < 10°). Are LMDs generated by the mirror instability or by another mechanism? Is it possible that there are several different types of LMDs involving different generation mechanisms? At the present time, no one knows the answers to these latter questions.

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1. Introduction

1.1. Mirror Instability

[2] The mirror instability is a well studied phenomenon, from both theoretical and observational viewpoints. The condition for instability is: $\beta_\perp/\beta_\| > 1 + 1/\beta_\perp$, where β is the thermal plasma pressure divided by the magnetic pressure. The subscripts $\perp$ and $\|$ correspond to the components perpendicular and parallel to the ambient magnetic field B_0, respectively. The original works for this instability are found in work by *Chandrasekhar et al.* [1958] and *Vedenov and Sagdeev* [1958] and greatly clarified by *Hasegawa* [1969, 1975]. More recent works on the theory can be found in work by *Crooker and Siscoe* [1977], *Price et al.* [1986], *Migliuolo* [1986], *Brinca and Tsurutani* [1989], *Southwood and Kivelson* [1993], *Leubner and Schupfer* [2000], *Génot et al.* [2001], *Gedalin et al.* [2002], *Pokhotelov et al.* [2004, 2008], *Klimushkin and Chen* [2006], *Hellinger* [2008], and *Shoji et al.* [2009].

[3] There have been many observations of the end products of this instability both in space and in computer

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Table 1. Definitions of Acronyms Used in This Paper[a]

Acronym	Term	Description
AW	Alfvén Wave	In its linear form, noncompressive low-frequency transverse fluctuations of the magnetic field. The linear waves propagate at a characteristic speed equal to $(B_0^2/4\pi N)^{1/2}$.
IMDAD	Interplanetary Magnetic Decrease Automatic Detection (Code)	A code developed for the detections of MDs. This is available upon request.
LMD	Linear Magnetic Decrease	A MD where the angular change across it is <10°.
LMH	Linear Magnetic Hole	Same as LMD.
HCS	Heliospheric Current Sheet	A surface that separates the two polarities of interplanetary magnetic fields. The magnetic field is generally one polarity in the north and the opposite polarity in the south so just one surface divides the two polarities. This configuration is typical during the declining phase of the solar cycle and at solar minimum.
HPS	Heliospheric Plasma Sheet	A region of high-density plasma that is found adjacent to and at the HCS.
MD	Magnetic Decrease	A local decrease in the magnetic field magnitude <50% of the ambient value. The total (plasma plus magnetic) pressure is constant across these structures. MDs are often bounded by discontinuities.
MH	Magnetic Hole	A general term indicating a dip in the magnetic field magnitude. In interplanetary space, the same as MD.
MM	Mirror Mode	Magnetic (and plasma) structures generated by the mirror instability where $\beta_\perp/\beta_\| > 1 + 1/\beta_\perp$. The oscillations are quasiperiodic varying from $\sim 20\ r_p$ to $\sim 57\ r_p$. There are only small ($\theta < 10°$) angular variations across the structures.

[a] There are other technical terms used in this paper. We refer the reader to *Suess and Tsurutani* [1998] for further details.

simulations. Large amplitude mirror mode structures have been found to occur most typically in planetary magnetosheaths [*Tsurutani et al.*, 1982; *Treumann et al.*, 1990, 2000; *Lacombe et al.*, 1992; *Balogh et al.*, 1992a, 1992b; *Anderson and Fuselier*, 1993; *Violante et al.*, 1995; *Erdös and Balogh*, 1996; *Bavassano Cattaneo et al.*, 1998; *Chisham et al.*, 1998, 1999; *Lucek et al.*, 1999a, 1999b, 2001; *Dunlop et al.*, 2002; *Tátrallyay and Erdos*, 2002, 2005; *Constantinescu et al.*, 2003, 2006; *Horbury et al.*, 2004; *Narita and Glassmeier*, 2005; *Narita et al.*, 2006; *Joy et al.*, 2006; *Soucek et al.*, 2008; *Volwerk et al.*, 2008a, 2008b; *Horbury and Lucek*, 2009]. MMs have been detected in the Earth's cusp [*Shi et al.*, 2009]. MMs have also been identified as occurring in the heliosheath [*Liu et al.*, 2007; *Génot*, 2008; *Tsurutani et al.*, 2010]. MM structures are also found within magnetospheres [*Rae et al.*, 2007], in distant magnetotails [*Tsurutani et al.*, 1984; *André et al.*, 2002] and in cometary sheaths [*Russell et al.*, 1987; *Glassmeier et al.*, 1993; *Tsurutani et al.*, 1999a]. MMs have been detected in interplanetary space [*Tsurutani et al.*, 1992; *Liu et al.*, 2006; *Russell et al.*, 2009; *Enriquez-Rivera et al.*, 2010], but with far less frequency than in magnetosheaths.

1.2. Magnetic Decreases (MDs) and Linear Magnetic Decreases (LMDs)

[4] Short-term dips in the interplanetary magnetic field magnitude were first observed and reported by *Turner et al.* [1977]. These were called "magnetic holes" (MHs) by the authors. Other observers, using different spacecraft in different spatial locations gave these phenomena different names such as "magnetic depressions" [*Fränz et al.*, 2000; *Tsubouchi and Matsumoto*, 2005] or "magnetic decreases (MDs)" [*Tsurutani and Ho*, 1999; *Tsubouchi*, 2009]. Some observers [*Winterhalter et al.*, 1994a, 1995, 2000; *Neugebauer et al.*, 2001; *Stevens and Kasper*, 2007] still called these phenomena magnetic holes. There was a brief work using different techniques to show that at least for Ulysses magnetometer data, MHs and MDs appeared to be the same thing [*Tsurutani et al.*, 2002a].

[5] Since there are many different terms and structures referred to in this paper, all acronyms used are defined in Table 1.

[6] MDs have been found to be pressure balance structures [*Winterhalter et al.*, 1994a; *Neugebauer et al.*, 2001; *Stevens and Kasper*, 2007]. The total pressure, the plasma thermal pressure plus the magnetic pressure, is constant across these structures. It has also been shown that there is a $\beta_\perp/\beta_\| > 1$ anisotropy within MDs [*Fränz et al.*, 2000; *Neugebauer et al.*, 2001; *Tsurutani et al.*, 2002b].

[7] *Tsurutani and Ho* [1999], *Sperveslage et al.* [2000], *Winterhalter et al.* [1994a], *Stevens and Kasper* [2007], and *Tsurutani et al.* [2009a] have all done statistical studies of the angular changes across MDs. All surveys agree that MDs have a broad range of angular changes across them. The distribution is smoothly exponential or power law. Thus many of the theoretical mechanisms proposed in the literature [*Buti et al.*, 1998; *Vasquez and Hollweg*, 1999; *Tsurutani et al.*, 2002a, 2002b; *Vasquez et al.*, 2007; *Tsubouchi*, 2009] address general mechanisms to generate all MDs without regard to angular changes, "linear" or not.

1.3. "Linear" Magnetic Decreases

[8] *Burlaga and Lemaire* [1978] noticed that some of the MDs had little or no magnetic field directional changes across them. They called these "linear" events. *Winterhalter et al.* [1994a] later focused on these linear magnetic decreases (LMDs) and suggested that it could be the mirror instability that is generating them. The LMDs studied by *Winterhalter et al.* [1994a] were generally found in localized high-β regions and were found to be marginally mirror stable. These plasma conditions could be explained as being remnants of instability that had occurred earlier in time and closer to the Sun [*Winterhalter et al.*, 1994a; *Zhang et al.*, 2009]. However, LMDs are typically only ~10–30% of all MDs. It is also possible that the general MD generation mechanisms could create the LMDs in addition to the MDs that are not "linear."

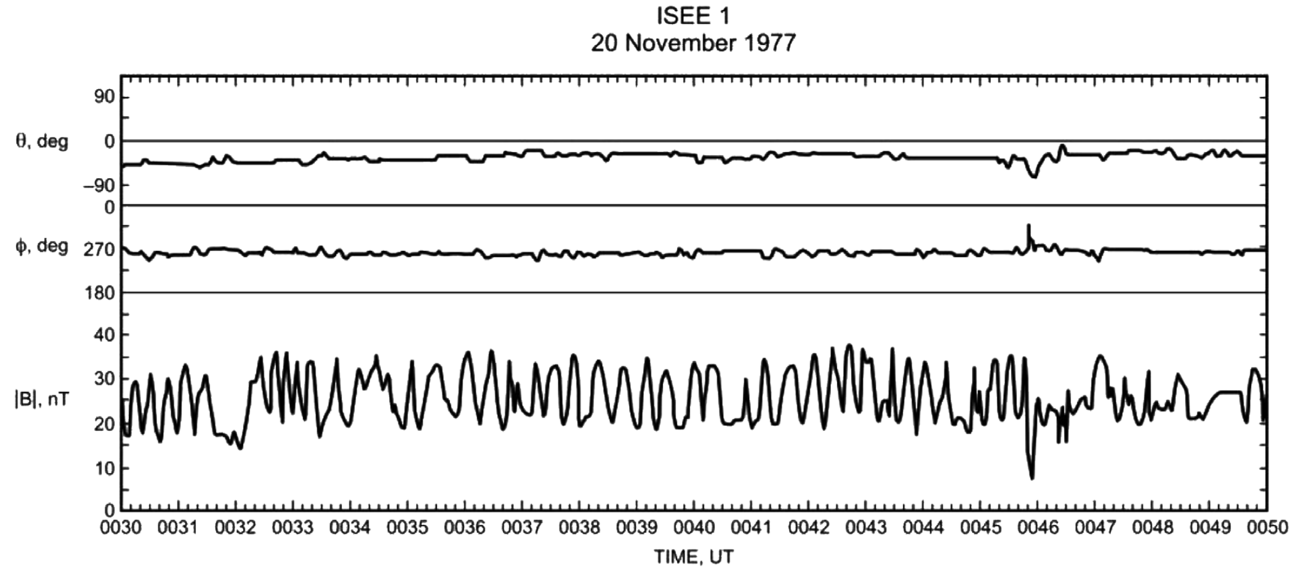

Figure 1. Mirror mode structures observed by ISEE 1 on 20 November 1977 in the Earth's magnetosheath (taken from *Tsurutani et al.* [1982]).

[9] The approach that we will take in this paper is to establish the observational features of MMs to show that they are observationally different than MD structures. These differences, which appear in many different articles are well established and will be reviewed for the reader. These analyses can be done with magnetic field data alone.

[10] The purpose of this review will be to use published observational results to explain the differences between MM, MD and LMD structures. We will show that statistically the three are easily identified and are distinct from each other. Once this is established, we will briefly discuss the different proposed generation mechanisms. Finally we will try to identify productive areas of future research for interested investigators.

2. Observational Results

2.1. Mirror Mode Characteristics

[11] Mirror mode characteristics have been defined by observations of the structures in planetary magnetosheaths. They are noted to (1) have little or no magnetic angular changes across the structures ($\theta < 10°$), (2) occur as quasi-periodic oscillations, (3) have magnetic dips that do not have sharp edges, and (4) have total pressure (magnetic plus plasma pressure) constant, to first order. They are generated by the mirror instability where $\beta_\perp/\beta_\parallel > 1$ (see specific condition stated earlier). All the extensive magnetosheath observations to date have the above characteristics [*Tsurutani et al.*, 1982, 1984; *Treumann et al.*, 1990, 2000; *Lacombe et al.*, 1992; *Balogh et al.*, 1992a, 1992b; *Anderson and Fuselier*, 1993; *Violante et al.*, 1995; *Erdös and Balogh*, 1996; *Bavassano Cattaneo et al.*, 1998; *Chisham et al.*, 1998, 1999; *Lucek et al.*, 1999a, 1999b, 2001; *André et al.*, 2002; *Dunlop et al.*, 2002; *Tátrallyay and Erdos*, 2002, 2005; *Constantinescu et al.*, 2003, 2006; *Horbury et al.*, 2004; *Narita and Glassmeier*, 2005; *Narita et al.*, 2006; *Joy et al.*, 2006; *Rae et al.*, 2007; *Volwerk et al.*, 2008a, 2008b; *Horbury and Lucek*, 2009].

[12] Figure 1 shows mirror mode (MM) structures in the Earth's magnetosheath (taken from *Tsurutani et al.* [1982]). Only the magnetic field magnitude and the two polar angles are shown. The first three MM features noted above are clearly identifiable upon inspection. (1) There are little or no

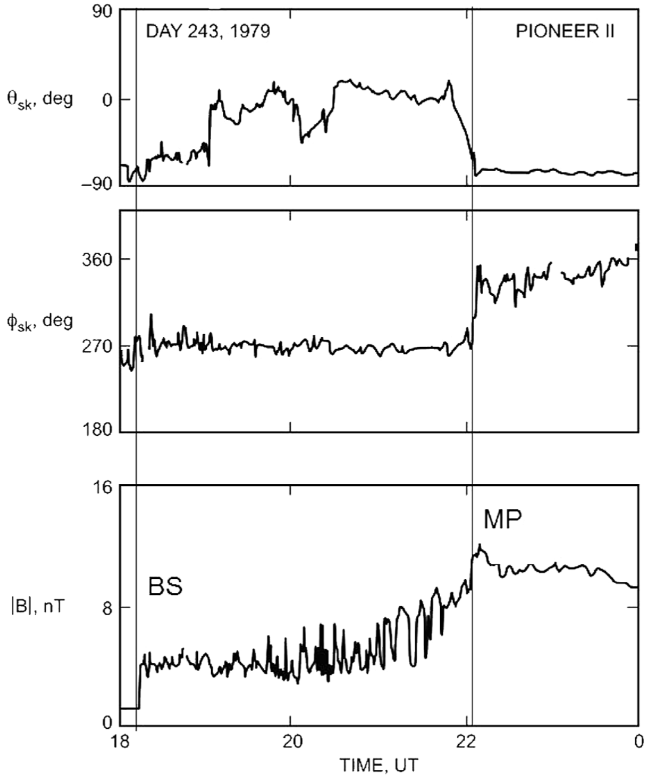

Figure 2. Mirror modes in the Saturnian magnetosheath observed by Pioneer 11 on day 243, 1979. The structures have the largest amplitudes close to the magnetopause (taken from *Smith et al.* [1980]).

Table 2. Approximate Scale Size (in Proton Gyroradii) of Mirror Mode Structures in Planetary Magnetosheaths and the Heliosheath

Magnetosheath Environment	MM Scale (ρ_p)	Source
Earth	20	*Tsurutani et al.* [1982]; *Lucek et al.* [2001]; *Narita et al.* [2006]; *Horbury and Lucek* [2009]
Jupiter	20–25	*Tsurutani et al.* [1982]; *Erdös and Balogh* [1996]
Saturn	40	*Tsurutani et al.* [1982]
Heliosheath	80	*Burlaga et al.* [2007]
	57	*Tsurutani et al.* [2010]

changes in the magnetic field orientation across the MM structures, and (2) the MM structures have a quasiperiodic nature. The magnetic dips (3) vary smoothly and do not have sharp edges. For the case of the Earth, typical scale sizes are ~20 r_p.

[13] Figure 2 shows MM structures in the Saturnian magnetosheath (taken from *Smith et al.* [1980] and *Tsurutani et al.* [1982]). The bow shock is crossed at ~1800 UT and the magnetopause at ~2200 UT. It is noted that there are little or no MM oscillations for the first third of the magnetosheath crossing. MMs start to form at ~1900 UT and have their largest amplitudes close to the magnetopause. These features of MM amplitudes are typical of planetary magnetosheath MM structures.

[14] The scale sizes of MM structures at various planetary magnetosheaths and the heliosheath are shown in Table 2. The value is ~20 r_p at Earth and increases to ~57 r_p in the heliosheath. An explanation of this variation in size is not obvious from present MM instability theory. This topic will be discussed later.

[15] The first computer simulation of mirror mode structures was performed by *Price et al.* [1986]. This is shown in Figure 3. The simulation used a 1D hybrid code, which assumed an ion β of 2.5 and for a range of values with $T_\perp/T_\parallel > 1$. For an ion temperature anisotropy of 1.5, the most unstable mirror waves propagate at ~74° relative to B_0. The most unstable wave has a wavelength of 14 r_p, where r_p is the proton gyroradius. If one visualizes variations in the along-the-magnetic-field direction, the mirror mode structures are elongated tubular sections of high-β plasma separated by low-β plasmas. In the direction orthogonal to the magnetic field, the tubes are offset so again the high-β and low-β regions are adjacent to each other. As indicated in Figure 3 (and experimentally by *Horbury and Lucek* [2009]) the scale in the two different directions are different. The *Price et al.* [1986] figure is extremely useful for the reader to make a 2D/3D visualization of the spacecraft observations.

2.2. MD Characteristics

2.2.1. MDs in Pure High-Speed Solar Wind Streams

[16] Figure 4 shows a 30 day interval of pure high-speed solar wind data detected by Ulysses. Ulysses was over the southern pole of the Sun at a latitude of ~−80° and a distance of ~2 AU. Shown in Figure 4 from top to bottom are the velocity (V) and magnetic field (B) components in the RTN coordinate system, the solar wind speed (V_{SW}), magnetic field magnitude (B_0) and the heliolatitude of the Ulysses spacecraft. In the RTN coordinate system, R is the radial direction from the Sun to the spacecraft, $T = (\Omega \times R)/|\Omega \times R|$ where Ω is the north rotation pole of the Sun, and N completes a right-hand coordinate system.

[17] Figure 4 shows large amplitude fluctuations (~±1 nT) in B_R, B_T and B_N in a ~1.3 nT ambient field. There are similarly large amplitude fluctuations in the velocity components as well. These magnetic and velocity fluctuations are components of nonlinear Alfvén waves which are propagating outward from the Sun [*Belcher and Davis*, 1971; *Tsurutani et al.*, 1994; *Balogh et al.*, 1995].

[18] The next to bottom panel shows the magnetic field magnitude B_0. There are many dips in B_0. These are the MDs that are of primary interest in this paper. It can be noted that MDs are a prominent feature of the pure high-speed solar wind at ~2 AU.

[19] Many researchers have used a criterion of $\Delta|B_0|/B_0 < -0.5$ for the identification of MDs. However, it is obvious that this is an arbitrary criterion used to facilitate analyses. One can notice many smaller structures that do not meet this criterion. These smaller magnitude structures are most likely caused by the same mechanism.

[20] The interval shown covers days 240–270, 1994. This interval occurred during the declining phase of the solar cycle. Ulysses was over a large polar coronal hole (not

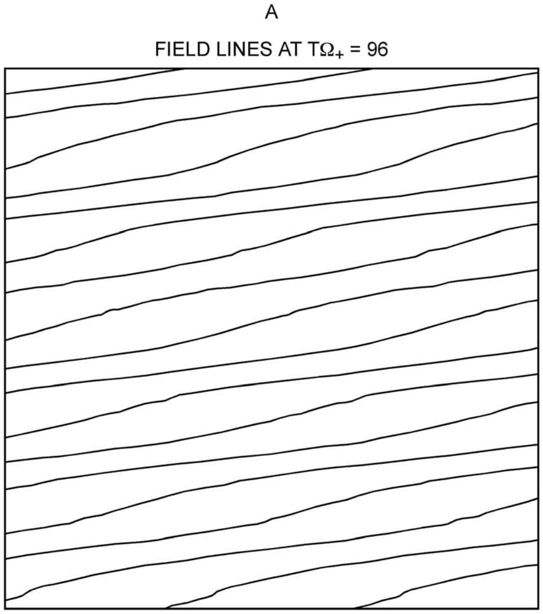

Figure 3. The magnetic field configuration of mirror mode structures for 80° simulation at $\Omega_+ t = 96$, where Ω_+ is the proton gyrofrequency (from *Price et al.* [1986]). The vertical axis (the simulation z axis) is along the wave vector direction. The horizontal axis (the simulation x axis) is perpendicular to the wave vector. The background magnetic field lies in the simulation $x - z$ plane. Alternating high-β plasmas (where the magnetic fields bulge apart) and low-β plasmas (where the magnetic fields converge) are characteristic structures both along the magnetic field and orthogonal to it. The magnetic fields have only small angular deviations in the high-β regions.

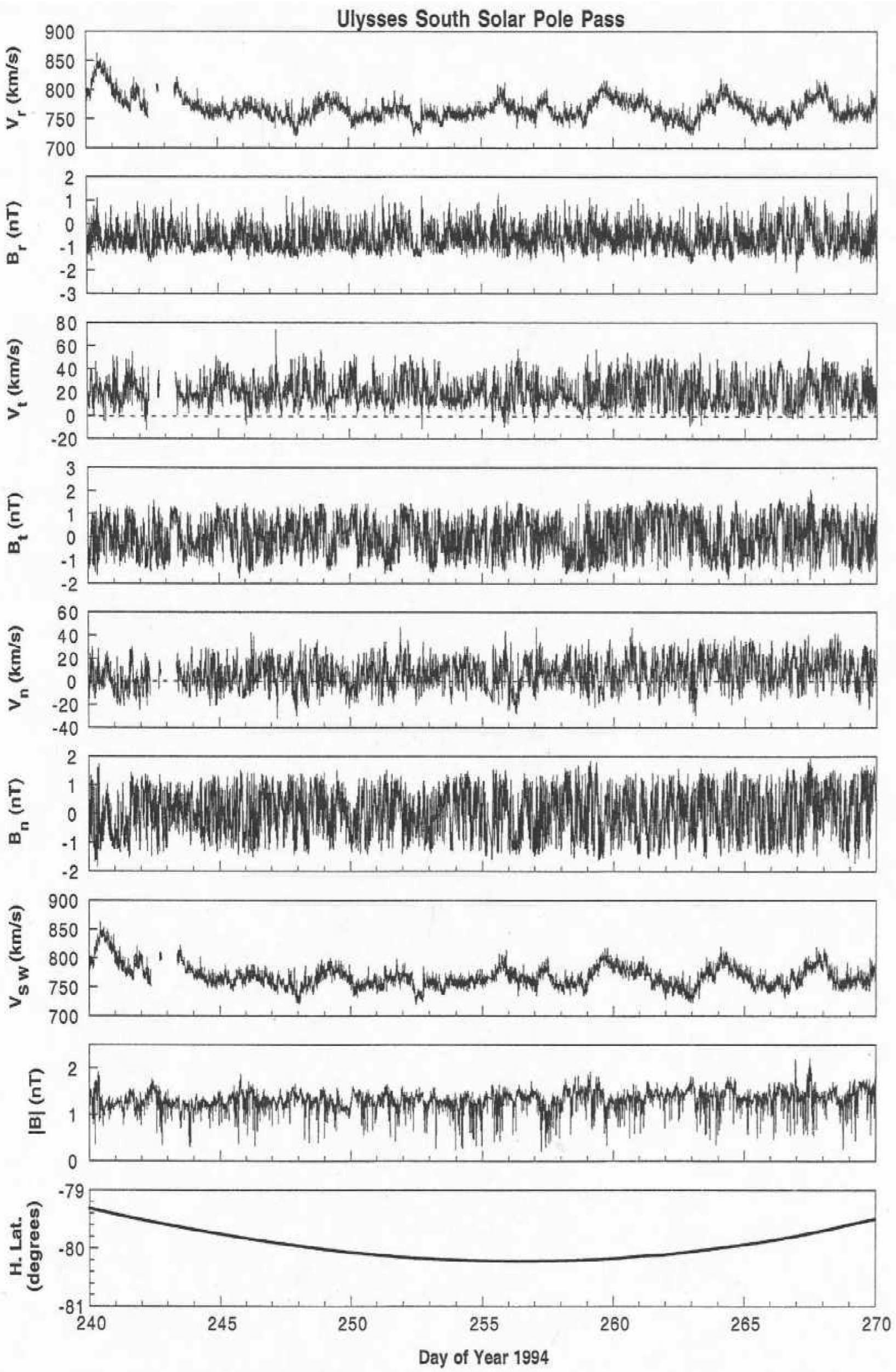

Figure 4. The solar wind velocity (components and magnitude) and magnetic field (components and magnitude) in a high-speed solar wind stream over the Sun's pole. There are many dips in the magnetic field magnitude. These are called magnetic decreases (MDs). They are characteristic of high-speed solar wind streams, but their occurrence rate is less than that within CIRs (shown later). The fluctuations of the velocity and magnetic field components are Alfvén waves propagating outward from the Sun. Figure 4 is taken from *Tsurutani and Ho* [1999].

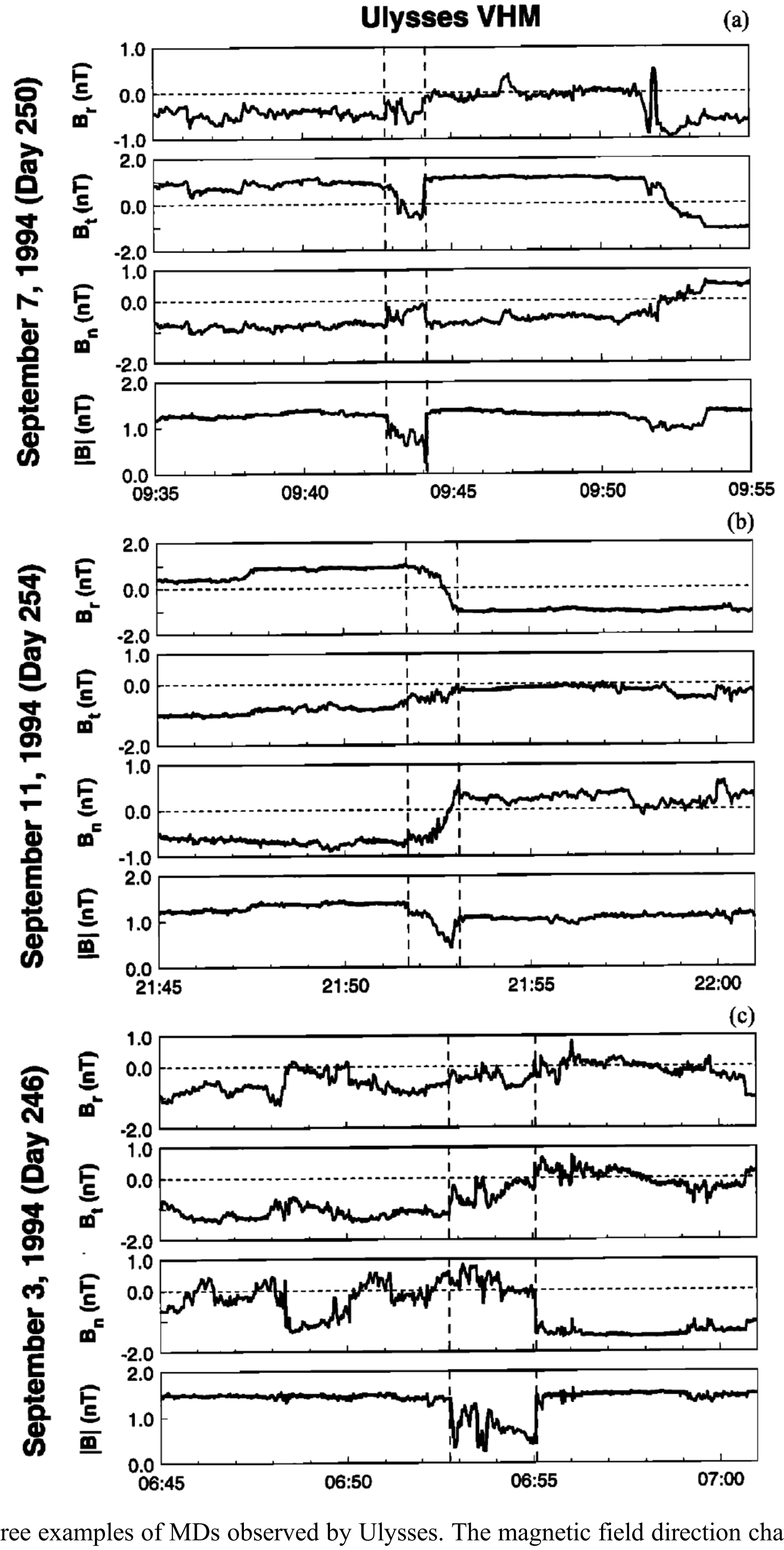

Figure 5. Three examples of MDs observed by Ulysses. The magnetic field direction changes across all three. All three are bounded by sharp edges (discontinuities).

shown for brevity). Excluding the possibility of microstream-microstream interactions, this is a pure high-speed solar wind. There were no major stream-stream interactions occurring between the Sun and the point of observation.

[21] Figure 5 shows some typical MDs observed by Ulysses from the data interval of Figure 4. Three examples are shown, with the field components given in RTN coordinates. Several features should be noted in the examples.

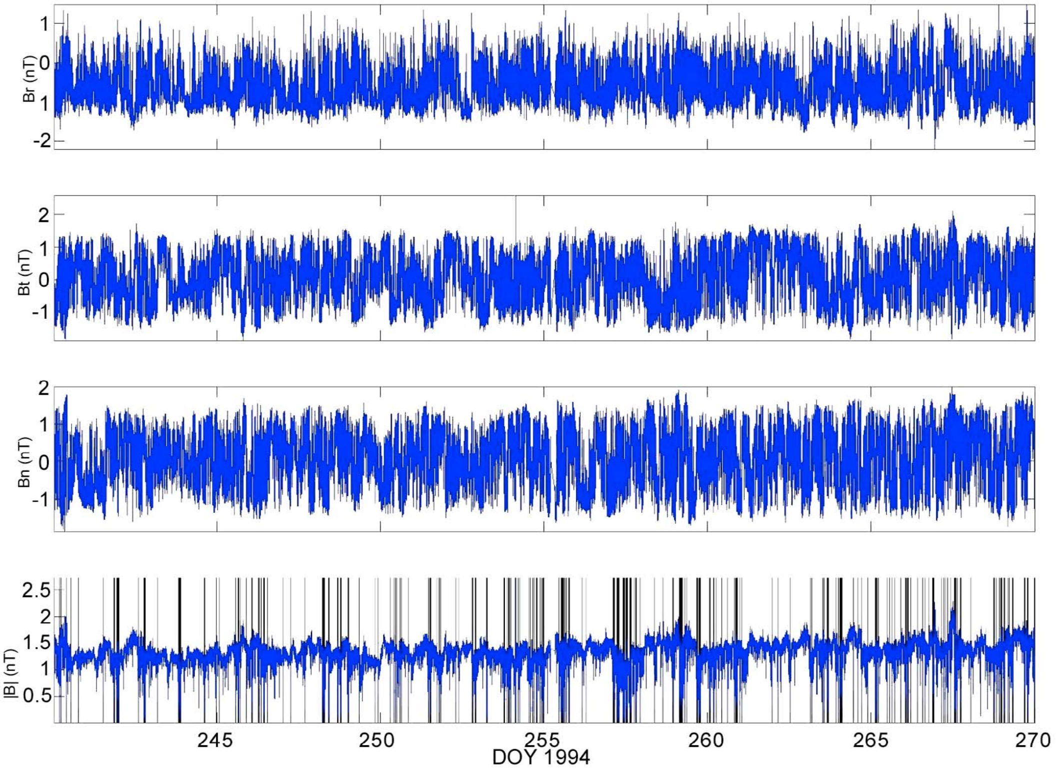

Figure 6. The MDs in the Figure 4 interval are denoted by vertical lines. The IMDAD code was used to identify the MDs.

There can be a large magnetic field directional change that can occur across the MDs. This can be noted in all three events. The top event has the most modest changes of the three. There can even be a magnetic field magnitude change across the MD (center event) or a sharp field component change (bottom event). All of the MDs shown are bounded by sharp discontinuities [*Tsurutani and Ho*, 1999].

[22] *Ho et al.* [1996] used a criterion $\Delta B_0/B_0 < -0.5$ within 1 min to identify discontinuities, where $\Delta \mathbf{B}_0$ is the change in the magnetic vector across the MD. Using the minimum variance technique [*Sonnerup and Cahill*, 1967], the authors identified the discontinuities as tangential in nature assuming the *Smith* [1973] method. *Fränz et al.* [2000] analyzed 115 "thick" MDs and determined that 78% of all events were bounded by tangential discontinuities. *Farrugia et al.* [2001] examined one MD boundary in detail and concluded that for their case, it was a slow shock. Further work needs to be done on this interesting area.

[23] The Interplanetary Magnetic Decrease Automatic Detection (IMDAD) code [*Guarnieri et al.*, 2009] was run over the interval of Figure 4 to identify MDs and MD properties. The results are shown in Figure 6. From top to bottom are the 3 magnetic components and the field magnitude. The MD events identified are indicated by vertical lines in the B_0 panel. There is a good correlation between when the field magnitude is generally low and MDs frequency of occurrence. One example can be found at ~day 257.5.

[24] There are occasional regions where the MDs occur in "clusters." A small cluster can be found at day 242 and a broader one on day 258.

[25] The number of MDs per day is shown in Figure 7. The average MD occurrence rate is 12.2 MDs per day and the standard deviation is 8.5 MDs per day. The peak number of MDs/day is 40 MDs on day 257 and the minimum 2 MDs on day 262. There are clearly large

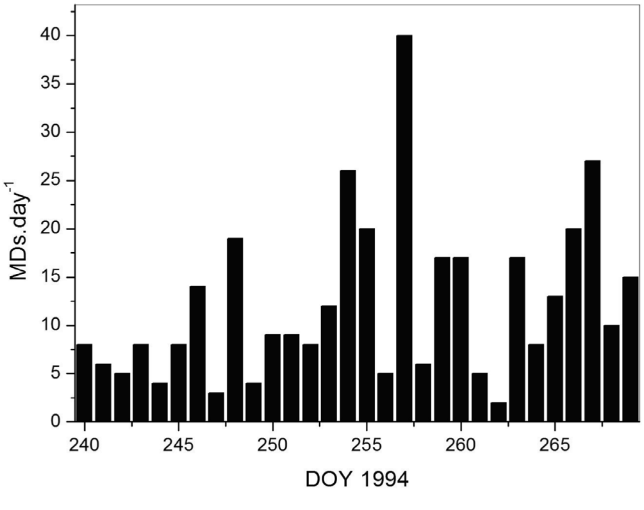

Figure 7. A histogram of the number of MDs per day for the Figure 2 interval.

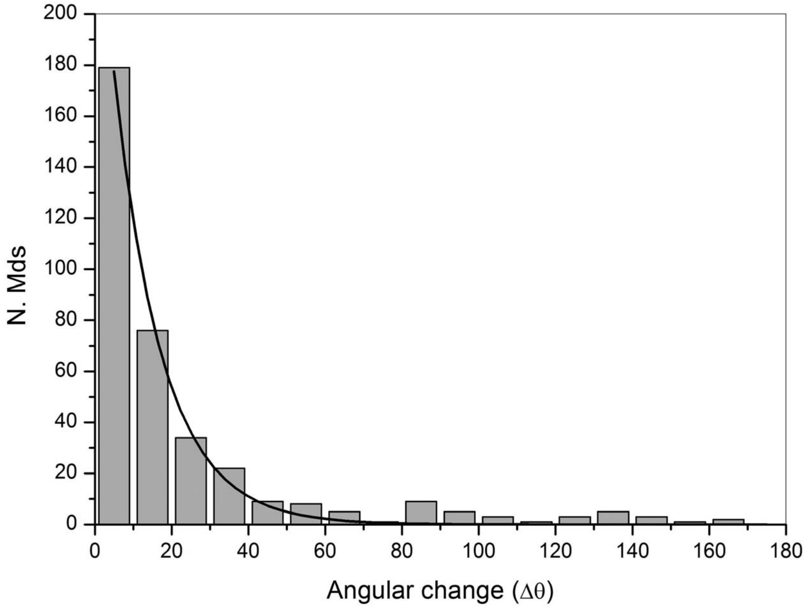

Figure 8. The distribution of magnetic field angular changes across MDs identified in Figure 6. The convection time for a proton gyroradius assuming solar wind parameters is shown for comparison.

nonstatistical deviations in MD occurrence rates even in "pure" high-speed streams.

[26] The distribution of magnetic field angular changes across the MDs for the events in Figure 6 is shown in Figure 8. There is a broad range of angular changes, ranging from 0° to 180°. The distribution can be given as $N_{MD} = 264e^{-(\Delta\theta°/12.5°)}$ where $\Delta\theta$ is the angular change across the MD. A total of 366 MDs are used in the distribution, with 48.9% of the events having small angular changes ($\Delta\theta < 10°$). It should be noted that this large percentage of LMDs is considerably different than previous results. This will be discussed later in the paper.

[27] The distribution of the (temporal) thicknesses of MDs is shown in Figure 9. This is an exponential distribution with $N_{MD} = 259\ e^{-t/13.5}$ where t has units of seconds. Assuming a proton temperature of 2×10^5 K [*Riley et al.*, 1997], a B_0 of ~1.3 nT, and a solar wind speed of ~750 km/s (from Figure 5), the convection time for a proton cyclotron radius is calculated to be 0.61 s. This value is indicated in Figure 9.

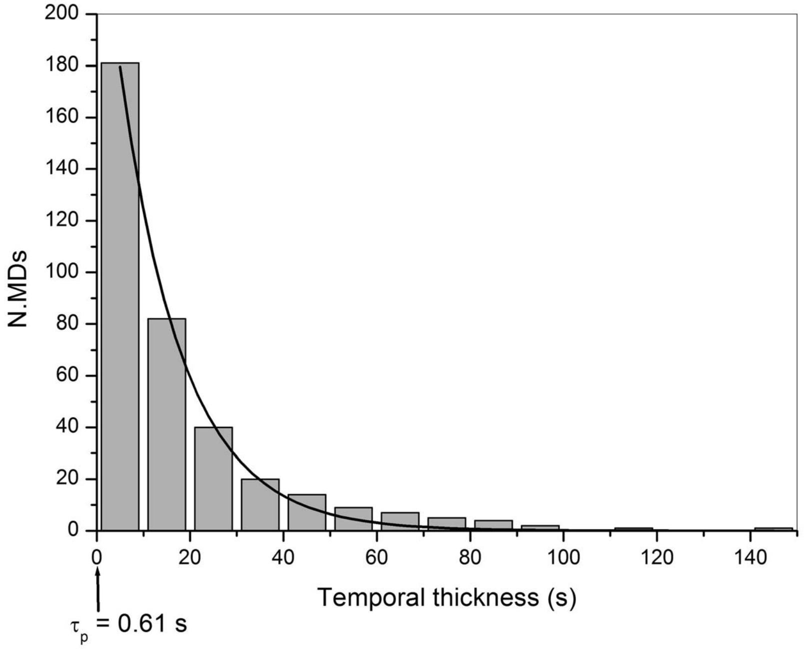

Figure 9. The temporal thickness distribution of MDs identified in Figure 6.

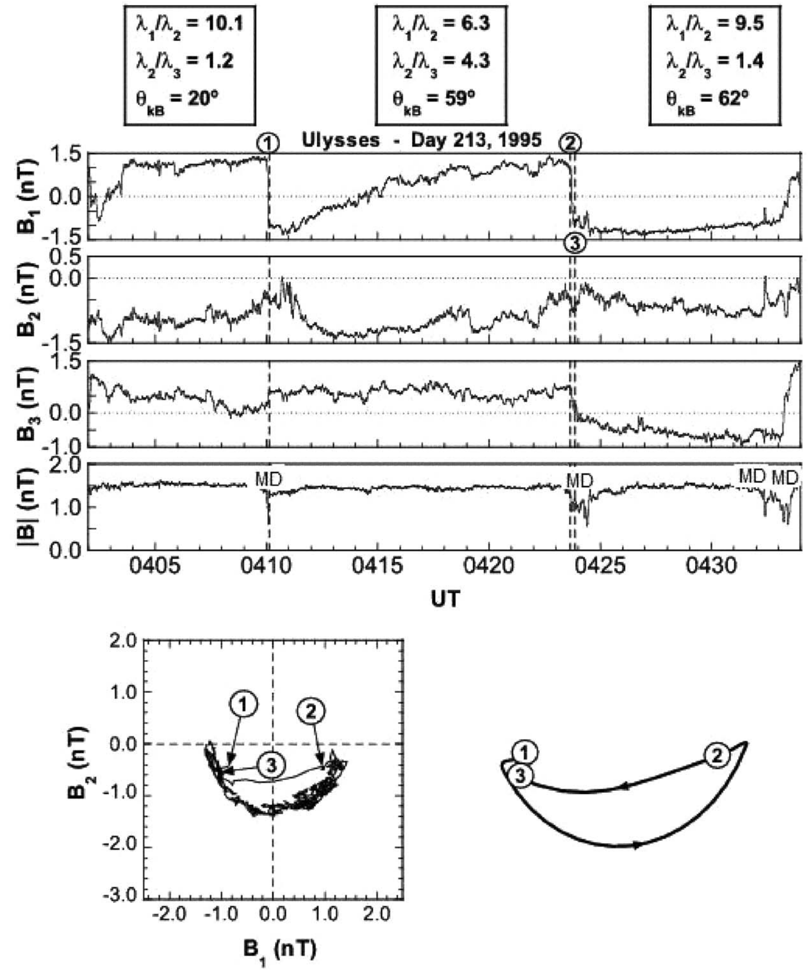

Figure 10. Three cycles of an interplanetary Alfvén wave. The wave is phase-steepened. There are MDs present coincident with the phase-steepened edges. It has been hypothesized that the ponderomotive force associated with the phase-steepened edges is accelerating the solar wind plasma, and the plasma in turn creates the MD because of a diamagnetic effect.

[28] *Tsurutani and Ho* [1999], *Winterhalter et al.* [1994a], *Fränz et al.* [2000], and *Stevens and Kasper* [2007] have performed similar statistical studies on MDs in different regions of the heliosphere. Similar power law or exponential results were obtained. We refer the reader to those articles if they wish to have more detailed information or to make intercomparisons.

[29] Figure 10 shows the relationship between MDs, directional discontinuities (DDs) and Alfvén waves (AWs) for one particular case (taken from *Tsurutani et al.* [2002b]). The top three panels are the magnetic field components plotted in minimum variance coordinates [*Sonnerup and Cahill*, 1967; *Smith and Tsurutani*, 1976], where B_1, B_2 and B_3 are the field components along the maximum, intermediate and minimum variance directions, respectively. The bottom panel contains B_0. Three cycles of an Alfvén wave are noted: 0401 to 0410 UT, 0410 to 0424 UT and 0424 to 0434 UT. At the three edges of the AW (~0410, ~0424 and ~0434 UT) there are discontinuities (the phase-steepened edges of the AWs). These discontinuities are also time coincident with MDs. This relationship led to the suggestion that the dissipation of phase-steepened Alfvén waves are heating the local plasma and the diamagnetic effect of the plasma are creating the MDs [*Tsurutani et al.*, 2002b; *Dasgupta et al.*, 2003].

2.2.2. MD Formation at Corotating Interaction Regions (CIRs)

[30] Section 2.2.1 illustrated that MDs are a characteristic feature of high-speed solar wind streams over the Sun's poles. The main purpose was to illustrate the statistical and detailed properties of MDs. Now we will show another feature of MDs in the interplanetary medium: their relationship to CIRs.

[31] Figure 11 shows a CIR observed by Ulysses near the ecliptic plane near ~5 AU. From top to bottom are the solar wind parameters: speed (V_{sw}), density (N), temperature (T), B_R, B_T, B_N, B_0, and the plasma β. Note that the scale for β is logarithmic. The black vertical lines indicate a forward shock (day 361.8), the stream-stream interface (day 363.3) and a reverse shock (day 365.0). For more information on these structures, we refer the reader to two of the original discovery/defining articles on CIRs: those by *Smith and Wolfe* [1976] and *Pizzo* [1985]. Vertical red lines indicate MDs detected by the IMDAD code. There are 56 MDs per

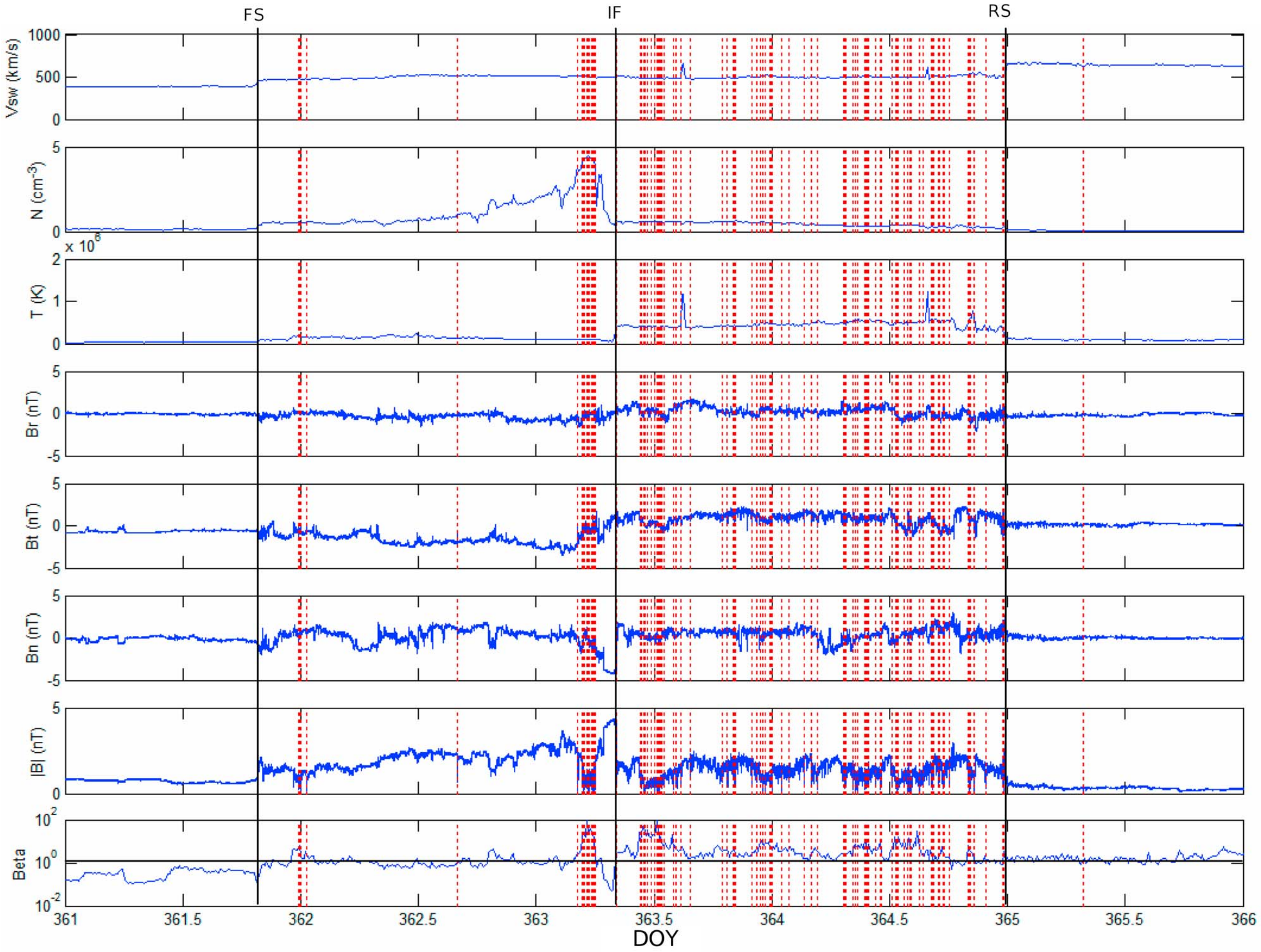

Figure 11. A CIR with MDs identified by vertical red lines. The forward shock (FS), interface (IF), and reverse shock (RS) are also denoted. Figure 11 is taken from *Tsurutani et al.* [2009a].

day on day 363, 1992 and 67 MDs/day on day 364, 1992. Note that these 2 days have higher MD occurrence rates than the highest rate at the solar pole (Figures 6 and 7) and is a factor of 4 to 6 times the average rate over the pole.

[32] There are several important points to note in Figure 11. The first is that MDs occur in regions of high β $(1 < \beta < 10^2)$ and are absent in regions of low β $(\beta < 1)$. The high-β regions were suggested as being generated by quasi-parallel shock compression (we refer the reader to *Tsurutani et al.* [2009a] for a description of this mechanism). This is a general finding determined from an examination of 15 CIRs and other interplanetary structures. The second important feature is that in this interval from day 361 to day 366, almost all of the MDs were detected within the CIR (the occurrence frequency of MDs within CIRs is much higher than that in the pure high-speed stream shown earlier). The MDs that were detected within the CIR are located mainly in the trailing portion, from the interface to the reverse shock. This relationship was typical of the 15 CIRs studied.

[33] A large data interval from 29 February 1992 to 14 September 1993 (which includes the above CIR interval) was used to study the properties of the 3,920 MDs that were detected [*Tsurutani et al.*, 2009a]. The temporal "thicknesses" of the MDs were determined. A fit of $N = A_1\ e^{-(t/t_1)}$, where $A_1 = 2173 \pm 35$ and $t_1 = 17.3$s was made to the distribution. The e-folding time scale here is 17.3 s comparable with 13.5 s over the solar pole.

[34] The distribution of magnetic field angular changes across MDs was also determined (Figure 12). An exponential form: of $N_{MD} = 2 + 48e^{-(\Delta\theta°/18.8°)}$ where $\Delta\theta$ is the angular change. This is similar to the high-latitude distribution of Figure 8 except this low-latitude distributional shape is a bit broader (an 18.8° e-folding compared to 12.5° over the poles).

2.2.3. Summary of Observational Properties of MDs

[35] From the above, the general properties of MDs are as follows: (1) they have variable magnetic field angle changes across them, (2) they have random spacings between adjacent events, and (3) they are typically bounded by discontinuities. Previous studies have noted that MDs with small angular changes $(\Delta\theta < 10°)$ across them represents only ~10 to 30% of the distribution, but here at high latitudes, it was ~49%. This difference is not understood at this time.

[36] The properties of magnetosheath MM structures and interplanetary MDs were illustrated and were shown to be considerably different from each other. MM structures are approximately monoscale structures and are quasiperiodic in nature. MDs are variable-scale structures, have a wide variety of magnetic field angular changes occurring across

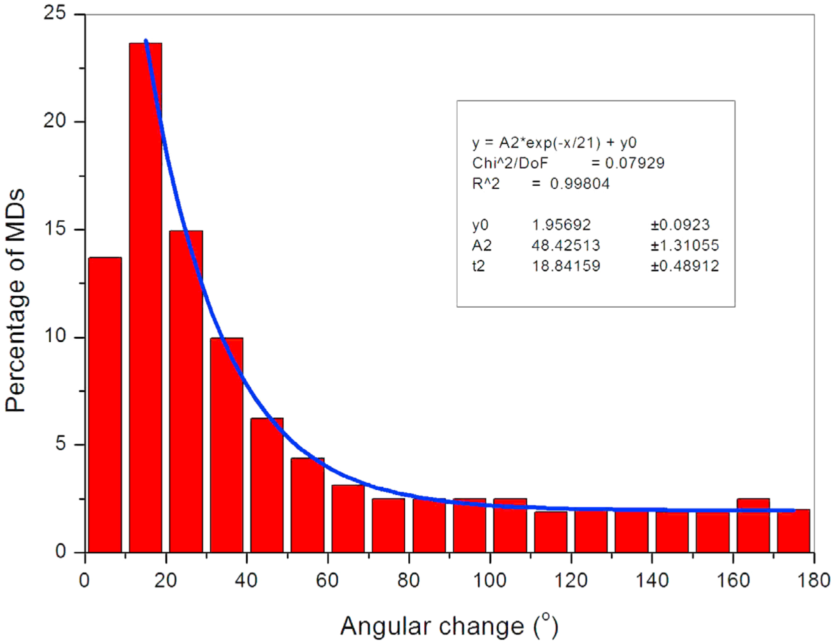

Figure 12. The angular change in the magnetic field across MDs. A large time interval when Ulysses was near the ecliptic plane was used to obtain this distribution (taken from *Tsurutani et al.* [2009a]).

them, and are not quasiperiodic. This is true at high latitudes, in the ecliptic plane and at small and large distances from the Sun. It is concluded that observationally MMs and MDs are quite different from each other and therefore must be produced by different physical processes.

3. Generation Mechanisms for MMs, MDs, and LMDs

3.1. MM Generation in Planetary Magnetosheaths

[37] There are several sources of “free energy” for the mirror instability in planetary magnetosheaths, in cometary magnetosheaths and in the heliosheath. For each case, the source(s) of free energy can be different. For planetary magnetosheaths, quasi-perpendicular shock compression will asymmetrically heat the ions in the $T_\perp$ component [*Kennel et al.*, 1985]. Deeper in the magnetosheath, magnetic field draping around the magnetopause [*Midgley and Davis*, 1963; *Zwan and Wolf*, 1976] provide continuous additional free energy as the plasma is convected from the shock toward the magnetopause and the fields draped around it. Magnetic field draping leads to squeezing of the hot $T_{||}$ plasma along the lines of force into the downstream region and the magnetic tension near local noon leads to an increase in $T_\perp$ [*Crooker and Siscoe*, 1977].

[38] *Tátrallyay and Erdos* [2005] have statistically examined the location of MM structures in the Earth’s magnetosheath. They found that the major location of MMs was found close to the magnetopause and not near the bow shock. They also found symmetry between the dawn and dusk MM concentrations. *Tátrallyay and Erdos* [2002, 2005] concluded that magnetic draping is the dominant source of instability for the Earth’s magnetosheath. *Erkaev et al.* [2001] modeled AMPTE/IRM MM observations assuming magnetic field line stretching. They obtained good agreement between the model calculations and the observations.

[39] It is likely that both sources of free energy (shock compression and field line draping) are necessary to drive the MM structures to such large amplitudes. There is no apparent evidence that these structures are saturating in amplitude. For the magnetic field draping mechanism, the free energy is injected continuously as the plasma is convected inward, thus growth from that mechanism should be continuous all the way to the magnetopause. A hybrid simulation is needed to model both the shock compression and the draping mechanism for various Mach number shocks and make comparison with spacecraft data. In particular the local time dependence of the amplitude of the MM structures could give interesting and illuminating new results.

[40] The cometary magnetosheath case has an additional source of free energy. Continuous plasma injection to the system is accomplished by photoionization and charge exchange of outflowing cometary neutrals [*Wu and Davidson*, 1972; *Tsurutani and Smith*, 1986a, 1986b; *Wu et al.*, 1988; *Brinca*, 1991; *Tsurutani et al.*, 1997]. If the magnetic field is orthogonal to the magnetosheath (or to the upstream solar wind) flow, the ions will attain a perpendicular velocity of V_{sw} upon pickup. If the magnetic field is parallel to the solar wind velocity the ions will form a beam in the solar wind. This source of free energy will occur everywhere around the comet. Different wave modes are generated with different magnetic field orientations relative to the solar wind flow direction [*Brinca*, 1991; *Tsurutani et al.*, 1997]. We refer the reader to the landmark paper by *Wu and Davidson* [1972] for a general discussion of this physical process.

[41] The physics of MMs in the heliosheath is quite similar to the cometary case. In this case pickup of inter-

stellar neutrals in the upstream region, shock compression and further pickup of neutrals within the heliosheath are all sources of free energy for mirror instability [*Tsurutani et al.*, 2010].

3.2. MD Generation in High-Speed Streams

[42] The relationship between the steepened edges of Alfvén waves and MDs (Figure 10) led *Tsurutani et al.* [2002a] and *Dasgupta et al.* [2003] to speculate that the ponderomotive force associated with the phase-steepened edges of the nonlinear waves leads to local solar wind heating. The perpendicularly heated plasma (from Alfvén wave dissipation) creates the MD by a diamagnetic effect. Evidence in support of this suggestion are the observations of both hot anisotropic ($T_\perp/T_\parallel > 1$) protons [*Fränz et al.*, 2000; *Neugebauer et al.*, 2001; *Tsurutani et al.*, 2002a] and a variety of plasma waves detected within the MDs [*Lin et al.*, 1995, 1996; *MacDowall et al.*, 1996; *Tsurutani et al.*, 2002b]. Proton anisotropies where $T_\perp/T_\parallel > 1$ is most certainly a local heating process. Electromagnetic plasma waves can propagate away from their generation region, thus detection of waves localized within MDs are indicative of recent in situ plasma heating and instability. For general reviews on this topic, see *Tsurutani et al.* [2003, 2005].

[43] Other mechanisms might also produce these features. *Baumgärtel* [1999] has suggested that MDs could be the dark soliton solutions of the Derivative Nonlinear Schrodinger (DNLS) equation. However, the applicability of the DNLS equation for highly obliquely propagating nonlinear waves has been questioned by *Buti et al.* [2001]. *Buti et al.* [2001] have suggested an alternative mechanism: local inhomogeneities introduced by large-amplitude Alfvén wave packets that evolve into MDs.

3.3. MD Generation Within CIRs

[44] CIRs are formed by high-speed solar wind–slow-speed solar wind interactions [*Smith and Wolfe*, 1976; *Pizzo*, 1985]. CIRs do not exist at distances close to the Sun (at least in the form that we know it) and become larger as they propagate to large distances from the Sun. Forward and reverse shocks do not typically form before ~1.5 AU from the Sun [*Smith and Wolfe*, 1976]. The forward shock propagates into the slow stream plasma and magnetic fields. The forward shock (FS) heats, compresses and accelerates the slow stream plasma which is added to the downstream CIR. The reverse shock (RS) propagates toward the Sun through the fast stream plasma and magnetic field. The RS heats, compresses and decelerates the fast stream plasma, and adds it to the upstream CIR. Thus in a way a CIR is a large heliospheric fossil. It contains structures that were altered (by shock compression), swept up (passed through the shocks), and stored within the CIR. *Tsurutani et al.* [2009a] have suggested that the MDs found near the CIR interface were formed and stored in the CIR inside 1 AU. Those detected inside the CIR near either the forward or reverse shocks were formed close to the present location of Ulysses at the time of measurement (in this case ~5 AU). The high MD occurrence rates inside the CIR (56 and 67 MDs per day on days 363 and 364, respectively) preclude a simple sweeping up of MDs (the average nonpeak value for the interval is 4.3 ± 6.1 MDs per day) into the CIR. MD formation must be occurring locally (~5AU) as well.

[45] This is a recent result and at present it is not clear what the mechanism or mechanisms are for MD formation. Clearly those mechanisms suggested in the literature that involve fast magnetosonic shocks should be studied and examined carefully. Below are some ideas presented in the literature.

[46] *Tsubouchi and Matsumoto* [2005] have modeled interplanetary rotational discontinuity interactions with the Earth's bow shock with resultant MD formation. In their simulation, proton parallel heating occurs from enforced conversion of proton perpendicular motion into parallel motion by the imposed rotational magnetic field. The resultant intense parallel/antiparallel flows are believed to generate the field gradient at the edges, acting as a mirror force reducing the magnetic intensity.

[47] *Vasquez and Hollweg* [1999] and *Vasquez et al.* [2007] have suggested that wave-wave interactions in the turbulent sheaths behind interplanetary shocks could create MDs. Their idea is that MD generation occurs when a pair of oppositely traveling Alfvén waves (AWs) generate pressure-balance structures. *Tsubouchi* [2009] has used a 1D MHD simulation to show that Alfvénic fluctuations in the high-speed stream interacting with a velocity gradient structure will form MDs. The initial AW disintegrates into two Alfvén modes traveling in opposite directions. The field components are amplified when passing through the magnetic compression region, causing a local current reversal. The resulting force sweeps the plasma backward to form a pressure increase and the MD. The *Vasquez et al.* [2007] model predicts that MDs are nonexpanding, standing structures, while *Tsubouchi* [2009] predicts that MDs will expand with time.

[48] The aforementioned pure high-speed solar wind streams MD generation mechanisms [*Buti et al.*, 1998; *Tsurutani et al.*, 2002a, 2002b, 2003, 2005] can be applied here as well. The only difference is that the compression of the Alfvén waves by the shocks must enhance the phase-steepening/nonlinear processes, leading to a more rapid evolution and formation of MDs.

3.4. LMD Generation in Interplanetary Space

[49] Because the $\beta_\perp/\beta_\parallel$ ratio was found to be close to marginal stability within LMDs, *Winterhalter et al.* [1994a] proposed the mirror instability as a possible generation mechanism. However, the previously mentioned general MD generation mechanisms [*Buti et al.*, 1998; *Vasquez and Hollweg*, 1999; *Tsurutani et al.*, 2002a, 2002b; *Vasquez et al.*, 2007; *Tsubouchi*, 2009] are also candidates. Are LMDs just a subset of all MDs and generated by the same mechanism, or are LMDs special, being generated by a separate mechanism, e.g., the mirror instability? For the case of generation of MDs inside CIRs, *Tsurutani et al.* [2010] have argued that because the reverse shocks are generally quasi-parallel in nature, mirror instability seems unlikely.

[50] Why are the percentages of LMDs higher in pure high-speed streams over the solar poles (~49%, Figure 8) than in the ecliptic plane (~13%, Figure 12)? Is it due to the radial orientation of the magnetic fields in this part of the heliosphere? This is a new result borne by the writing of this review and there is no clear answer at this time. Are the LMDs over the poles mostly MM structures? If so, is the general ponderomotive force proton heating at phase-

steepened Alfvén waves creating not only MDs but also generating mirror instability such that MMs are found within MDs as has been shown for one case [*Tsurutani et al.*, 2002b]? Only further research can answer this intriguing question.

4. Summary and Conclusions

[51] Observations were presented to show that MMs that are occurring in planetary and cometary magnetosheaths are different than MDs in interplanetary space. The two different phenomena can be distinguished by magnetic field characteristics alone. Mechanisms for the formation of MMs and MDs were discussed, and current research problems were indicated for the interested reader. Research is needed to explain the scale sizes of MM structures. Theoretical scale sizes [*Hasegawa*, 1969] are about a factor of 3 too small for the case of MMs at Earth and even smaller for more distant magnetosheaths. There is no satisfactory explanation for this at the present time. We would like to mention an interesting possibility suggested by one referee based on the deformation of MM structures by diffusion. Diffusion would cause the high–wave number components of the mirror mode to decay more rapidly than the low–wave number components. Then using an analogy of a smoke ring where the ring increases in size and decreases in intensity as it moves away from its source, it is easily seen that MM structures would have the largest sizes in the largest magnetosheaths. However, we emphasize that this is only an idea at this stage and the details need to be worked out.

[52] We have emphasized MMs in sheaths (magnetosheaths, cometary sheaths and the heliosheath) and MDs in interplanetary space because the contrast is large and easy to understand. Clearly there can be exceptions. MM structures have been observed in interplanetary space [*Tsurutani et al.*, 1992, 2002b; *Liu et al.*, 2006; *Zhang et al.*, 2009; *Russell et al.*, 2009], but are much rarer in occurrence frequency. Pockets of LMDs (or even individual LMDs) may be formed in interplanetary space by the mirror instability. Some conditions for instability are within high-β plasma regions such as the Heliospheric Plasma Sheet (HPS) [*Winterhalter et al.*, 1994b] which is adjacent to or surrounds the Heliospheric Current Sheet (HCS) [*Smith et al.*, 1978]. If these regions are compressed or shocked perpendicular to the field direction, the mirror instability criterion could be easily attained. *Tsurutani et al.* [2009b] discussed other possible interplanetary mechanisms. *Burlaga and Lemaire* [1978] and *Zhang et al.* [2008a] have identified current sheets causing MDs. We refer the interested reader to these latter references for further details.

[53] Interplanetary MDs passing through planetary bow shocks will certainly be altered and may be present in some form in the downstream magnetosheath as well. However, their evolution has been little studied to date, as attention has been focused primarily on the much larger amplitude MM structures. Studies of this type, although far less dramatic, are of equal importance and should be done by interested plasma physicists.

[54] One more question should be asked and addressed: “why aren’t there MM structures and MDs behind interplanetary forward shocks? Why are most of the MDs detected in the trailing part of the CIR (see Figure 11) rather than in the forward part of the CIR”? The answer for the MM part of the question is that observationally large amplitude, semi-coherent MMs like those shown in Figure 11 have rarely been reported downstream of either CIR (or ICME) forward shocks. What could be the cause of this? There are several possible explanations. For one, interplanetary shocks typically have magnetosonic Mach numbers of 2 to 3 (relatively weak shocks) and are also rarely purely perpendicular in nature [*Tsurutani and Lin*, 1985; *Echer et al.*, 2010; *Tsurutani et al.*, 2009b]. Therefore a lack of sufficient ion anisotropy (from both effects) may be one explanation. Another possibility is the lack of sufficient magnetic field draping, a mechanism that occurs in planetary magnetosheaths.

[55] There have been reports for few cycles of MM structures in interplanetary events [*Liu et al.*, 2006]. An interesting exercise would be to determine if these were unusual events: particularly high-β plasma intervals, high–Mach number shocks, compound interplanetary events, or perpendicular shocks, etc. Studies like this would help in understanding the general criteria for instability.

[56] Finally one comes to the question of the generation mechanism of interplanetary LMDs [*Winterhalter et al.*, 1994a; *Zhang et al.*, 2008b, 2009; *Xiao et al.*, 2010]. It would be highly useful if the researchers could say whether they detected pockets of LMDs alone or if the LMDs were interspersed with MDs that were not linear. For the former case, the interplanetary medium in which the MDs have been detected should be identified: high-speed streams, slow-speed streams, interplanetary coronal mass ejections (ICMEs), CIRs, the heliospheric plasma sheet (HPS), the HCS, etc. This could help identify the source of free energy for the mirror instability.

4.1. Consequences of MDs in the Heliosphere?

[57] Very little was stated about the consequences of MDs, since that was not the main goal of this paper. However, it would be useful to the reader to try to understand the implications of these microscale physical phenomenon. Figure 4 shows that MDs are an integral part of the heliospheric magnetic field and that the medium is a compressive one, thus compressible magnetic turbulence should be incorporated into particle propagation modeling in the heliosphere. These dips in the magnetic field will have strong consequences for particles interacting with them. The interaction will not be the typical “cyclotron resonant” ones, but charged particles will also be scattered perpendicular to the magnetic field. We refer the interested reader to *Tsurutani et al.* [1999b], *Tsurutani and Lakhina* [2004], and *Costa et al.* [2011]. This “cross-field diffusion” could have significant implications for particle circulation in our heliosphere. If MDs are present everywhere in the high-latitude region and are also found near the HCS, particle circulation as we currently perceive it, may be altered. Although preliminary work has been done in this area, further modeling would be quite useful.

4.2. Recommendations for Researchers of Magnetic Dips

[58] For future researchers in magnetic dips occurring in either interplanetary space or in sheath regions, it is recommended that they first identify the properties of all the

dips within their interval of analyses. If all the dips have properties of mirror mode structures, a source of free energy for instability should be identified. If on the other hand the properties of the magnetic structures are mixed, the researchers should attempt to address the properties and generation mechanisms of all structures and not just a subset of them.

[59] We have focused primarily on the magnetic properties of the dips. At the present time researchers have not identified any plasma characteristics that can distinguish between the two phenomena. Both MMs and MDs are pressure balance structures. Both have been noted to have proton $\beta_\perp/\beta_\parallel > 1$ anisotropies. If such distinguishing plasma features exist, it would be highly useful for researchers to identify it/them.

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