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RELATIONSHIPS AMONG MAGNETIC CLOUDS, CMES, AND GEOMAGNETIC STORMS

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Abstract. During solar cycle 23, 82 interplanetary magnetic clouds (MCs) were identified by the Magnetic Field Investigation (MFI) team using *Wind* (1995 – 2003) solar wind plasma and magnetic field data from solar minimum through the maximum of cycle 23. The average occurrence rate is 9.5 MCs per year for the overall period. It is found that some of the anomalies in the frequency of occurrence were during the early part of solar cycle 23: (i) only four MCs were observed in 1999, and (ii) an unusually large number of MCs (17 events) were observed in 1997, just after solar minimum. We also discuss the relationship between MCs, coronal mass ejections (CMEs), and geomagnetic storms. During the period 1996 – 2003, almost 8000 CMEs were observed by SOHO-LASCO. The occurrence frequency of MCs appears to be related neither to the occurrence of CMEs as observed by SOHO LASCO nor to the sunspot number. When we included "magnetic cloud-like structures" (MCLs, defined by Lepping, Wu, and Berdichevsky, 2005), we found that the occurrence of the joint set (MCs + MCLs) is correlated with both sunspot number and the occurrence rate of CMEs. The average duration of the MCL structures is ~40% shorter than that of the MCs. The MCs are typically more geoeffective than the MCLs, because the average southward field component is generally stronger and longer lasting in MCs than in MCLs. In addition, most severe storms caused by MCs/MCLs with $Dst_{\min} \leq -100$ nT occurred in the active solar period.

1. Introduction

A magnetic cloud (MC) is defined as a region of high magnetic-field strength, low proton temperature, low proton β, and smoothly-changing (rotating) magnetic field (Burlaga *et al.*, 1981). The plasma β is very low in MCs and, hence, they are magnetic-field dominated. By using 1995 – 1998 *Wind* data, Wu and Lepping (2002) found that ~90% (30 in 34) of MCs generated geomagnetic storms with $Dst_{\min} \leq -30$ nT ($Dst_{\min}$: the minimum Dst within a geomagnetic storm). Wu, Lepping, and Gopalswamy (2003) reported that (1) the occurrence frequency of magnetic clouds was related neither to the occurrence of solar coronal mass ejections (CMEs) as observed by SOHO nor to the solar activity cycle, (2) the intensity of geomagnetic storms related to magnetic clouds is correlated with both solar activity and the occurrence frequency of CMEs, and (3) ∼91% of magnetic clouds induced geomagnetic storms with $Dst_{\min} \leq -30$ nT. A growing number of solar and solar wind physicists believe that many, if not all, magnetic clouds (Burlaga, Lepping, and Jones, 1990) are directly associated with (or are part of) ICMEs (interplanetary CMEs) (*e.g.*, Marubashi, 1986; Gosling, 1990; Bothmer and Schwenn, 1996; Cane, Richardson, and Wibberenz, 1997; Gopalswamy *et al.*, 1998; Mulligan, Russell, and Gosling, 1999). It is now believed that MCs are an important subset of ICMEs or are contained within them. However, our previous study shows that the MC and CME rates are poorly correlated (Wu, Lepping, and Gopalswamy, 2003). Therefore, this motivates us to re-investigate the relationship between MCs and CMEs. We also study the relationship between the periods of time when MCs occur and the related *Dst*s on a yearly-average basis.

2. Data Analysis

Three data sets are used in this study: (1) magnetic clouds that are listed on the *Wind*-MFI (MFI: magnetic field investigation) Web-site from January 1995 to August 2003 (*http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html*) that satisfy the classic definition of a magnetic cloud (Burlaga *et al.*, 1981), (2) coronal mass ejections (CMEs) that are listed on the SOHO LASCO Website (*http://cdaw.gsfc.nasa.gov/CME_list*), and (3) magnetic cloud-like structures (MCLs) that are listed in (*http://lepmfi.gsfc.nasa.gov/mfi/MCL1.html.*) An MCL event is one which is identified by an automatic scheme (Lepping, Wu, and Berdichevsky, 2005), using the same criteria as for an MC, but it cannot be shown to be a flux rope by using the MC-fitting model developed by Lepping, Jones, and Burlaga (1990).

The Lepping, Wu, and Berdichevsky (2005) scheme, which automatically identifies both MCs and MC-like (MCLs) events, found 122 MCLs from solar minimum through the maximum of solar cycle 23. In developing the automatic scheme, Lepping, Wu, and Berdichevsky required that an MC/MCL must have proton plasma β less than 0.3; the average of the magnetic-field magnitude at least 7 nT; χ^2 of θ_{B} less than 500 continuously for eight hours; and the duration at least eight hours. Under these specific criteria, (*i.e.*, through use of these limits), this automatic MC identification scheme successfully found ∼90% of the MFI team's previously identified MCs, as well as two new ones (that satisfied MC parameter-fitting by the Lepping, Jones, and Burlaga (1990) model) while attempting to minimize "false positive events"(Lepping, Wu, and Berdichesky, 2005). (Essentially, the false positive events are the MCLs.) Both of these new MCs are now included in the list of

TABLE I

The occurrence frequency of magnetic clouds (MCs)/magnetic cloud-like structures (MCLs), and coronal mass ejections (CMEs) during 1995 – 2003.

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total
MC	8	4	17	11	4	14	10	10	4[a]	82
MCL	6	1	6	16	16	24	21	21	11[b]	122
MC + MCL	14	5	23	27	20	38	31	31	15	204
CME[c]	[d]	204	351	929[e]	1044[f]	1580	1466	1652	1080	8360
Sunspot no.[g]	17.5	8.6	21.5	64.3	93.3	119.6	111	104	65.9	

[a] There were four MCs for the period of January – August 2003.

[b] The number of MCLs observed for the period of January to mid-October 2003.

[c] The proportionally adjusted CME number.

[d] There were no data for 1995.

[e] There were no data for July, August, and September 1998.

[f] There were no data for January 1999.

[g] The yearly-averaged sunspot number.

MFI MCs. Hence, the newly developed MC identification scheme can identify real MCs that were not initially found by visual inspection.

Table I summarizes MFI MCs, MCLs, CMEs, and sunspot number from solar minimum through the maximum of solar cycle 23 (during the period of 1995 – 2003.) Eighty-two MCs are listed in Table I. There might be some other MCs in the interval of interest that have not yet been identified. However, we believe that it is unlikely that many are missing, if we require that each MC must have a duration of five or more hours. The average occurrence rate is $\sim$9.5 magnetic clouds per year for the overall period (*i.e.*, 82 events/8.6 years). There were 122 MCLs that were observed and the average occurrence rate is $\sim$13.9 MCLs per year for the the overall period (*i.e.*, 122 events/8.8 years). We refer to the total of the MCs and MCLs as the "joint set" (MCs + MCLs), for which there were 204 cases. It is easy to understand why only four MCs were observed in 1996, since this was solar minimum. However, it is difficult to understand why only four MCs were observed in 1999 which is in the rising phase of the solar cycle. The automatic detection procedure identified many more events in 1998 (27 *versus* 11) and 1999 (20 *versus* 4) than found by visual inspection.

The bottom panel of Figure 1 shows the averages of yearly MCs, MCLs, joint set, and sunspot number (SN); and the correlation coefficient (c.c.) between MCs, MCLs, joint set, and SN. The yearly number of MFI MCs has a poor c.c. with sunspot number; the c.c. is 0.12. However, the correlation is good between yearly-averaged sunspot number and the yearly joint events (the c.c. is 0.81); and the correlation is very good between yearly averaged sunspot number and the yearly MCLs (the c.c. is 0.97). In addition, the c.c. is 0.11 between CMEs and MCs, 0.78 between CMEs and the joint set, and 0.97 between MCLs and CMEs. The top

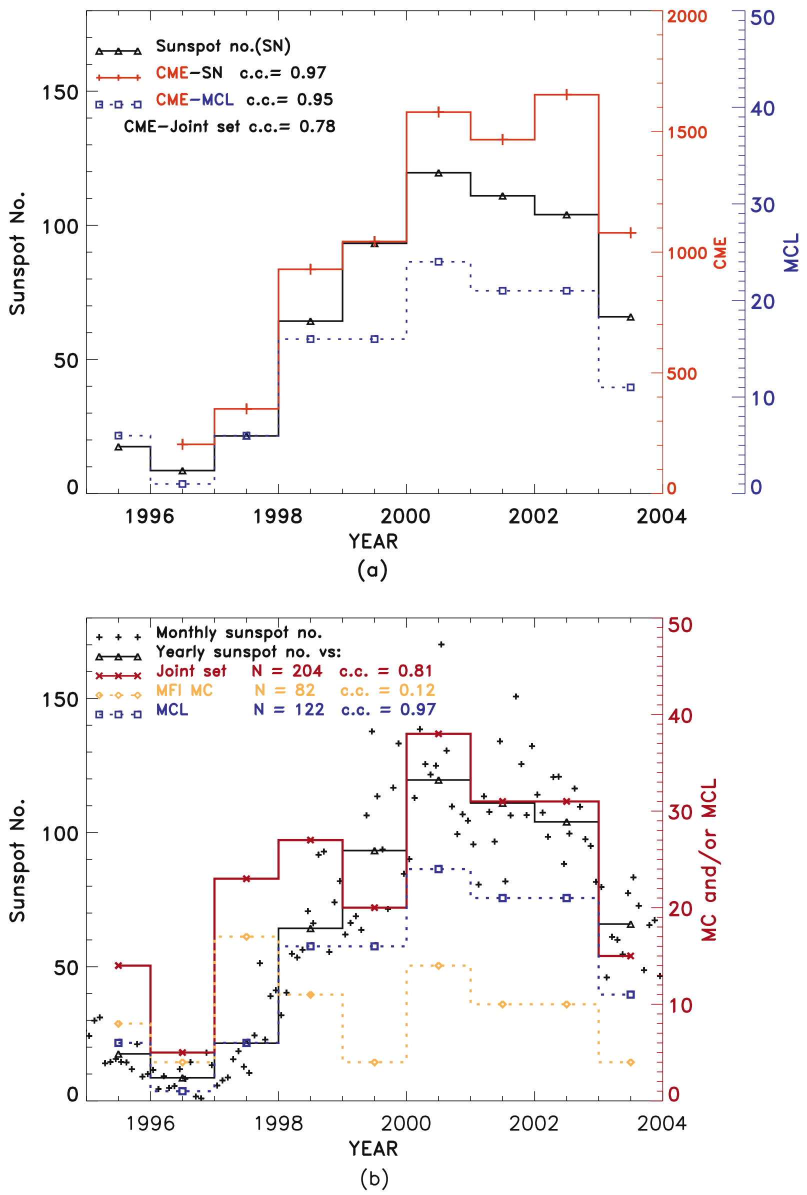

Figure 1. Histogram of MCs, MCLs, CMEs, and sunspot number during 1995 – 2003. Joint set refers to the combined (MCs + MCLs) set.

panel of Figure 1 shows the monthly sunspot number and yearly occurrence rate of CMEs. The correlation coefficient (c.c.) is 0.97 between yearly-average sunspot number and yearly-occurrence rate of CMEs. The correlation coefficient is 0.95 between the yearly-occurrence rate of CMEs and yearly number of MCLs.

Figure 2 shows histograms of the durations of MCs/MCLs during 1995 – 2003. It is clear that the average duration, $\langle \Delta T \rangle$ ($\Delta T = t_2 - t_1$ where t_2 and t_1 are start and end times of a MC/MCL), of MCs ($\langle \Delta T \rangle = 21.1$ hours) is much longer than that of MCLs ($\langle \Delta T \rangle = 15.0$ hours). The average duration of the joint set is 17.5 hours. And more important is the fact that there is a significant difference between the general form of the distributions of the durations of MCs and MCLs, as Figure 2 shows. As we see in the figure, the distribution of MCs is approximately a broad Gaussian with an average of 21.1 hours and a σ of 10.6 hours, whereas that for the MCLs is highly skewed (to the right) with a probable value at $\approx$10 hours, an average of 15.0 hours, and a σ of 6.9 hours. The only common feature is that they cover more-or-less the same domain, which is partly a selection effect.

Figure 3 shows a histogram of $Dst_{\min}$ related to MCs/MCLs during 1995 – 2003 indicating that the yearly-averaged geomagnetic activity caused by MCs is more severe than that caused by MCLs. The averaged storm intensity, $\langle Dst_{\min} \rangle$, for the MCs, MCLs, and joint set are −89, −37, and −58 nT, respectively. Table II shows the occurrence frequency of geomagnetic storms with $Dst_{\min} \leq -30$ nT which are caused by MCs or MCLs during 1995 – 2003. It is clear that most MCs (89%, 73 out of 82 events) caused a geomagnetic storm, but only about a half of the MCLs (53%, 65 out of 122 events) induced a geomagnetic storm. Table II also shows the occurrence frequency of severe geomagnetic storms with $Dst_{\min} \leq -100$ nT

TABLE II

The occurrence frequency of MC/MCL that caused a geomagnetic storm with $Dst_{\min} \leq -30$ nT and $Dst_{\min} \leq -100$ nT during 1995 – 2003.

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total
MC										
$Dst \leq -30$ nT	$5^{a}/8^{b}$	2/4	17/17	8/11	4/4	12/14	10/10	9/10	4/4	71/82
	63%	50%	$100\%^{c}$	73%	100%	86%	100%	90%	100%	87%
$Dst \leq -100$ nT	$1^{d}/8^{b}$	0/4	5/17	3/11	2/4	9/14	5/10	5/10	2/4	32/82
	13%	0%	29%	27%	50%	64%	50%	50%	50%	39%
MCL										
$Dst \leq -30$ nT	4/6	1/1	6/6	10/16	4/16	14/24	9/21	8/21	7/11	60/122
	67%	$100\%^{c}$	100%	63%	25%	58%	43%	38%	72%	49%
$Dst \leq -100$ nT	0/6	$0^{d}/1^{b}$	0/6	5/16	1/16	1/24	2/21	1/21	0/11	10/122
	0%	0%	0%	31%	6%	4%	10%	5%	0%	8%

[a] The occurrence frequency of the events (MCs or MCLs) which induced a geomagnetic storm, meaning $Dst_{\min} \leq -30$ nT.

[b] The occurrence frequency of the events (MCs or MCLs).

[c] All the events (MCs or MCLs) produced storms.

[d] The occurrence frequency of the events (MCs or MCLs) which induced a severe geomagnetic storm, meaning $Dst_{\min} \leq -100$ nT.

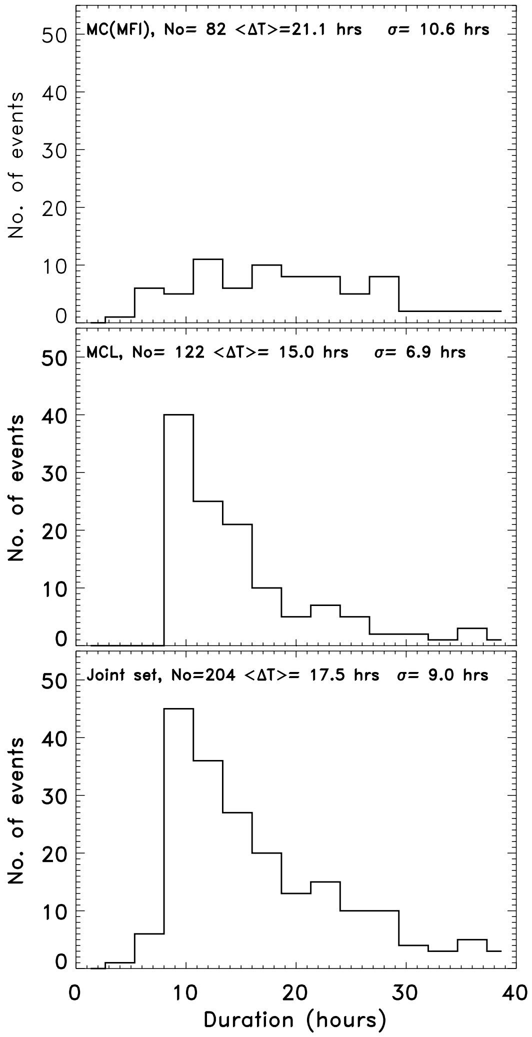

Figure 2. Histogram of duration of MCs/MCLs during 1995 – 2003. Joint set refers to the combined (MCs + MCLs) set.

which are caused by MCs or MCLs during 1995 – 2003. It is clear that less than half of the MCs (39%, 32 out of 82 events) caused severe geomagnetic storms, and less than 10% of the MCLs (8%, 10 out of 122 events) induced severe geomagnetic storms. In addition, Table II shows that MCs occurring in the solar active period generated more geomagnetic storms (particularly for the severe storms with $Dst_{\text{min}} \leq -100$ nT), but MCLs show markedly different results. It is interesting to point out that no severe storms (with $Dst_{\text{min}} \leq -100$ nT) were caused by MCs/MCLs in 1996. Furthermore, no MCLs induced a severe storm during 1995 – 1997.

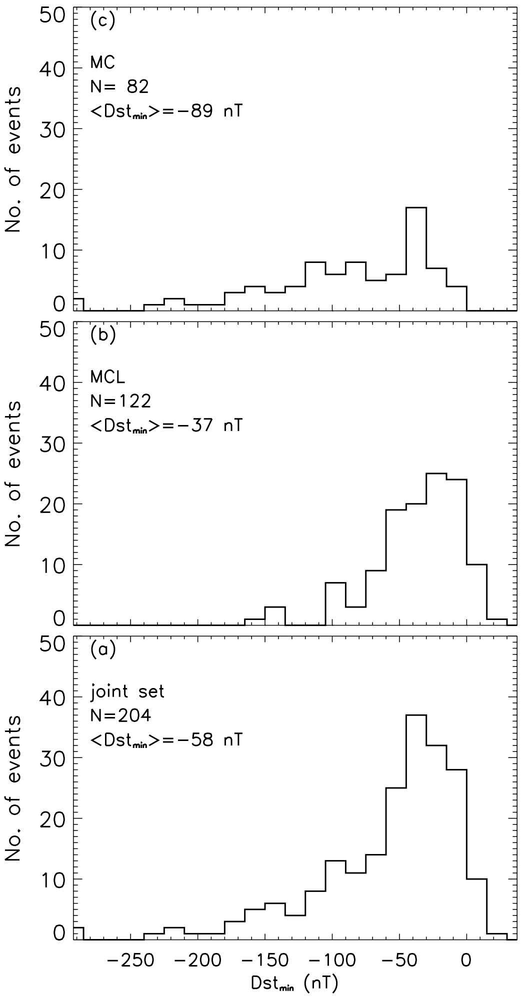

Figure 3. Histogram of storm intensity, $Dst_{\rm min}$ related to MCs/MCLs during 1995–2003. Joint set refers to the combined (MCs + MCLs) set.

Table III summarizes the yearly averages of duration (ΔT), $Bz_{\rm min}$, velocity (V) and $Dst_{\rm min}$ for MCs/MCLs. It shows the following results: (1) stronger MC storms follow solar maximum, but MCLs do not show such a trend; (2) average duration of MCs is longer than that for MCLs; (3) average $Bz_{\rm min}$ is more intense within MCs than within MCLs; (4) average $Dst_{\rm min}$ is more intense when the storm results from MCs than from MCLs; and (5) average V is faster within MCs than within MCLs. The correlation coefficient for sunspot number *versus* yearly-averaged intensity of geomagnetic storms due to magnetic clouds and MCLs are 0.83 and 0.62, respectively. It is interesting to point out that the average V within MCs increases when the sunspot number increases.

TABLE III

The magnitude of yearly averages of $Bz_{\rm min}$, $Dst_{\rm min}$, velocity, and duration (ΔT) for MCs/MCLs.

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	Average
$\langle Dst_{\rm min} \rangle$ (nT)										
MC[a]	−56	−27	−75	−74	−83	−133	−111	−91	−111	−89
MCL[b]	−43	−41[c]	−58	−57	−27	−35	−32	−32	−37	−37
MC + MCL[d]	−50	−30	−71	−64	−38	−71	−57	−51	−57	−58
$\langle \Delta T \rangle$ (h)										
MC	18.4	28.0	20.6	25.1	20.1	18.8	24.1	20.4	13.7	21.1
MCL	12.4	14.6	17.8	14.8	13.2	14.0	16.6	16.5	14.5	15.0
MC + MCL	15.9	25.3	20.1	18.9	14.5	15.8	19.1	17.8	14.2	17.5
$\langle Bz_{\rm min} \rangle$ (nT)										
MC	−7.9	−8.2	−10.1	−10.1	−8.3	−12.9	−8.9	−10.5	−14.1	−10.3
MCL	−5.9	−6.4	−7.2	−7.6	−5.4	−6.9	−4.2	−5.7	−6.0	−6.0
MC + MCL	−7.0	−7.8	−9.3	−8.6	−6.0	−9.1	−5.7	−7.3	−8.1	−7.7
$\langle V \rangle$ (km/s)										
MC	372	354	418	421	442	504	501	469	401	447
MCL	373	405	361	399	417	407	423	410	477	412
MC + MCL	373	364	403	408	422	442	448	429	483	419

[a] For MCs identified manually by the *Wind* MFI team (Lepping *et al.*, 2006).

[b] MCLs identified by an automatic MCs identification scheme (Lepping, Wu, and Berdichevsky, 2005).

[c] Only one MCL in 1996.

[d] Joint set, (MCs + MCLs) identified by automatic MCs identification scheme.

Figure 4 shows a histogram of $Bz_{\rm min}$ (the minimum Bz found within the MC/MCL) for each event. The averaged $Bz_{\rm min}$ for the MCLs, joint set, and MCs are −6, −7.7, and −10.2 nT, respectively. The magnitude of $Bz_{\rm min}$ for the MCs is much larger than the magnitude of $Bz_{\rm min}$ for both the joint set and the MCLs.

3. Discussion

Using both *Wind* and ACE data, Cane and Richardson (2003) reported 214 ICMEs (interplanetary CMEs) for the period 1996 – 2002. We compared our MC and MCL data with the ICME list made by Cane and Richardson (2003) (CR ICME list), and we found that 54 out of 70 ($82-8-4=70$) MCs and 44 out of 105 ($122-6-11=105$) MCLs were listed in the CR ICME list. We have checked both *Wind* and ACE data for the 105 ICMEs which are neither a MC nor a MCL. Some of these 105 events have durations that are shorter than eight hours or possess relatively high

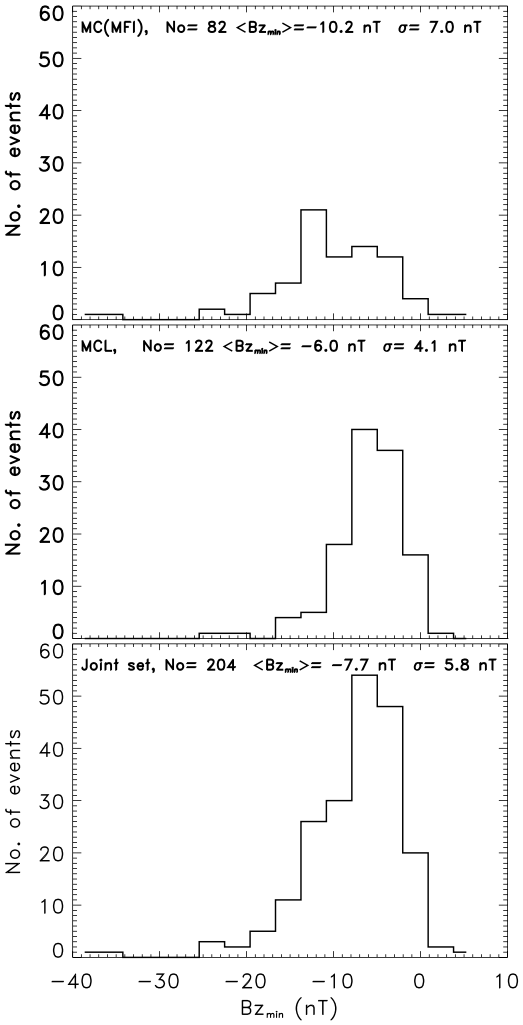

Figure 4. Histogram of average Bz of MCs/MCLs during 1995 – 2003. Joint set refers to the combined (MCs + MCLs) set.

plasma βs or have sharp angle changes in magnetic field within them, contrary to criteria that we use for MCs. It is interesting to note that all of the four CR's ICMEs found in 1998 are MCs, and we also found an additional MCL in 1998.

Huttunen *et al.* (2005) found a few MC's at ACE that passed Earth during *Wind* data gaps or at times when *Wind* was not in the solar wind. (Huttunen *et al.* (2005) required that a MC must have the average values of plasma β less than 0.5, the maximum value of the magnetic field at least eight nT and the duration at least six hours.) Thus, it does seem likely that some MCs were missed. We have compared the list of Huttenen *et al.,* and our data set. In the list of Huttunen *et al.* (2005), 59 out of 80 MCs are listed in the MFI web-site (*http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html*) and 4 out of 80 MCs are listed in the MCL MFI web-site (*http://lepmfi.gsfc.nasa.gov/mfi/MCL1.html*). The unlisted 17 events ($80 - 59 - 4 = 17$) are either too short (MC's duration is less than eight hours) or the χ^2 of θ_B is too high ($\chi^2 \geq 500$), or the definition of a MC or an MCL structure (Lepping, Wu, and Berdichevsky, 2005) was not satisfied. (This is because the criteria for finding MCs used by Huttunen *et al.* (2005) are looser than those used by Lepping, Wu, and Berdichevsky (2005). There are 12 MFI MCs not on the list of Huttunen *et al.* (2005). This report has included most MCs and MCLs during 1995 – 2003.

Our earlier study (Wu, Lepping, and Gopalswamy, 2003) showed that the occurrence frequency of MCs appeared to be related neither to the occurrence of CMEs as observed by SOHO LASCO nor to the sunspot number. In 1999, the heliosphere-current-sheet tilt angle was unusually large, and prominence eruptions occurred at very high latitudes. Therefore, CMEs associated with such prominences are less likely to arrive at Earth than those from lower latitudes (Gopalswamy, 2003). Wu, Lepping, and Gopalswamy (2003) suggested that those features might explain the anomalies of the occurrence frequency of MCs for the years 1997 and 1999. However, in this study the automatic detection procedure identified many more transient events in 1998 (27 *versus* 11) and 1999 (20 *versus* 4) than found by visual inspection. In addition, the correlation coefficient increases from 0.12 for the CMEs *versus* MCs relationship to 0.78 for the CMEs *versus* the joint set (MCs + MCLs). This implies that there is a strong relationship between CMEs and the joint set, MCs + MCLs. In addition, the correlation coefficient even increases to 0.95 between CMEs and MCLs. This suggests that CMEs did reach the Earth throughout the ascending phase of the cycle and that our previous suggestion (Wu, Lepping, and Gopalswamy, 2003), as mentioned above, might not be correct. This requires further detailed investigation on the one-to-one relationship between CMEs and MCLs.

Figure 2 shows clearly that the duration of MCLs is typically much shorter than the duration of MCs. The shorter durations for MCLs might be caused by the solar source locations at higher latitudes of the associated prominence eruptions for these events. (This requires further investigation by carrying out a one-to-one comparison with MCLs and solar sources.) The center of a MCL associated with such a prominence is less likely to arrive at Earth than one from a low-latitude prominence. Figure 4 also supports this suggestion indirectly by showing that $\langle Bz_\mathrm{min} \rangle$ (the minimum Bz within an MC or MCL) is generally less intense within MCLs than within MCs. Since the magnitude of southward Bz is typically more intense within MCs than within MCLs, the averaged Dst_min of MCs is more intense than the averaged Dst_min of MCLs. This is consistant with the fact that the generally lower $|\mathbf{B}|$ in a typical MCL means lower $|Bz|$. Also the shorter Bz-south intervals in MCLs generally contribute to their being less geoeffective. And it is found that $\langle V \rangle$ for the MCLs is somewhat slower than for MCs; see Table III. Together these three features support the notion that MCs are generally more geoeffective, but there are some exceptions.

Using seven years of data (1995 – 2001), Wu, Lepping, and Gopalswamy (2003) reported that the yearly-averaged intensity of geomagnetic storms related to magnetic clouds is correlated with both solar activity and the occurrence frequency of CMEs. The results of this study shows a similar trend. The correlation coefficient for the yearly averaged intensity of geomagnetic storms (related to magnetic clouds) is 0.83. This reconfirms the results of Wu, Lepping, and Gopalswamy (2003).

4. Conclusion

The main results of this study are that: (1) the average occurrence rate for MCs per year is ~9.5 for the period 1995 – August 2003 (8.6 years), (2) the occurrence rate of visually-determined MCs is not related to either solar activity or to the occurrence frequency of CMEs, but (3) the MCLs and joint set (MCs + MCLs) are related to both solar activity and the CME occurrence rate, (4) the duration of a MC is typically longer than that of a MCL, (5) the average geomagnetic storm intensity for the MCs is stronger than that for the MCLs, (6) stronger MC storms follow solar maximum, but MCLs do not show such a trend, (7) average $Bz_{\min}$ is more intense within MCs than within MCLs, (8) average-solar-wind speed is faster within MCs than within MCLs, and (9) most severe storms caused by MCs/MCLs with $Dst_{\min} \leq -100$ nT occurred in the solar active period.

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