On the variation of interplanetary magnetic cloud type through solar cycle 23: Wind events

R. P. Lepping[1] and C.-C. Wu[1,2]

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[1] This statistical study examines the change in interplanetary magnetic cloud (MC) type, based on Wind observations of 100 MCs, taken during solar cycle 23 and split into three intervals: the minimum and rising phase of the cycle (over the years 1995–1998), the maximum phase (1999–2001), and the declining phase (2002 to early 2006). MC type refers to the profile of the latitude (or B_Z, in geocentric solar ecliptic (GSE) coordinates) of the magnetic field within the MC, such as N-to-S (i.e., north-to-south from start to end), S-to-N, all S, almost all S, and so forth, with 10 categories in all. One of the main findings is that the strictly S-to-N events were very prevalent early in the cycle (i.e., 33% for the first phase) and tended to decrease in number as the cycle proceeded and that the strictly N-to-S cases had very low frequency of occurrence early in the cycle (i.e., 8% for the first phase) but tended to increase in number (22%) toward the end of the cycle, equal to the number of S-to-N events in that phase. When all S-to-N and N-to-S types for the full cycle are considered, the former clearly dominated over the latter by 1.4-to-1.

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1. Introduction

[2] We examine the variation of the occurrences of interplanetary magnetic cloud (MC) type with respect to solar cycle phase for the years 1995 through the early part of 2006 using Wind magnetic field data. Interplanetary MCs were first identified by Burlaga and coworkers [e.g., see *Burlaga*, 1995, and references therein]. A MC is defined as a region in the solar wind having: (1) enhanced magnetic field strength, (2) a smooth change in field direction as observed by a spacecraft passing through the MC, and (3) low proton temperature (and low proton plasma beta) compared to the ambient proton temperature (e.g., *Burlaga et al.* [1981], *Klein and Burlaga* [1982], *Burlaga* [1988, 1995], *Farrugia et al.* [1997] (on flux rope evolution), *Lepping and Berdichevsky* [2000], and *Lepping et al.* [2006]). Magnetic clouds are also understood to be large structures, at large distances from the Sun, so that their durations are long, i.e., between about 7 and 48 hours at 1 AU, averaging about 21 hours in duration for the better examples [e.g., *Lepping et al.*, 2006]; this feature is to be part of our definition of an interplanetary MC in contrast to the earlier one by Burlaga and coworkers. (Also see *Bothmer and Schwenn* [1998], who discuss MCs at other distances than 1 AU, e.g., at Helios 1 and the Voyagers, and they stress MC expansion and its role in a definition of a MC.) It has been shown that a disappearing filament/eruptive prominence is probably the strongest candidate for the source of a MC [e.g., *Wilson and Hildner*, 1986; *Marubashi*, 1986; *Bothmer and Schwenn*, 1994]. MC type refers to the profile of the latitude (θ, in geocentric solar ecliptic (GSE) coordinates) of the magnetic field (or equivalently B_Z) within the MC, such as N-to-S (north-to-south from start to end), S-to-N, all S, all N, almost all S, almost all N, etc.; see Table 3 and Figure 12 of *Lepping et al.* [2006]. Also see *Bothmer and Schwenn* [1998] and *Huttunen et al.* [2005] concerning MC type classification; however, they use a slightly different notation scheme. Figure 1 shows sketches of four examples of MCs as flux ropes, stressing their different attitudes, and the kind of θ signature expected for each one, or equivalently, the kind of B_Z component signature expected, where **Z** is normal to the ecliptic plane and where $\theta = \sin^{-1}(B_Z/|B|)$, $|B|$ being the magnetic field magnitude. Note that for each type we can have two possible handedness (H) "states" (for right-handed or left-handed). As we see, in the top sketch of the figure, B_Z is almost all northward, and in the bottom sketch it is almost all southward. The other two cases show a southward B_Z early in the MC (on the left) and late in the MC (on the right). The specific profile of B_Z usually depends on several factors, but the attitude of the flux rope is one of the main ones, as indicated in Figure 1. For the 11.3 year interval of interest (specifically from early 1995 to mid-April 2006) 100 MCs were identified and their modeled properties described on the NASA Goddard Space Flight Center Wind/MFI Web site http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_S1.html.

[3] These 100 MCs are the basis for this study. This overall interval was split into three phases according to a scheme defined by Figure 4 of *Gopalswamy et al.* [2007]:

[1]Space Weather Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]University of Alabama in Huntsville, Hunstville, Alabama, USA.

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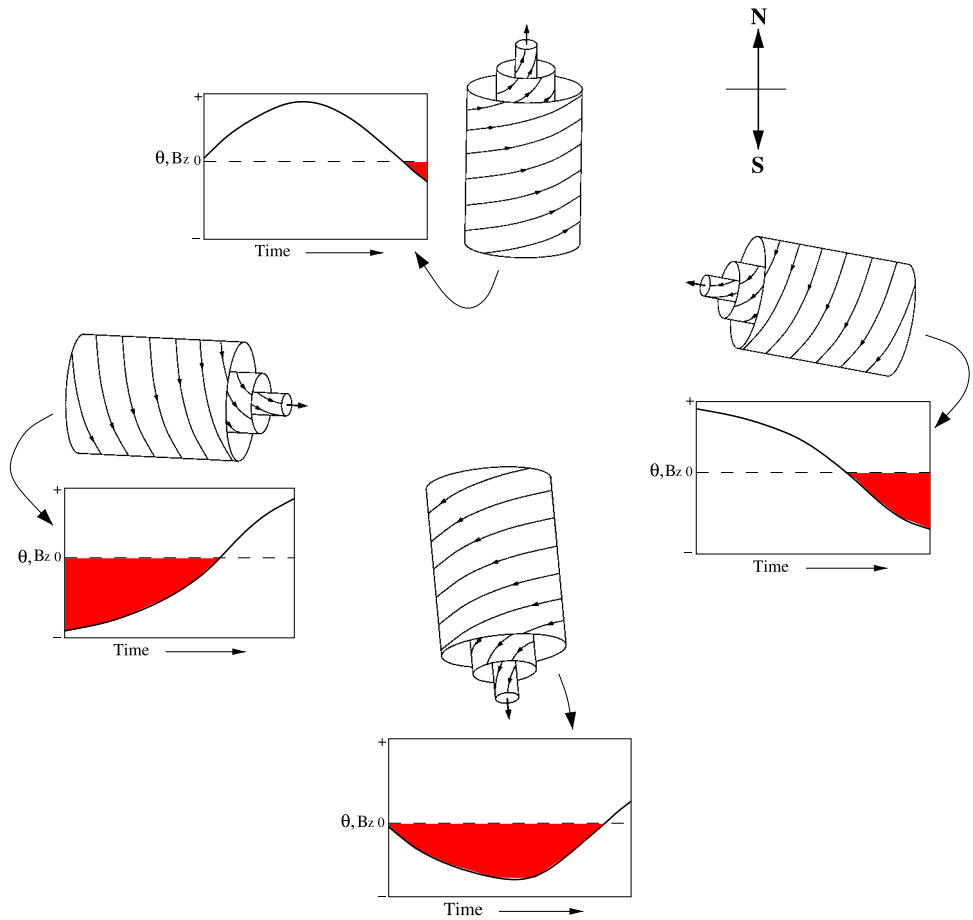
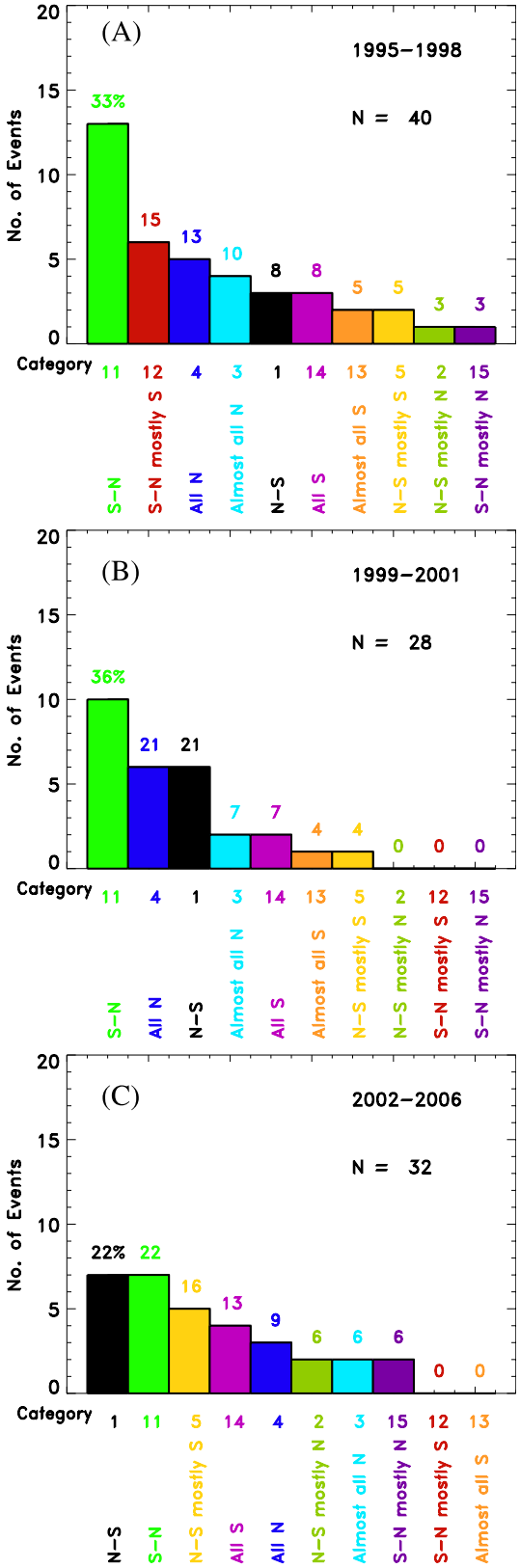


Figure 1. The profile of the θ (or IMF B_Z) within a MC can be understood in terms of the orientation of the interplanetary magnetic cloud (MC) as a flux rope. Here are sketches of four examples of different flux rope orientations and their associated θ (or IMF B_Z) profiles in GSE coordinates. The end-points of the boxes represent the boundaries of the MCs, and the shaded regions are where the B_Z components are southward. The ropes on the right and left have axes nearly parallel to the (-) Y (GSE) axis.

1995–1998 (minimum and rising phase, 40 cases), 1999–2001 (maximum phase, 28 cases), and 2002 to early 2006 (declining phase, 32 cases). The issue of MC type, and therefore the prevalence of the southward or northward polarity of IMF B_Z within a MC and in what portion of the MC it occurs, is obviously important with regard to: (1) a MC's ability, or not, to trigger a geomagnetic storm, generally assumed to be via magnetic reconnection [e.g., *Fairfield and Cahill*, 1966; *Burton et al.*, 1975; *Wu and Lepping*, 2002, 2005, 2007; *Wu et al.*, 2003, 2006; *Bothmer*, 2004; *Bothmer and Zhukov*, 2007; *Gonzalez*, 1994], (2) the kind of storm, (3) the specific phasing between the start of the MC and the storm, and (4) any attempt to make solar source correlations. *Lepping et al.* [2005] have stressed the usefulness of the N-to-S type of MCs in their ability to facilitate forecasting of minimum Dst, usually many hours (~6 hours) in advance, for those types of MCs of typical duration (around 21 hours; see *Lepping et al.* [2006]), especially when the observing spacecraft are at L1. This is because of the possibility, through the use of MC parameter model fitting, of predicting the time of minimum B_Z (and its specific value) from real time observations of only the earliest 2/3 of a MC, provided the fitting model is robust enough. This consideration was, in fact, one of the motivations behind this study of MC "type."

[4] *Huttunen et al.* [2005] studied the geoeffectiveness of MCs for part of solar cycle 23 (years 1997 to 2003) and reviewed some statistics on MC occurrence rate and other properties, such as the solar cycle distributions of MC handedness and "unipolar" events, meaning those that had inclination angles with respect to the ecliptic plane of greater than 45°. (We do not consider all cases greater than 45° to be in the category of unipolar; we believe that only the most severe (e.g., 70°–90°) of these can be called truly unipolar.) *Mulligan et al.* [1998] also studied solar cycle evolution of the structure of magnetic clouds in the inner heliosphere using Pioneer-Venus Orbiter data in terms of eight categories, four of low inclination and four of high inclination. Their period of interest covered an earlier interval, that from 1979 to 1988. Here we concentrate only on the interplanetary statistics of MC type and variation of type during solar cycle 23, to stress the great variety of magnetic field profiles that MCs present, as part of the overall study of the relationship between MCs and geomagnetic storms. Our study differs from the *Huttunen et al.* [2005] and the *Mulligan et al.* [1998] studies in that we



cover a longer/different period (respectively) and distribute MC type over 10 possible categories, including "extreme types" that are highly inclined (70°–90°), some of which (i.e., those called "all S" or "almost all S") are expected to be optimum for geomagnetic storm triggering. In fact, we cover slightly more than a full solar cycle (i.e., cycle no. 23, including 1995 through early 2006), which recently collected data has allowed. The *Huttunen et al.* [2005] study of ACE and Wind MC types covered ~2/3 of solar cycle 23.

[5] Besides the obvious issue of geoeffectiveness in studying the distribution of MC type, and the change of type over a solar cycle, another important issue of concern is to see if the expected changes of solar field [e.g., *Bothmer and Rust*, 1997] are mirrored by related changes in the interplanetary medium, through ICMEs/MCs, especially in the B_Z component. We concentrate here on types of MCs, which are easily identified, and not specifically ICMEs. Further, using a large number of cases, as we have here, is needed to make a strong case. We also stress that observations/measurements of magnetic fields are much easier when made in situ, as in a MC than when inferred from images of the Sun's surface, for such solar-solar wind associations.

2. Findings

[6] We direct the reader to Table 5 of the NASA Space Flight Center Wind/MFI Web site http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_CA1.html, which provides the individual assessments of MC type from the ten possible choices for the 100 MCs of interest; the definitions of these types are again given for convenience below the histograms in Figures 2a, 2b, and 2c. On the Web site the specific assessments of H are also shown for each case. If we had included H (for right-handed or left-handed) in the "state" of the MCs, the 10 choices would become 20. However, we will not include H in this study. The designation of type was done through visual inspection. There was no formal MC parameter modeling needed directly in these designations.

[7] Figure 2a shows a histogram of MC types, mainly for the minimum and rising phase of the solar cycle, in color-coded representation. Figure 2b shows the maximum phase, and Figure 2c shows the declining phase, both with the same color key as used in Figure 2a. In these figures the two major contrasting types, S-to-N and N-to-S, are designated by dark green and black, respectively. Those that were predominately southward (i.e., S-to-N mostly S, all S, almost all S, N-to-S mostly S) are shown on the "reddish

Figure 2. (a–c) Histograms of various Wind MC types in color-coded form for three phases of solar cycle 23. (Both kinds of field handedness (right and left) are combined in these histograms.) There are 10 possible MC type profiles, as defined below the figures with category numbers given to each. At the top of each bar is the percentage of cases for that bar with respect to the full number of MCs (denoted by N at the top right) for that phase. Figure 2a is for the rising phase (plus a short portion of the minimum phase, occurring just before the rising phase), Figure 2b is for the maximum phase, and Figure 2c is for the declining phase, 11.3 years in all.

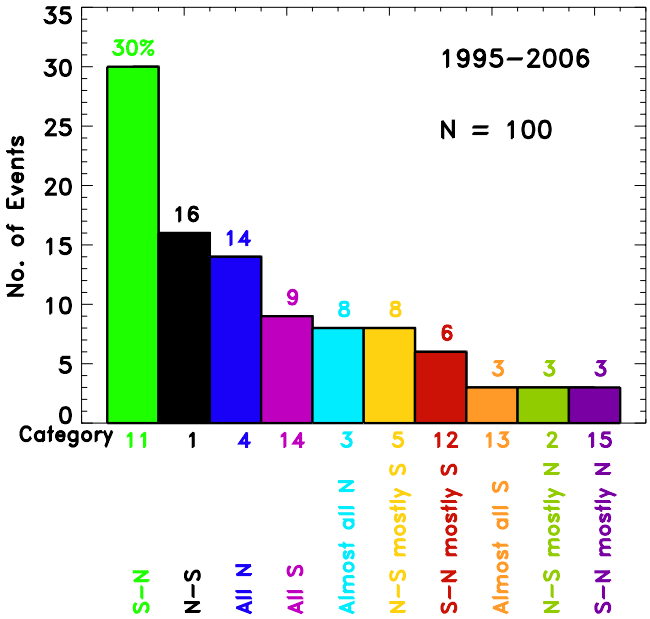


Figure 3. Similar to those histograms of Figure 2, except now we combine all $N = 100$ MCs occurring over the full "cycle" of 11.3 years, i.e., early 1995 to mid-April 2006.

side" of the spectrum, being red, reddish purple, orange, and yellow, respectively. Similarly, those that were predominately northward (i.e., all N, almost all N, N-to-S mostly N, and S-to-N mostly N) are shown on the "bluish side," being dark blue, light blue, light green, and purple, respectively. Our two main concerns here are to show the absolute distribution of MC type for each of the three phases of the solar cycle and to discuss the change in type as time progresses from one phase to another.

[8] In Figure 2a, S-to-N types (33%) were overwhelmingly the most frequent summing to 51% of all cases if all related categories are considered (categories 11, 12, and 15). All N or almost all N (categories 4 and 3, respectively) were next, summing to 23%. The N-to-S cases (categories 1, 2, and 5) summed to only 16%, and all S or almost all S (14 and 13, respectively) sum to 13%. This is consistent with the remarks by *Bothmer and Rust* [1997] that in solar cycle 23 S-to-N flux ropes are expected to be most prevalent and that around the years 2006 or 2007 (i.e., at the beginning of solar cycle 24) N-to-S types should become most prevalent. If one traces from Figure 2a, through Figure 2b, to Figure 2c, it is obvious that category 11 (S-to-N), in absolute numbers (13, 10, and 7 MCs, respectively) is decreasing over the three phases, and that category 1 (N-to-S) in absolute numbers (3, 6, and 7 MCs, respectively) is tending to increase. Likewise, if we include all types of S-to-N (categories 11, 12, and 15) and all types of N-to-S (categories 1, 2, and 5), we see the former (20, 10, and 9 MCs) is decreasing and the latter (6, 7, and 14 MCs) is increasing, as we go through the three phases given in Figures 2a, 2b, and 2c. To summarize, if we exclude the extreme cases where the flux rope is very steeply inclined, we see that the S-to-N type of events was very prevalent early in cycle 23 and clearly tended to decrease in number as the cycle proceeded and that the N-to-S type of cases was almost absent early in the cycle but tended to increase in number as it proceeded. As we see (N, top right in Figures 2a, 2b, and 2c) there were 40, 28, and 32 MCs in the phases in Figures 2a, 2b, and 2c, respectively.

[9] In Figure 3 we show a histogram of MC types where now all N = 100 MCs occurring over the full cycle 23 are considered. Again, as expected, S-to-N types clearly dominate in this interval over N-to-S types, and in fact, if we combine all S-to-N related categories (categories 11, 12, and 15), we get 39% of all cases, whereas by combining all N-to-S related categories (categories 1, 2 an 5), we get 27% of all cases, the rest being the "extreme" cases, discussed below, giving 34% remaining (12% for S and 22% for N) cases. Strictly for S-to-N types (cat. 11) and N-to-S types (cat. 1), there were about twice as many of the former as the latter.

3. Extreme Categories: All N, All S, Almost All N, Almost All S

[10] We examine here a few categories that were underemphasized above, such as all N and almost all N (categories 4 and 3) and all S and almost all S (categories 14 and 13). We call these extreme, because they are somewhat uncommon and geometrically possess an extreme axial inclination with respect to the ecliptic plane. Also, generally the MCs that are all S or almost all S will be most geoeffective, although not in all cases, as discussed below. To some extent, these four categories suffer from poor statistics, but we can probably obtain an approximate picture when the categories in the three phases are compared for a given type(s), and we help by combining categories 3 and 4 for N and categories 13 and 14 for S, in our discussion. We again examine Figures 2a through 2c and start with "N" extreme types. There are 9, 8, and 5 N-extreme types for the three phases, in the order of Figures 2a, 2b, and 2c, showing a tendency to decrease. Also there are 5, 3, and 4 S-extreme types for the three phases, for the same order, showing no obvious tendency. When the full solar cycle is considered (Figure 3), we see that N-extreme types occurred 22% of the time and S-extreme types occurred 12% of the time. Hence for about 22% of the MCs in this cycle it is likely that a geomagnetic storm will occur only if a southern B_Z in a sheath region upstream of the MC is the cause, not the MC itself. Usually such storms have been observed to be less intense than average storms induced by MCs.

4. Summary and Discussion

[11] We see that the strictly S-to-N events were very prevalent early in cycle 23 (i.e., 33% for the first phase) and clearly tended to decrease in number as the cycle proceeded. The strictly N-to-S cases had very low frequency of occurrence early in the cycle (i.e., 8% for the first phase) but tended to increase in number (22%) toward the end of the cycle, equal to the number of S-to-N events in that phase. In fact, when we combine all S-to-N types for the full 11.3-year interval, they clearly dominate over all N-to-S types for the full interval by 1.4-to-1. These trends are in qualitative agreement with the findings of *Mulligan et al.* [1998] for the earlier period 1979 to 1988, where they show

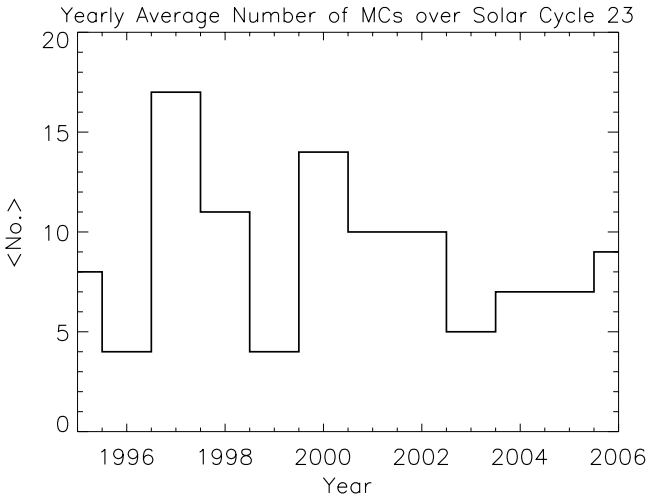


Figure 4. The yearly average number of MCs as observed by Wind over solar cycle 23.

yearly changes of S-to-N and N-to-S types over that period. The extreme cases, when split into the S-types and N-types separately, were not very frequent during any of the three phases of the cycle. For example, in considering the full 11.3 years of the solar cycle, there were 12% and 22%, for extreme S-types and N-types, respectively. However, 12% of all S or "almost all S" is expected to be very geoeffective, all other factors being equal (these factors being strength of $\langle B \rangle$ across the MC, its duration, and its speed), because of the usually strong, long-lasting, value of $|B_Z|$ for such cases. (This is especially true because the axial fields, which are mainly the B_Z (GSE) components for the extreme types, are generally stronger than the tangential fields in ideal MCs/flux ropes, although commonly occurring front-side compression can alter this in actuality.) In fact, only a small percentage of all "extreme" cases are not expected to be geoeffective. These will be most of the all Ns and "almost all Ns," but both types of even these MCs may have southward fields in their upstream sheath regions, behind an upstream shock, which is expected to occur about half of the time for MCs generally [e.g., see *Lepping et al.*, 2002]. By its nature a MC has strong fields almost everywhere, and therefore in the southward portion $|B_Z|$ is likely to have a strong field; this is aside from the axial versus tangential field strength issue, mentioned above. The probability of where the southward magnetic field region will be specifically changes over the solar cycle, as we have seen in Figures 2a, 2b, and 2c, and it changes from cycle to cycle, as pointed out by *Bothmer and Rust* [1997].

[12] According to *Bothmer and Rust* [1997], we should expect N-to-S types (and similar cases) to become predominant, starting over the years 2007–2009. Hence for those years, and likely for long afterward, a histogram like that in Figure 2a should show categories 1 (black) and 11 (dark green) more-or-less reversed as far as frequency of occurrence is concerned, and similarly for categories 2 and 12 and for 5 and 15. For magnetic storm forecasting, for the N-to-S types, schemes may be developed whereby the latter half of the MC (which would be of southward B_Z) may be predicted from knowledge of the first half of the MC. For maximum effectiveness of such schemes, this requires that the N-to-S types to be most prevalent, and that has not been the case over the interval studied here, solar cycle 23. However, if *Bothmer and Rust* [1997] are correct, such types will be most prevalent starting around 2006, 2007, and, indeed, we see some evidence that there is such a (slow) transition to the N-to-S types already over many years of cycle 23.

[13] This study depended on obtaining a rather large sample N = 100 MCs and to some degree on subjectivity (visual inspection), applied judiciously, in estimating into what category-type to place each MC. Most of the categories allowed easy judgments, especially S-to-N, N-to-S, clearly all S, and clearly all N, and some were not, such as the "extreme types." Other researchers may have done the separation somewhat differently, but the overall results would not likely to have been altered very much from ours, since these "extreme types" do not constitute a large percentage of the overall set.

[14] Concerning the "extreme" cases, *Huttunen et al.* [2005] included all cases where $|\theta_C|$ was greater than 45° inclination (where the angle $|\theta_C|$ is the MC's axis measured with respect to the ecliptic plane) to be in the category of "unipolar." This means that they reveal only one polarity for B_Z(GSE) within the MC, or almost only one. However, we find that only the most severe of these cases are truly unipolar. Many cases with $|\theta_C| > 45°$ show both positive and negative B_Z, and therefore many of these are capable of some geomagnetic activity. See, for example, the top and bottom sketches of Figure 1 where a rather severely tilted MC may have some portion that is southward.

[15] Finally, we point out that the Wind data set suffers some "observation gaps" for such studies, due to periods when the spacecraft was behind the Earth's bow shock where the measurements (although taken at the time) are generally not proper for MC studies nor usually for any solar wind studies. Most of these "gaps" are short and not very disruptive to our study. However, there is one relatively large gap, from 13 October 2003 to about 1 March 2004, i.e., of about 4.5 months, when Wind was not in the solar wind. In Figure 4, which is an updated histogram of part of Figure 1 of *Wu et al.* [2006], we show the rate of occurrence of MCs over the solar cycle in terms of the yearly average number. Notice that there is a dip around the year 2003 which is partly due to this "observational gap." However, we did include a MC, the 20 November 2003 case, within this period because it was in the distant magnetosheath of the magnetotail where the medium was more solar wind-like than sheath-like due to its great distance from Earth (i.e., at about $X_{GSE} = -210\ R_E$) and from the bow shock. We also point out the very marked dip in year 1999, which was earlier pointed out by *Wu et al.* [2003], *Gopalswamy et al.* [2003], and *Bothmer* [2004], which is clearly an anomaly. *Bothmer* [2004, Figure 2] and *Bothmer and Zhukov* [2007] show and discuss a depression of CMEs (apparently meaning ICMEs) in 1999 in terms of an increase in the number of fast solar wind flows and CIRs/Coronal Holes. *Wu et al.* [2006, Figure 1] show that actual CMEs do not have a decrease in 1999, and in fact, are rising in number from 1996 through 2002. *Gopalswamy et al.* [2003] explains this paucity of ICMEs/MCs at and around

1999 in terms of an evolution of CME solar sources to higher latitudes on the Sun at this time making it less likely that the associated ejecta will reach Earth. Generally, we expect that low-latitude CMEs to have a direct correlation with the number of ICMEs/MCs at 1 AU.

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[17] Wolfgang Baumjohann thanks the reviewers for their assistance in evaluating this paper.

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R. P. Lepping and C.-C. Wu, Space Weather Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (ronald.p.lepping@nasa.gov)