A statistical study of interplanetary shocks and pressure pulses internal to magnetic clouds

Michael R. Collier,[1] Ronald P. Lepping,[1] and Daniel B. Berdichevsky[1,2]

Received 10 March 2006; revised 7 October 2006; accepted 8 November 2006; published 2 June 2007.

[1] We have examined Wind field and plasma data over the time period from November of 1994 through August of 2003 to find cases of interplanetary shocks and pressure pulses internal to magnetic clouds for which we could determine accurate shock normal directions. We have found eight cases in 82 clouds, so these shocks and pressure pulses occurred in approximately 10% of the Wind magnetic clouds. Of the eight cases, six were forward shocks and two were pressure pulses. The internal shocks and pressure pulses tend to occur in the latter half of the clouds, i.e., timewise, about two-thirds of the way through. In every case the magnetic field change is highly compressive at the shock showing little or no change (<10°) in angle during or after the magnitude jump. These shocks and pressure pulses internal to magnetic clouds appear to be associated with outline asymmetric halo coronal mass ejections of greater than average speed which may imply an interaction between an earlier, slower halo CME and a later, faster, off-center CME driving a strong shock, but other interpretations are possible and they are discussed.

Citation: Collier, M. R., R. P. Lepping, and D. B. Berdichevsky (2007), A statistical study of interplanetary shocks and pressure pulses internal to magnetic clouds, *J. Geophys. Res.*, *112*, A06102, doi:10.1029/2006JA011714.

1. Introduction

[2] Magnetic clouds are a subset of interplanetary (IP) ejecta which have three characteristics: (1) strong magnetic fields, (2) a smooth rotation of the magnetic field direction through a large angle, and (3) a low proton temperature and proton plasma β_p [*Burlaga*, 1995]. They are associated with solar flares and disappearing filaments and, although there are interplanetary coronal mass ejections (ICMEs) without these signatures [*Bothmer and Rust*, 1997], magnetic clouds are also associated with ICMEs [e.g., *Berdichevsky et al.*, 2002]. Typically, magnetic clouds at 1 AU have a radial cross section whose diameter is about 0.25 AU and last for about a day, although the determination of the beginning and end times of magnetic clouds can be subjective [*Burlaga*, 1995; *Lepping and Berdichevsky*, 2000; *Lepping et al.*, 2006].

[3] A small fraction of magnetic clouds exhibits large and sudden magnetic field magnitude increases inside, which we will show are frequently internal interplanetary (IP) shocks or pressure pulses (PPs). The phenomenon of internal shocks and pressure pulses, although recognized for many years [e.g., *Lepping et al.*, 1997], has not been studied systematically until now.

[4] An example of a well-studied magnetic cloud which exhibits an internal shock passed the Wind spacecraft on 18–19 October 1995 [*Lepping et al.*, 1997; *Collier et al.*, 2001]. One of the unusual features of this particular internal shock is its normal orientation, which was roughly perpendicular to the magnetic field (θ_{nB} = 105°) and close to antiparallel to the cloud axis ($\theta_{\mathrm{axis-norm}}$ = 150°).

[5] As will be discussed later, many of the features of the 18 October 1995 internal shock are general features statistically present for almost all of the cases where interplanetary shocks and pressure pulses were observed internal to magnetic clouds in the Wind data set. These features include: (1) appearing in the latter half of the cloud, (2) having associated density and velocity increases, and (3) showing little or no change in the magnetic field direction across the transition. In spite of these similarities, there is also some indication that the shock internal to the 18–19 October 1995 magnetic cloud is not typical [*Lepping et al.*, 1997].

[6] This paper reports a study of all shocks and pressure pulses internal to magnetic clouds observed by the Wind spacecraft from November of 1994 through August of 2003. Although this paper addresses magnetic clouds only at 1 AU, this phenomenon is not restricted to 1 AU or its vicinity. For example, the magnetometer on Ulysses appears to have observed a shock internal to a magnetic cloud at about 5 AU late on day 228 in 1997 [*Forsyth et al.*, 1999].

[7] Although the term "internal shock" is used throughout the remainder of this manuscript, it should be noted that this really means "internal shock or pressure pulse" as two of our cases, to be discussed, have magnetosonic Mach numbers below unity (cases 1 and 5).

2. Method

[8] All cases of magnetic clouds that appear in the Wind data set from launch in November of 1994 through August

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]Now at L-3 Government Services, Inc., Largo, Maryland, USA.

Copyright 2007 by the American Geophysical Union.
0148-0227/07/2006JA011714

Table 1. Magnetic Cloud and Shock Times

Case	LN	Magnetic Cloud Start Time	Magnetic Cloud End Time	Duration, hours	Shock Time	Frac	Type
1	02	95 Mar 04 (063) 10.8	95 Mar 05 (064) 03.8	17.0	95 Mar 04 (063) 20.0	0.54	PP
2	06	95 Oct 18 (291) 19.8	95 Oct 20 (293) 01.3	29.5	95 Oct 19 (292) 17.9	0.75	FS
3	25	97 Nov 07 (311) 15.8	97 Nov 08 (312) 04.3	12.5	97 Nov 07 (311) 17.8	0.16	FS
4	34	98 Jun 24 (175) 16.8	98 Jun 25 (176) 21.8	29.0	98 Jun 25 (176) 16.2	0.81	FS
5	51	00 Oct 03 (277) 17.1	00 Oct 04 (278) 14.1	21.0	00 Oct 04 (278) 06.6	0.64	PP
6	64	02 Mar 19 (078) 22.9	02 Mar 20 (079) 15.4	16.5	02 Mar 20 (079) 13.4	0.88	FS
7	65	02 Mar 24 (083) 03.8	02 Mar 25 (084) 22.8	43.0	02 Mar 25 (084) 01.2	0.50	FS
8	74	03 Jun 17 (168) 17.8	03 Jun 18 (169) 08.3	14.5	03 Jun 18 (169) 04.7	0.75	FS

of 2003 were considered candidate magnetic clouds for this study. An internal shock or pressure pulse is defined as an unbalanced (in a pressure sense), sharp (quicker than 12 min), large ($\Delta B/B > 0.23$) change in the magnitude of the magnetic field within the boundaries of a magnetic cloud and which is well-fit by the Rankine-Hugoniot jump conditions, so an accurate structure normal can be determined from the data.

[9] This search, which included 82 clouds, resulted in the eight cases listed in Table 1. The first column shows the case number for the purpose of this paper while the second column shows the magnetic cloud number from the Wind/MFI Web page (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html) and links from there. This table also includes the cloud start and end times based on the magnetic cloud parameter fits of *Lepping et al.* [1990] from the Wind/MFI Web page along with the cloud duration in hours, the time of the internal shock, the fraction of the way through the cloud that the shock occurs (timewise) and finally the type of discontinuity, either a pressure pulse (PP) or a fast forward shock (FS). The related magnetic cloud fit parameters are provided in Table 1 of *Lepping et al.* [2006]. Forward shock (FS) applies to the cases in which the upstream speed exceeds the Alfvén speed and magnetosonic speed, and pressure pulse (PP) applies when the ratios are less than unity.

[10] The first two columns in Table 2, again for convenience, list the case numbers from this study and the numbers from the Wind/MFI Web page. The next three columns are the components of the shock normal unit vector in GSE coordinate directions x, y, and z. The sixth column is the angle θ_{Bn} between the upstream magnetic field and the shock normal. The seventh column is the cloud axis angles in the ecliptic plane (longitude, ϕ_A) and out of the ecliptic plane (latitude, θ_A) so that the orientation of the cloud axis in GSE coordinates is given by the unit vector $\hat{n}_{cloud} = \cos\theta_A\cos\phi_A\hat{\mathbf{x}} + \cos\theta_A\sin\phi_A\hat{\mathbf{y}} + \sin\theta_A\hat{\mathbf{z}}$. The next three columns are the magnetic cloud axis vector in GSE coordinates, and the last column is the angle between the magnetic cloud axis and the shock normal vector, with the related acute angle in parentheses.

[11] The Rankine-Hugoniot jump conditions were determined using the method of *Berdichevsky et al.* [2000, 2001]. The uncertainties in the angles between the magnetic field and the normal, θ_{Bn}, were evaluated using the root-mean-square deviation for a distribution of solutions.

3. Previous Work

[12] There has been relatively little work done on these shocks and pressure pulses internal to magnetic clouds and, indeed, they appear to have been largely unrecognized as a class of phenomena by the community. However, some cases have been addressed by a few investigators.

[13] *Chao et al.* [1999] examined number 2 of our cases. The unusual normal orientation of the shock in the 18–19 October 1995 magnetic cloud led them to suggest that this internal shock is related to an X-ray flare observed on the Sun at 9°N, 54°W on 16 October 1995 at 1221 UT. The propagation of the interplanetary disturbance associated with this flare would have produced the observed shock orientation from simple geometrical considerations.

[14] *Collier et al.* [2001] also examined case 2 using a greater variety of Wind data. On the basis of the unusual shock orientation as well as an electron heat flux dropout that occurred on the same side of the cloud from whence the shock came and a cold 5 keV proton beam observed nearly coincident with the shock, they proposed that the internal shock was due to some of the magnetic cloud's field lines reconnecting near the foot points of the magnetic cloud.

[15] *Burlaga et al.* [2003] discuss cases 6 and 7. They interpret case 6 as being due to ejecta related to a halo CME

Table 2. Magnetic Cloud and Shock Parameters

				MC Axis					
Case	LN	Shock Normal GSE	ϑ_{Bn}, deg	ϕ_A, deg, GSE	ϑ_A, deg, GSE	x, GSE	y, GSE	z, GSE	$\vartheta_{axis-norm}$, deg
1	02	−0.87 −0.05 0.50	82 ± 7	205	−76	−0.22	−0.10	−0.97	107 (73)
2	06	−0.58 0.74 0.37	75 ± 1*	287	−8	0.29	−0.95	−0.14	156 (24)
3	25	−0.61 0.78 −0.18	63 ± 3	244	38	−0.35	−0.71	0.62	117 (63)
4	34	−0.85 −0.50 −0.20	81 ± 6	151	21	−0.82	0.45	0.36	67
5	51	−0.92 0.35 0.18	75 ± 7	58	33	0.44	0.71	0.54	93 (87)
6	64	−0.70 0.31 0.64	89 ± 1	45	20	0.66	0.66	0.34	92 (88)
7	65	−0.70 0.14 0.70	85 ± 2	288	35	0.25	−0.78	0.57	83
8	74	−0.73 −0.68 0.00	55 ± 1	264	−52	−0.06	−0.61	−0.79	63

*The values are correct here. The article as originally published is online.

observed on 18 March 2002 (day 77). They interpret case 7 as being associated with a CME observed on 22 March 2002 (day 81). As will be discussed later in this paper, these identifications are consistent with an association between fast shocks internal to magnetic clouds and outline asymmetric CMEs.

[16] *Berdichevsky et al.* [2005] discuss a magnetic cloud observed near Earth on 20 March 2003 which was preceded by about 8 hours by a shock. Although not one of the cases listed in Tables 1 and 2, this case is notable because the authors argue that the upstream shock is not driven by the magnetic cloud. This conclusion was based on the fact that the velocity of the magnetic cloud's leading edge was less than the shock propagation velocity, the orientations of the cloud boundaries and the shock normal were inconsistent with the cloud driving the shock, and the ram pressure at the front of the cloud was less than that in the shock sheath. The implication of the *Berdichevsky et al.* [2005] study is that, apparently, the shock had encountered and overtaken the magnetic cloud. It is possible that the shocks and pressure pulses studied here, which are internal to magnetic clouds, are cases like those in the *Berdichevsky et al.* [2005] study in which the shocks are caught in the process of traversing a magnetic cloud. If this should be the case, then the common behavior of these internal shocks and pressure pulses may suggest that some interesting processes occur in the traversal.

[17] These ideas address the origin of particular internal shocks and pressure pulses inside particular magnetic clouds which may not be representative of the origin of shocks and pressure pulses inside of magnetic clouds in a general sense.

4. Discussion

[18] Figure 1 shows the magnetic field and plasma parameters from the eight cases of shocks internal to magnetic clouds found in this study. The thin solid grey vertical line is the time of the shock ramp and the two thicker lines are the start and end times of the magnetic clouds.

[19] Figure 2 shows a series of higher-resolution images similar to those of Figure 1 but covering a 2 hour time period centered on the shock. In each of the eight cases in Figure 2, the rows show the magnetic field magnitude, latitude, and longitude and the solar wind convection speed, density, and thermal speed from top to bottom. These profiles give "plausibility" support for the nature of these signatures as being shock-like, i.e. either bona fide shocks or pressure pulses, as claimed. In every case, the shock is most notable in the magnetic field magnitude, given at the top, while hardly appearing at all in the two magnetic field angles. Thus the shocks are compressive also in magnetic field. In every case, both the magnetic field magnitude and density increase across the discontinuity.

[20] For the 18 October 1995 magnetic cloud, the shock normal was quasi-perpendicular to the magnetic field and quasi-parallel to the cloud axis. To compare these characteristics with those of the other seven cases, Figure 3 shows a scatterplot of the angle between the shock normal and the upstream magnetic field, θ_{Bn}, versus the angle between the cloud axis and the shock normal, $\theta_{\mathrm{axis-norm}}$. Seven of the eight cases suggest a loose linear relationship, with θ_{Bn} correlating with $\theta_{\mathrm{axis-norm}}$.

[21] Interestingly, these seven cases also have angles between the cloud axis and the shock discontinuity normal greater than 50 degrees; i.e., they are propagating largely perpendicular to the cloud axis, a property that would ostensibly support the idea that another structure has impacted the rear of the cloud causing the observed internal shock. The one notable exception to this behavior is the internal shock of the 18 October 1995 magnetic cloud which appears to be propagating primarily antiparallel to the magnetic cloud axis, as was pointed out by *Lepping et al.* [1997] and *Collier et al.* [2001]. This behavior along with the other signatures reported by Collier et al. suggest that the 18 October 1995 internal shock may have a different origin than most shocks internal to magnetic clouds.

[22] The Figure 4 scatterplot indicates another very interesting characteristic of these internal shocks and pressure pulses, namely that they appear to occur preferentially in the latter half of the cloud, timewise. This is indicated by the clustering of the points above the central horizontal line in the plot. The choice of plotting the fraction of the cloud traversed in time prior to the passage of the shock or pressure pulse versus θ_{Bn} rather than some other parameter was arbitrary.

[23] Referring to Table 1, most of the cases (6 of 8) considered here were fast interplanetary shocks rather than pressure pulses.

5. Conclusions

[24] The internal shocks and pressure pulses studied here occurred in eight of 82 magnetic clouds observed by Wind from November of 1994 through August of 2003, i.e., in about 10% of the clouds. Considering that the magnetic field profile within magnetic clouds is almost always very steady and slowly rotating, to observe such sudden, large, and systematic changes in the field in 10% of magnetic clouds may be surprising. However, even though 10% may constitute a minority of magnetic clouds, it is frequently through an understanding of such unusual cases that we gain the greatest insight into the subject at hand.

[25] Table 3 addresses the question whether or not there exists any obvious correspondence between the frequency of these shocks internal to magnetic clouds and the frequency of CMEs themselves. The first column of this table shows the calendar year 1996 (solar minimum) through 2002 (late solar maximum). The second column shows the number of observed CMEs based on SOHO Large Angle and Spectrometric Coronagraph Experiment (LASCO) data from *Yashiro et al.* [2004]. The third column shows the number of magnetic clouds observed by Wind at 1 AU and the fourth column shows the number of these clouds containing internal shocks.

[26] There are many caveats concerning the CME number listed in the second column mentioned by Yashiro et al., not the least of which are that manual CME identification is subjective and that SOHO suffered many months of downtime in late 1998. Nevertheless, low statistics notwithstanding, Table 3 does appear to suggest that the occurrence of magnetic clouds with internal shocks does not increase with

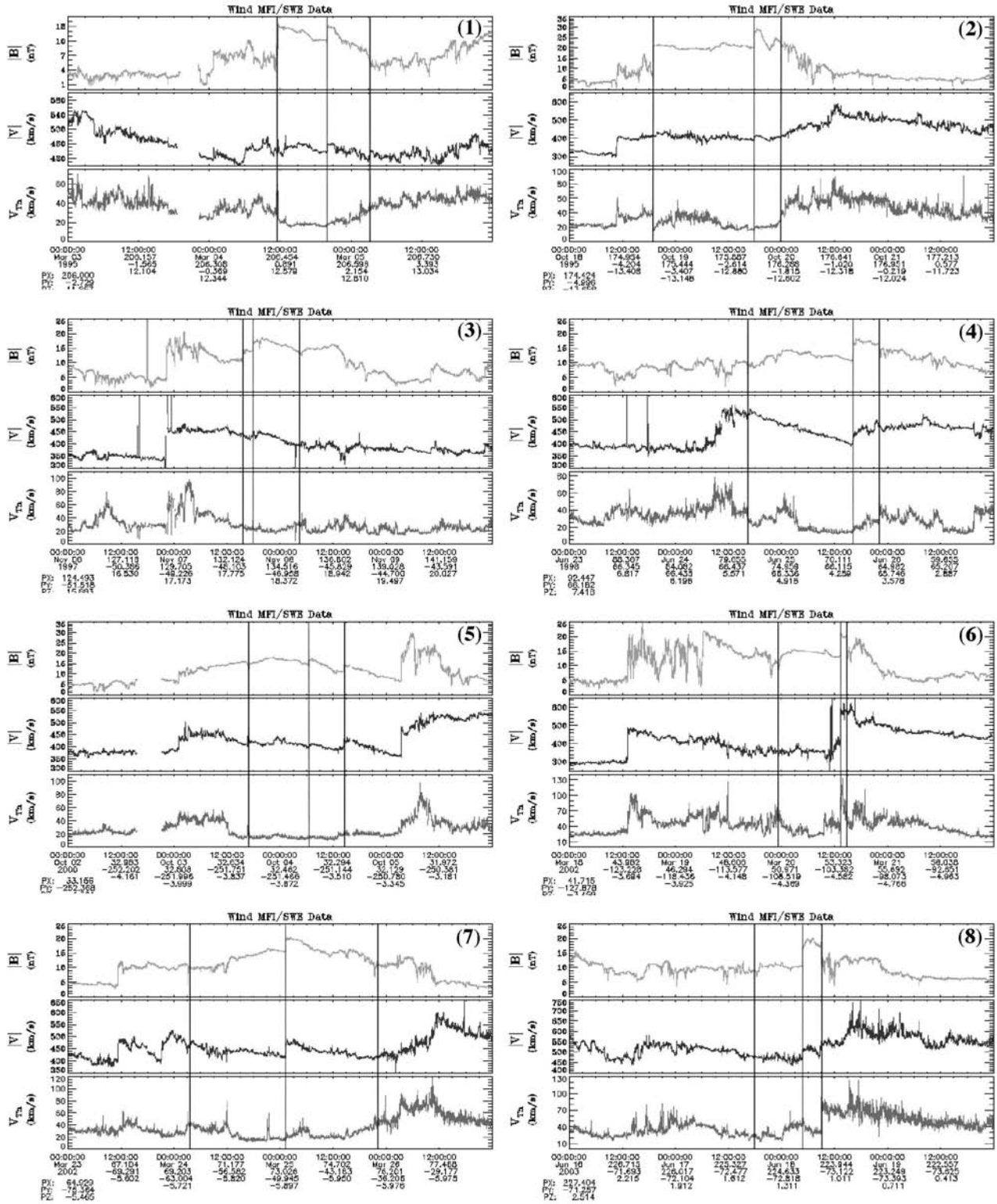

Figure 1. The cases of internal shocks and pressure pulses considered in this study. Each case is labeled with this study's case number in the upper right corner. Each row in each case is the magnetic field magnitude, the bulk convection speed, and the thermal speed.

the number of CMEs observed at all solar latitudes, which might be expected if the internal shocks were due to CME interactions. However, it is also the case that when comparing the results of this study with the CME rate, the speed of the CMEs also plays a role, as will be discussed later.

[27] As discussed previously, in three of the eight cases (2, 6, and 7) examined, potential external sources of these

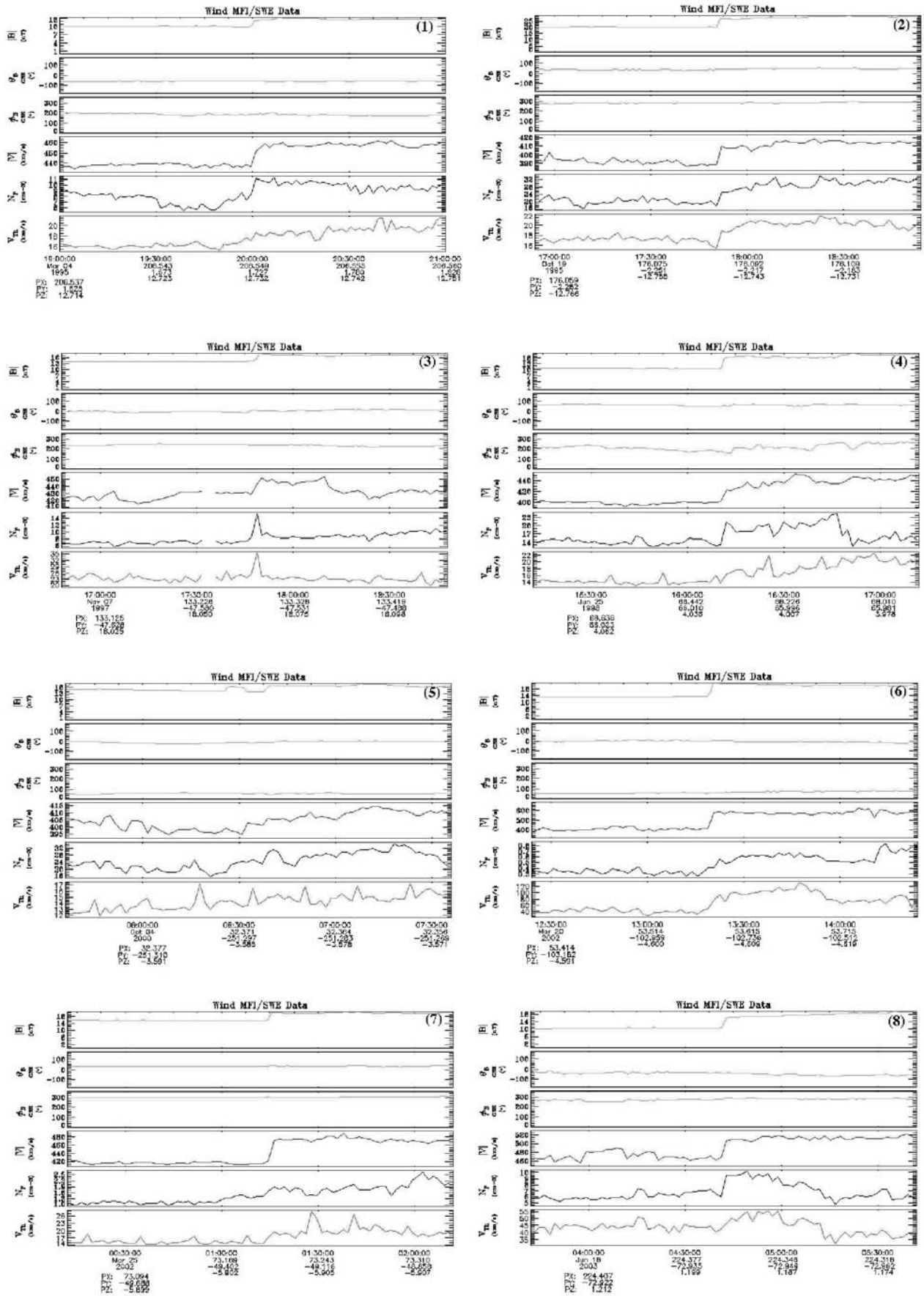

Figure 2

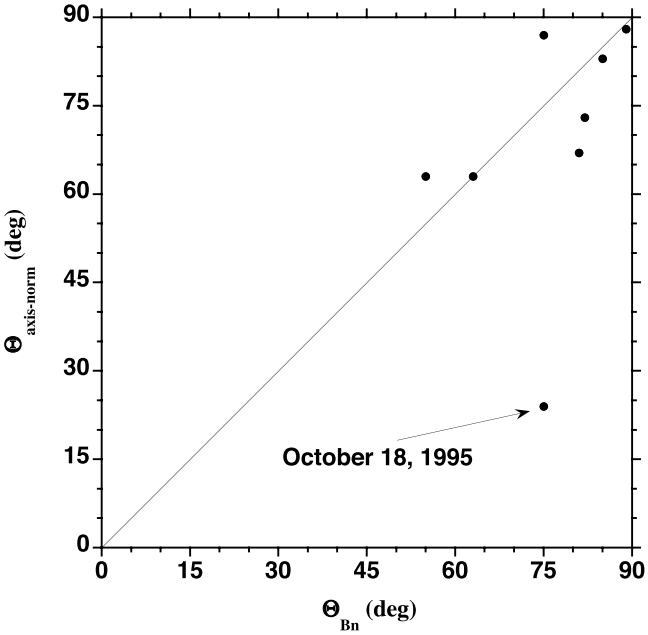

Figure 3. Scatterplot showing the angle between the cloud axis and the shock normal $\theta_{\mathrm{axis-norm}}$ versus the angle between the upstream magnetic field and the shock normal θ_{Bn}, both in degrees, for all eight of the cases comprising this study.

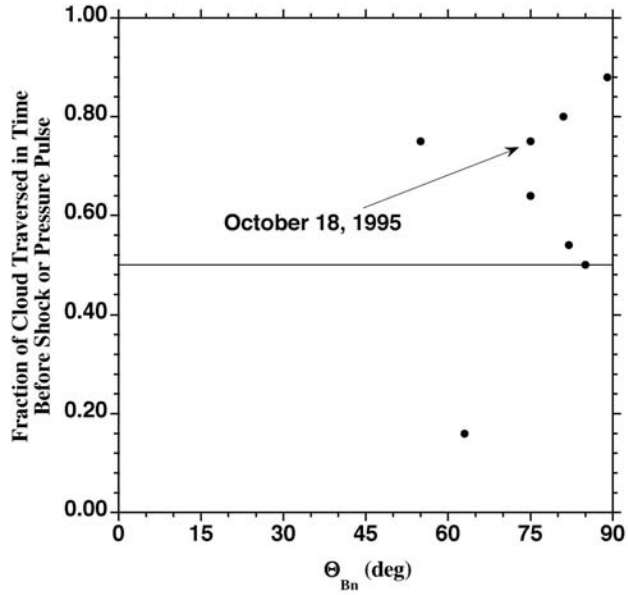

Figure 4. Scatterplot of the angle between the magnetic field and the shock normal θ_{Bn} in degrees versus the fraction of the way through the cloud, timewise, that the shock occurs.

internal shocks and pressure pulses have been identified [*Collier et al.*, 2001; *Burlaga et al.*, 2003]. However, in one of these cases (2) a flare was identified which may have been associated with a CME driving a shock [*Sheeley et al.*, 1986], but no evidence in the low corona for associated ejecta or shocks could be found [*Collier et al.*, 2001].

[28] One might expect that if diverse external sources are responsible for these internal shocks, then they would produce a wide range of characteristics. However, this does not seem to be the case. Remarkably, almost all, if not all, of the interplanetary shocks and pressure pulses internal to magnetic clouds have the following properties.

5.1.1* Occurrence Distribution

[29] The internal shocks and pressure pulses appear to occur preferentially in the latter half of the magnetic clouds, timewise. This is the case for seven of the eight cases studied here, as illustrated by Figure 4. This behavior seems odd and would ostensibly argue against an interpretation in which the shocks simply pass through the cloud, in which case the distribution might be expected to be more uniform, or at least not so clumped as observed.

[30] It is possible, of course, that this "nonuniform" distribution is simply the result of poor statistics. However, it is also possible that these interplanetary shocks and pressure pulses occur preferentially in the latter half of the magnetic clouds because generally the Alfvén speed is lower in the trailing part of the cloud than in the leading part. The asymmetry in the Alfvén speed is due to the asymmetry in $|\mathbf{B}|$ within most magnetic clouds caused mainly by the magnetic cloud's interaction with the upstream solar wind and partly is due to magnetic cloud expansion. That is, $|\mathbf{B}|$ is on average higher in front and lower in the rear of magnetic clouds. (Note that the shock Alvénic Mach number, $M = v_s/v_A$ with $v_A = |\mathbf{B}|/\sqrt{4\pi n}$, is larger in the rear of magnetic clouds because there $|\mathbf{B}|$ tends to be smaller and in some cases n is larger [see, e.g., *Lepping et al.*, 2003].) This property makes it easier to form shocks in the latter parts of most magnetic clouds. As Figure 1 shows, however, clearly not all of our cases can be explained this way. For example, cases 2, 3, and 7 could not. Also note that many clouds at 1 AU show a speed gradient from front to rear which may also contribute to making an internal shock encounter more likely in the rear.

5.2.1 Quasi-Perpendicular Character

[31] In all cases found in this study, the shocks are quasi-perpendicular in nature (i.e., the upstream magnetic field is approximately perpendicular to the shock normal), and therefore the magnetic field magnitude, the solar wind velocity, and the density all rise across the shock or pressure pulse (a fast forward mode wave).

5.3.1 Magnetic Field Orientation

[32] In every one of the internal shocks and pressure pulses examined, the field magnitude increases across them

Figure 2. A 2 hour period centered around the shock time for each of the eight cases shown in Figure 1. Each case is labeled with this study's case number in the upper right corner. Each row in each case is the magnetic field magnitude, the latitude and longitude angles of the field, the solar wind convection speed, the solar wind density, and the solar wind thermal speed from top to bottom.

*The section numbering is correct from here forward. The article as originally published is online.

Table 3. Relationship to CMEs

Year	CME Number[a]	Magnetic Clouds	Clouds With Internal Shocks
1996	204	4	0
1997	351	17	1
1998	697	11	1
1999	957	4	0
2000	1580	14	1
2001	1465	10	0
2002	1652	10	2

[a]CME number from *Yashiro et al.* [2004].

(as time increases), but the magnetic field direction remains almost unchanged through the transition. In one case (case 6) it is very close to perpendicular, consistent with an angle between the magnetic field just upstream of the shock and shock-normal of 90°, within a degree.

[33] However, the small angle between the shock normal and the cloud axis in the 18 October 1995 event (case 2) appears to be unusual (see Figure 3). In general for these events, the angle between the shock normal and cloud axis correlates well with the angle between the shock normal and the local magnetic field, with the angle between the shock normal and cloud axis typically being greater than 45°. The 18 October 1995 event, however, does not follow this trend. The correlation coefficient for the seven events shown in Figure 3 excluding the 18 October 1995 event is 0.71.*

[34] There are a number of possibilities that could explain the existence of these internal shocks:

[35] 1. The internal shocks arise by chance due to distant sources unrelated to the magnetic clouds [e.g., *Chao et al.*, 1999]. In this case, the nonuniformity shown in Figure 4, namely that the internal shocks appear to occur overwhelmingly in the latter half of the magnetic clouds, would be explained by poor statistics.

[36] 2. The internal shocks result from some solar wind structure impacting the rear of the magnetic cloud near the time of observations at 1 AU. One piece of evidence for such a process is the observation of a faster stream in the rear of the magnetic cloud than in the front, especially than in front of the upstream shock. Cases 2, 4, 5, 6, 7, and 8 all appear to exhibit this gradient in speed at the rear of the magnetic cloud consistent with interpreting the shock as the result of an impinging structure on the magnetic clouds. However, most of these cases are marginal (e.g., 7). Other possibilities may be at work in cases 1 and 3 which show a lower speed at the rear than upstream of the shock.

[37] Indeed, independent of whether or not the internal shocks result from some solar wind structure impacting the rear, the likelihood of encountering a shock in the rear of a cloud may be higher because many clouds at 1 AU show a speed gradient from front to rear, with higher speeds in the front. In this interpretation, the shocks will spend a longer time in regions of lower solar wind speed and hence will have a higher probability of being observed there. Note, however, from Figure 1 that the relative speed change across the cloud is generally not that large.

[38] Finally, it is worth mentioning SOHO observations associated with these events for which SOHO data are available. For all cases of fast shocks observed within magnetic clouds during the SOHO era (cases 3, 4, 6, 7, and 8), we were able to determine associated halo CMEs in the SOHO LASCO CME catalogue (cdaw.gsfc.nasa.gov/CME_list/). These were identified as the closest (in time) halo CME which occurred before the start of the magnetic cloud. Table 4 summarizes the properties of these halo CMEs. The first column indicates the case number of the study along with the start time of the magnetic cloud from Table 1 in column 2. Column 3 shows the date and time of the CME's first appearance in the LASCO/C2 field of view. Column 4 shows the linear speed of the CME observed by LASCO, and column 5 shows the type of halo CME: symmetric, brightness asymmetry, or outline asymmetry.

[39] Interestingly, all of these cases are "outline asymmetric" CMEs of greater than average speed. Outline asymmetric CMEs are characterized by a heliocentric distance of the CME's leading edge significantly different at different position angles around the disk.

[40] It has been suggested (N. Gopalswamy, private communication, 2006) that these internal shocks and pressure pulses may result from the interaction between an earlier, slower halo CME and a later, faster off-center CME which drives a strong shock. In this interpretation, the outline asymmetric CMEs identified in Table 4 would not directly correspond to the Wind magnetic clouds in the second column of Table 4 [*Gopalswamy et al.*, 2001] but rather would be responsible for the internal shocks.

[41] 3. The internal shocks represent an intrinsic property of some magnetic clouds. In this case, perhaps some shocks are created later in the same region as the magnetic cloud originated and propagate with almost the same speed as the magnetic cloud's leading edge. So, they are a "part" of the magnetic cloud, at least in some regions of the magnetic cloud. The shock forms close to the Sun either completely inside the cloud or partially inside and partially outside the cloud. Later, at say 1 AU, the shock is still inside of the magnetic cloud because the speed of the nose of the magnetic cloud is close to the shock's speed.

Table 4. Summary of SOHO Halo CME Observations Associated With Fast Shocks Internal to Magnetic Clouds

Case	Magnetic Cloud Start Time	Halo CME Time[a]	Speed, km/s	Type
3	97 Nov 07 (311) 15.8	97 Nov 06 (310) 12.2	1556	outline asym.
4	98 Jun 24 (175) 16.8	98 Jun 20 (171) 18.3	964	outline asym.
6	02 Mar 19 (078) 22.9	02 Mar 18 (077) 02.9	989	outline asym.
7	02 Mar 24 (083) 03.8	02 Mar 22 (081) 11.3	1750	outline asym.
8	03 Jun 17 (168) 17.8	03 Jun 15 (166) 23.9	2053	outline asym.

[a]From cdaw.gsfc.nasa.gov/CME_list/.

*The value is correct here. The article as originally published is online.

[42] These types of nondriven interplanetary shocks were formerly known as "blast shocks" [e.g., *Gopalswamy et al.*, 1998] but have since fallen out of favor and may not be physically possible, at least not all the way out to 1 AU (blast shocks may form close to the Sun but then damp quickly). However, some may have been observed at this greater distance. *Berdichevsky et al.* [2000] examined all interplanetary shocks observed by the Wind spacecraft between November 1994 and May 1997 to determine a number of different parameters including whether there was a driver associated with the shock. They found eight cases lacking apparent drivers (out of 42 total cases or 19%). Berdichevsky et al. point out that blast shockwaves generated at the Sun (which would have no association with any driver at all) cannot be easily distinguished from a shock having a driver with a single spacecraft, because the driver might be missed by a single spacecraft. Furthermore, they found that the distribution of weak shocks without apparent drivers shows orientations pointing well out of the ecliptic plane which might suggest unobserved drivers rather than the local observation of a blast wave with an origin at the Sun.

[43] 4. The one internal shock with a normal approximately aligned with the cloud axis (the 18 October 1995 case) may have a shock source at or near the footpoint which is ducted along the magnetic cloud axis [*Collier et al.*, 2001].

[44] Whatever their origin, these interplanetary shocks and pressure pulses have appeared inside about 10% of magnetic clouds observed over 9 years by Wind. They exhibit many surprising features but appear to constitute a class of physical phenomena that have largely gone unnoticed by the community.

[45] **Acknowledgments.** Special thanks to Keith Ogilvie and Alan Lazarus for the use of Wind/SWE data in this study and to Adam Szabo and Tom Narock for data handling. Also, thanks to Nat "Gopal" Gopalswamy for helpful conversations. DBB acknowledges the support of NASA LWS NASW-02035.

[46] Zuyin Pu thanks Volker Bothmer and another reviewer for their assistance in evaluating this paper.

References

Berdichevsky, D. B., A. Szabo, R. P. Lepping, A. F. Vinas, and F. Mariani (2000), Interplanetary fast shocks and associated drivers observed through the 23rd solar minimum by Wind over its first 2.5 years, *J. Geophys. Res.*, *105*, 27,289–27,314.

Berdichevsky, D. B., A. Szabo, R. P. Lepping, A. F. Vinas, and F. Mariani (2001), Correction to "Interplanetary fast shocks and associated drivers observed through the 23rd solar minimum by Wind over its first 2.5 years," *J. Geophys. Res.*, *106*, 25,133.

Berdichevsky, D. B., C. J. Farrugia, B. J. Thompson, R. P. Lepping, D. Reames, M. L. Kaiser, J. T. Steinberg, S. P. Plunkett, and D. Michels (2002), Halo-coronal mass ejections near the 23rd solar minimum: Lift-off at the Sun, interplanetary tracking, and in-situ observation at 1 AU, *Ann. Geophys.*, *20*, 891–916.

Berdichevsky, D. B., I. G. Richardson, R. P. Lepping, and S. F. Martin (2005), On the origin and configuration of the 20 March 2003 interplanetary shock and magnetic cloud at 1 AU, *J. Geophys. Res.*, *110*, A09105, doi:10.1029/2004JA010662.

Bothmer, V., and D. M. Rust (1997), The field configuration of magnetic clouds and the solar cycle, in *Coronal Mass Ejections, Geophys. Monogr. Ser.*, vol. 99, edited by N. Crooker, J. Joselyn, and J. Feynman, pp. 139–146, AGU, Washington, D. C.

Burlaga, L. F. (1995), *Interplanetary Magnetohydrodynamics*, pp. 89–98, Oxford Univ. Press, New York.

Burlaga, L., D. Berdichevsky, N. Gopalswamy, R. Lepping, and T. Zurbuchen (2003), Merged interaction regions at 1 AU, *J. Geophys. Res.*, *108*(A12), 1425, doi:10.1029/2003JA010088.

Chao, J. K., C. B. Wang, D. J. Wu, and R. P. Lepping (1999), Interaction of the Oct. 14–19, 1995 magnetic cloud with a solar interplanetary disturbance, *Eos Trans. AGU*, *80*(17), Spring Meet. Suppl., S269.

Collier, M. R., et al. (2001), Reconnection remnants in the magnetic cloud of October 18–19, 1995: A shock, monochromatic wave, heat flux dropout, and energetic ion beam, *J. Geophys. Res.*, *106*, 15,985–16,000.

Forsyth, R. J., A. Balogh, E. J. Smith, and J. T. Gosling (1999), Magnetic field structure of transients at Ulysses: Their relationship to coronal structure and CMEs, paper presented at IUGG99, Int. Union of Geod. and Geophys., Birmingham, U. K.

Gopalswamy, N., M. L. Kaiser, R. P. Lepping, S. W. Kahler, K. Ogilvie, D. Berdichevsky, T. Kondo, T. Isobe, and M. Akioka (1998), Origin of coronal and interplanetary shocks: A new look with WIND spacecraft data, *J. Geophys. Res.*, *103*, 307–316.

Gopalswamy, N., A. Lara, S. Yashiro, M. L. Kaiser, and R. A. Howard (2001), Predicting the 1 AU arrival times of coronal mass ejections, *J. Geophys. Res.*, *106*, 29,207–29,217.

Lepping, R. P., and D. Berdichevsky (2000), Interplanetary magnetic clouds: Sources, properties, modeling, and geomagnetic relationship, *Recent Res. Dev. Geophys. Res.*, *3*, 77–96.

Lepping, R. P., J. A. Jones, and L. F. Burlaga (1990), Magnetic field structure of interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *95*, 11,957–11,965.

Lepping, R. P., et al. (1997), The Wind magnetic cloud and events of October 18–20, 1995: Interplanetary properties and as triggers for geomagnetic activity, *J. Geophys. Res.*, *102*, 14,049–14,063.

Lepping, R. P., D. Berdichevsky, A. Szabo, C. Arqueros, and A. J. Lazarus (2003), Profile of an average magnetic cloud at 1 AU for the quiet solar phase: WIND observations, *Sol. Phys.*, *212*, 425–444.

Lepping, R. P., D. B. Berdichevsky, C.-C. Wu, A. Szabo, T. Narock, F. Mariani, A. J. Lazarus, and A. J. Quivers (2006), A summary of WIND magnetic clouds for the years 1995–2003: Model-fitted parameters, associated errors, and classifications, *Ann. Geophys.*, *24*, 215–245.

Sheeley, N. R., Jr., C. R. Devore, and L. R. Shampine (1986), Simulations of the gross solar magnetic field during sunspot cycle 21, *Sol. Phys.*, *106*, 251–268.

Yashiro, S., N. Gopalswamy, G. Michalek, O. C. St.Cyr, S. P. Plunkett, N. B. Rich, and R. A. Howard (2004), A catalog of white light coronal mass ejections observed by the SOHO spacecraft, *J. Geophys. Res.*, *109*, A07105, doi:10.1029/2003JA010282.

D. B. Berdichevsky, M. R. Collier, and R. P. Lepping, NASA Goddard Space Flight Center, Code 673, Building 2, Room 246, Greenbelt, MD 20771, USA. (michael.r.collier@nasa.gov)