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Statistical Comparison of Magnetic Clouds with Interplanetary Coronal Mass Ejections for Solar Cycle 23

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Abstract We compare the number and characteristics of interplanetary coronal mass ejections (ICMEs) to those of magnetic clouds (MCs) by using *in-situ* solar wind plasma and magnetic field observations made at 1 AU during solar cycle 23. We found that $\approx 28\%$ of ICMEs appear to contain MCs, since 103 magnetic clouds (MCs) occurred during 1995 – 2006, and 307 ICMEs occurred during 1996 – 2006. For the period between 1996 and 2006, 85 MCs are identified as part of ICMEs, and six MCs are not associated with ICMEs, which conflicts with the idea that MCs are usually a subset of ICMEs. It was also found that solar wind conditions inside MCs and ICMEs are usually similar, but the linear correlation between geomagnetic storm intensity (Dst_{min}) and relevant solar wind parameters is better for MCs than for ICMEs. The differences between average event duration (Δt) and average proton plasma β ($\langle\beta\rangle$) are two of the major differences between MCs and ICMEs: *i*) the average duration of ICMEs (29.6 h) is 44% longer than for MCs (20.6 hours), and *ii*) the average of $\langle\beta\rangle$ is 0.01 for MCs and 0.24 for ICMEs. The difference between the definition of a MC and that for an ICME is one of the major reasons for these average characteristics being different (*i.e.*, listed above as items *i*) and *ii*)), and it is the reason for the frequency of their occurrences being different.

Keywords Geomagnetic storm · Interplanetary coronal mass ejection · Magnetic cloud · Solar cycle

1. Introduction

Interplanetary magnetic clouds (MCs) and interplanetary coronal mass ejections (ICMEs) are very large-scale structures in the solar wind. For example, at 1 AU MCs are about $\frac{1}{4}$AU in

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diameter (see, *e.g.*, Lepping *et al.*, 2006) and usually are among the most important causes of strong geomagnetic storms (see, *e.g.*, Burlaga *et al.*, 1981; Zhang and Burlaga, 1998). For these reasons alone, understanding their properties is important. But MCs and ICMEs invoke interest for two other reasons as well: *i*) for their own sake as (large) structures that interact with the surrounding solar wind and *ii*) for what they tell us about their sources on the Sun (see, *e.g.*, Bothmer and Schwenn, 1994). Much progress has been made in all of these areas. In this study we attempt to investigate mainly their mutual relationship.

It seems to us that, except under the most unusual circumstances, one should always expect a MC (a large interplanetary flux rope or a close resemblance to one when the rope appears "noisy") to be embedded in (or be part of) an ICME, whether it is readily apparent or not. We say this, because an ICME is an interplanetary manifestation of a CME and such an event is the result of a large explosive event on the Sun of twisted magnetic field lines (usually an erupting prominence) and so also is a MC (see, *e.g.*, Burlaga *et al.*, 1981; Webb *et al.*, 2000). It is generally believed that these structures come from the same types of source. Gosling (1990) suggests that about 30% of CMEs (now these would be interpreted as ICMEs) appear to contain MCs, but Bothmer and Schwenn (1995) found that about 41% of the identified ICMEs were MCs. Investigating observations for the period of 1996 – 2003, Wu, Lepping, and Gopalswamy (2006) suggested that only about 25% of ICMEs appear to contain MCs, which confirmed the earlier finding of Cane and Richardson (2003). Both results, Wu, Lepping, and Gopalswamy (2006) and Cane and Richardson (2003), are close to the finding of Gosling (1990).

Part of the problem in attempting to settle this issue is that the interplanetary presence of some subset of 12 different physical entities have been invoked to identify the existence of an ICME (see, *e.g.*, Gosling and Bame, 1973; Bame *et al.*, 1981; Richardson and Cane, 2008), but rarely are all of them invoked, and sometimes only a few are used for any specific case (see, *e.g.*, Schwenn, 1996; Wimmer-Schweingruber, Crooker, and Balogh, 2006). The 12 potentially applicable quantities are: *i*) enhanced magnetic field intensity, *ii*) smoothly changing field direction, *iii*) relatively low proton temperature (Gosling and Bame, 1973), *iv*) low proton plasma beta, *v*) bidirectional streaming of electrons (Bame *et al.*, 1981), *vi*) bidirectional streaming of low energy protons (Marsden *et al.*, 1987), *vii*) high charge states of ions and compositional signatures, studied, *e.g.*, by examination of $\mathrm{Mg}^{10+}/\mathrm{O}^{6+}$ (see, *e.g.*, Henke *et al.*, 1998, 2001; Wimmer-Schweingruber, Crooker, and Balogh, 2006), *viii*) low charge states (see, *e.g.*, Zwickl *et al.*, 1982; Galvin, 1997; Burlaga *et al.*, 1998; Gopalswamy *et al.*, 1998), *ix*) singly charged He^{+} (Schwenn, Rosenbauer, and Muhlhauser, 1980), *x*) bidirectional particle flows at cosmic ray energies (1 MeV) (see, *e.g.*, Richardson *et al.*, 2000), *xi*) bidirectional solar wind electron heat flux events (BDEs) (see, *e.g.*, Gosling, 1990), and *xii*) including ground based data, the occurrence of a one- or two-step Forbush decreases (Forbush, 1937; Cane and Richardson, 2000; Cane and Lario, 2006). Note that the first four quantities are used for identifying MCs.

Perhaps the most satisfactory quantitative definition of an ICME has been one put forth by Russell, Shinde, and Jian (2005) wherein the net plasma and field pressure perpendicular to the local magnetic field, with consideration of its difference from the ambient value, is used, and even in their definition several classes appear to be possible.

By contrast, a MC is defined almost purely in terms of the interplanetary magnetic field and scalar proton temperature, *i.e.*, requiring only an enhanced $|B|$, depressed T_{P}, and smooth change in field direction over its duration (see Burlaga *et al.*, 1981; Klein and Burlaga, 1982; Burlaga, 1995), it being understood that the structure is large, say from 5 to 36 h (hours) duration (and occasionally, but rarely, even longer) at 1 AU, and that the MC was expanding within 2 AU (see, *e.g.*, Burlaga *et al.*, 1981).

There is usually little ambiguity in the identification of a flux rope/MC, but, admittedly, some cases are questionable, especially when it is apparent that the closest distance of approach of the spacecraft from the MC's axis is a large fraction of the MC's radius; we call this a case of *large* "impact parameter". We suggest that when this happens it should not be surprising that there is little variation in field direction nor even in field intensity during the encounter of the MC (therefore hiding the likelihood that the structure is a flux rope). And the field intensity of a MC at large impact parameter is often not much greater than the ambient interplanetary magnetic field (IMF), especially when the spacecraft is outbound. It is interesting that the parameter that is commonly used in the identification of both ICMEs and MCs is the magnetic field intensity, always used for MCs and often for ICMEs. It should be no surprise that this is so, since it is the magnetic field that through some mechanism causes the release of the related solar event in the first place, with the details often being controversial.

The term solar ejecta (or just ejecta) has sometimes been employed to cover both MCs and ICMEs, as a catch-all term. But that, although helpful in some cases, begs the question about the actual nature of the ejecta. Also it stresses material ejection while it is usually the magnetic field that is predominant in terms of pressure or energy density. It is important to find the true relationship between MCs and ICMEs. We start by studying aspects of the frequency of their occurrence. In fact, the main purpose of this study is to ascertain the statistical differences between the occurrence of MCs and ICMEs, noting overlapping and non-overlapping intervals of each kind, using data from the *Wind* spacecraft which cover the period 1995 to 2006, and then to explain any differences.

Understanding the statistical differences may help understand and may motivate further detailed study of these differences. For example, it was found recently that MC selection effects probably play some role in causing these statistical differences via MC selection identification (Lepping and Wu, 2010).

It is found that the frequency of the occurrence of MCs appears to be related neither to the occurrence of solar coronal mass ejections (CMEs) as observed by the *Solar and Heliospheric Observatory* (SOHO) spacecraft nor to the solar activity cycle; this became clear by studying data for events that occurred during 1996 – 2001 (Wu, Lepping, and Gopalswamy, 2003). Using longer-period data sets (1996 – 2003), Wu, Lepping, and Gopalswamy (2006) confirmed the finding of Wu, Lepping, and Gopalswamy (2003), but they also found that the occurrence of "MCs plus MCLs" is correlated with both sunspot number and the occurrence rate of CMEs. (MCL is a magnetic cloud-like structure, here one which is identified by an automatic identification scheme (Lepping, Wu, and Berdichevsky, 2005) using the same criteria as for identifying a MC, but which cannot be shown to be a flux rope by using the MC-fitting model developed by Lepping, Jones, and Burlaga (1990) or probably by any other reasonable fitting scheme.) This intriguing result motivated us to investigate the relationship between MCs and ICMEs. The statistical differences between the occurrence MCs and ICMEs are analyzed using data from the *Wind* and ACE spacecraft which cover the period from 1996 to 2006. Any physical differences between MCs and ICMEs will be discussed, and the reasons for some of these differences are explained.

2. Data Analysis

Four data sets are used in this study. The first data set, *Wind* solar wind plasma and magnetic field data, were obtained from the *Wind* SWE and MFI groups for the events after 1995 (Ogilvie *et al.*, 1995; Lepping *et al.*, 1995). The second data set (the geomagnetic activity

Table 1 Occurrence frequency of MCs and ICMEs during 1996 – 2006.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
No. of ICMEs	4	22	36	33	51	49	26	21	21	31	13	307
No. of MCs	4	17	11	4	14	10	10	5	7	7	6	95
Non-MC ICMEs	0	8	25	29	38	40	18	17	15	24	8	222
MCs/ICMEs %	100	77	31	12	27	20	38	24	33	23	46	31
Non-ICME MCs	0	2	0	0	1	0	2	1	0	0	0	6
2 MCs in 1 ICME	0	1	1	0	0	1	0	0	1	0	1	5
2 ICMEs in 1 MC	0	0	1	0	0	0	0	0	0	0	0	1

index, *Dst*) was obtained from the National Geophysical Data Center, Boulder, Colorado, USA (ftp.ngdc.noaa.gov). The third data set, magnetic cloud characteristics, are listed on the *Wind*/MFI (MFI: magnetic field investigation) web-site for January 1995 to November 2007 (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html) and satisfy the classical definition of a magnetic cloud (see, *e.g.*, Burlaga *et al.*, 1981). The fourth set, ICMEs and their related geomagnetic activity, are listed in http://www.ssg.sr.unh.edu/mag/ace/ACElists/ICMEtable.html for 1996 – 2007, which data were compiled by Ian Richardson and Hilary Cane.

Table 1 shows the occurrence frequency of MCs and ICMEs during 1996 – 2006. It is clear that about $\approx 28\%$ of ICMEs appear to contain MCs. In order to compare solar wind characteristics within both MCs and ICMEs, we use data observed only from the *Wind* spacecraft for consistency. There is a solar wind convection time-delay (approximately 1 h) between the ACE and *Wind* spacecraft positions during the period of our interest. In order to reduce any errors arising from this time delay, we use only the central 80% of both the ICMEs and MCs for this study. One-minute averages of solar wind plasma and magnetic field data from *Wind* and hourly averages of *Dst* during these cloud events were compiled into a single data base. Thus, using the *Wind* data set, we have a total of 103 MCs, which cover the period of 1995 – 2006, and 307 interplanetary coronal mass ejections (ICMEs), which cover the period of 1996 – 2006. Out of the 103 MCs, eight occurred in 1995, and six are not listed as ICMEs. In addition, five pairs of MCs are listed as ICMEs, which means that ten MCs are listed as five ICMEs. Also, one MC has crossed over two ICMEs. Therefore, 85 ICMEs appear to contain MCs. This implies that $\approx 28\%$ ($85/307 = 28\%$) of ICMEs have features of MCs. We found that six MCs, which occurred between 1996 and 2006, are not associated with ICMEs. This conflicts with the concept of "MCs being a subset of ICMEs".

Due to data gaps in the *Wind* data, four MCs and nine ICMEs are not included in this study. We will use this *Wind* data set for studying these 99 ($\equiv$ 103-4) MCs and 298 ($\equiv$ 307-9) ICMEs. Figure 1 shows the yearly mean (left panels) and median (right panels) values of MCs (solid black lines) and ICMEs (dashed red lines). Vertical solid black and red lines represent standard deviations for the MCs and ICMEs. In order to have clear view of the standard deviations, there is a shift of 0.5 year for the data for ICMEs with respect to those for the MCs. The top left panel shows the occurrence frequency for both MCs and ICMEs. It shows clearly that more ICMEs than MCs were observed each year, except for the year 1996, which has the same number of cases (four of each) for both MCs and ICMEs. (Note that no ICME in year 1995 is included in this study, because the ICME table is based on observations from ACE and SOHO/LASCO.) Table 2 lists various kinds of relevant solar wind parameter. In Figure 1 and Table 2 we define the following: $\epsilon_{\max}$ is the maximum value of the ϵ (defined by Akasofu, 1981) during a MC/ICME event (where "event" here and below usually means the entire "sheath"/cloud complex), $Dst_{\min}$ represents a minimum

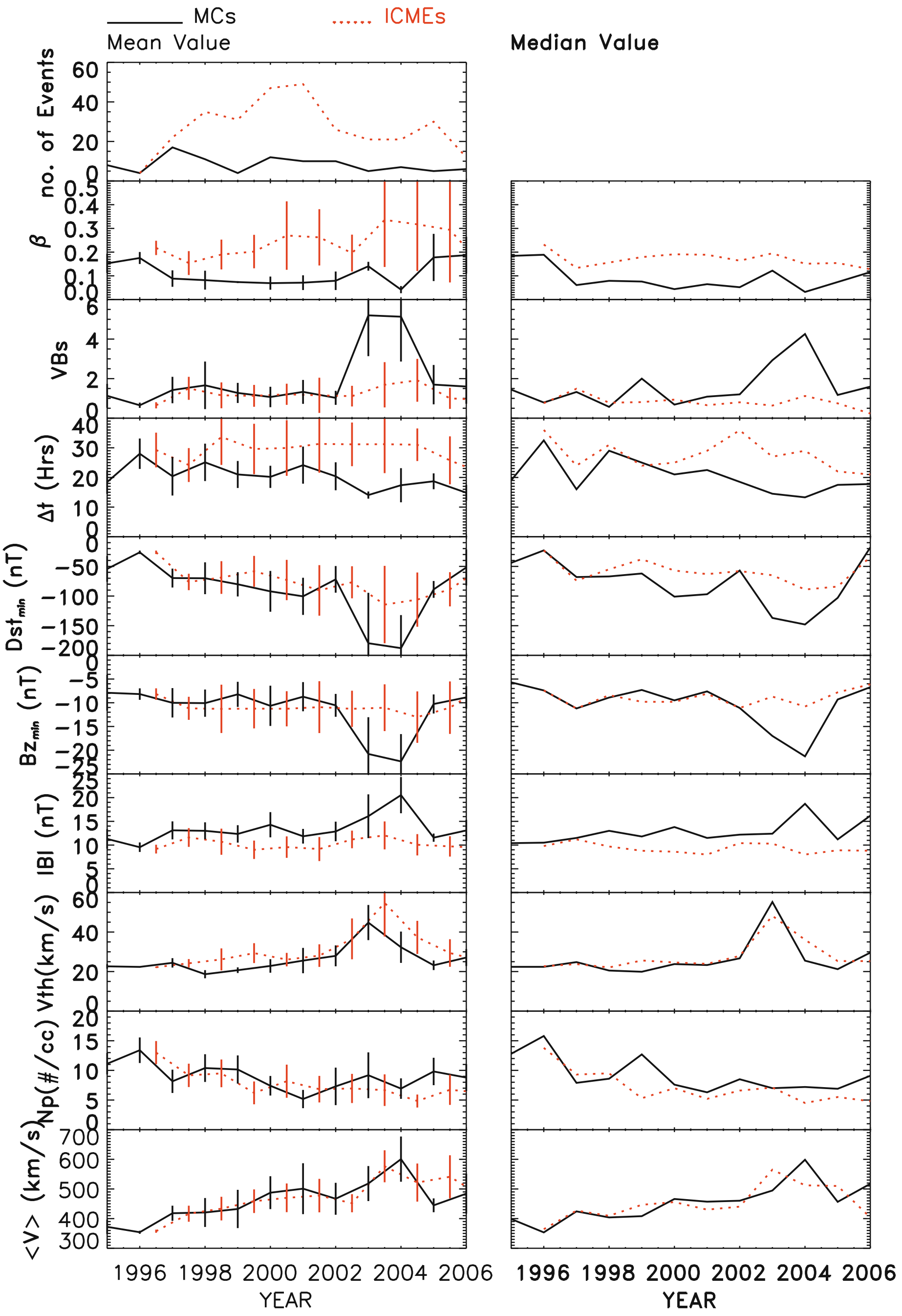

Figure 1 Yearly mean (left panels) and median (right panels) values of MCs (solid black lines) and ICMEs (dashed red lines). Vertical solid black and red lines represent standard deviations for the MCs and ICMEs. For the standard deviations, there is a shift of 0.5 year for the ICMEs data with respect to those for the MCs. The top left panel shows the occurrence frequency for both MCs and ICMEs.

Table 2 Summary of the mean[a] and median[b] of solar wind parameters for both MCs and ICMEs.

	Mean[a]			Median[b]		
	MCs	ICMEs	δ (%)	MCs	ICMEs	δ (%)
$\langle V\rangle$ (km s^{-1})	455.1	477.3	−5	427.0	446.8	−5
$\langle N_\mathrm{p}\rangle$ (cm^{-3})	8.6	7.4	14	8.1	6.6	19
$\langle V_\mathrm{th}\rangle$ (km s^{-1})	25.3	30.6	−21	22.7	25.0	−10
$\langle B\rangle$ (nT)	13.4	10.1	14	11.8	9.3	21
$\langle N_\mathrm{p,max}\rangle$ (cm^{-3})	24.7	24.2	2	20.3	18.7	8
$\langle V_\mathrm{max}\rangle$ (km s^{-1})	518.2	627.9	−21	481.1	528.8	−10
$\langle B_\mathrm{max}\rangle$ (nT)	17.7	20.8	−18	15.3	14.0	9
$\langle B_{z,\mathrm{min}}\rangle$ (nT)	−11.0	−11.1	1	−9.5	−9.3	−2
$\langle Dst_\mathrm{min}\rangle$ (nT)	−86.4	−79.7	8	−69.0	−60.0	13
$\langle \Delta t\rangle$ (h)	20.5	29.6	−44	18.5	26.0	−41
$\langle VB_\mathrm{s,max}\rangle$ (mV m^{-1})	1.743	1.243	29	1.173	0.794	33
$\langle \epsilon_\mathrm{max}\rangle(\times 10^{11}$ W)	8.113	5.190	36	3.953	2.298	42
$\langle \beta\rangle$	0.0972	0.242	−148	0.074	0.165	−123

[a] Mean: mean of the studied events of MCs (99 events) and ICMEs (298 events) from event-averaged solar wind parameters.

[b] Median: median of the studied events of MCs (99 events) and ICMEs (298 events) from event-averaged solar wind parameters.

value of Dst observed during a MC/ICME "event," and $VB_\mathrm{s,max}$ is the maximum value of VB_s observed during a cloud event, where B_s is the southward component of the IMF ($B_\mathrm{s} = |B_z|$ for $B_z < 0$ and $B_\mathrm{s} = 0$ for $B_z \geq 0$); $B_{z,\mathrm{min}}$ is the minimum B_z value observed during a cloud event.

For the mean values of the various parameters, both Figure 1 and Table 2 show the following statistical results.

i) The average ($\langle\beta\rangle$) of the proton plasma β is much smaller in the case of MCs than ICMEs.
ii) ϵ_max, $VB_\mathrm{s,max}$, averages of the total magnitude of the interplanetary magnetic field ($\langle|B|\rangle$), and the average of the solar wind proton density ($\langle N_\mathrm{p}\rangle$) are larger in MCs than in ICMEs.
iii) The maximum value of the solar wind bulk speed (V_max), the maximum value of IMF B ($|B_\mathrm{max}|$), the average of thermal speed ($\langle V_\mathrm{th}\rangle$), and the event duration (Δt) are smaller for MCs than for ICMEs.
iv) The maximum proton density ($N_\mathrm{p,max}$), $B_{z,\mathrm{min}}$, Dst_min, and the average of solar wind speed ($\langle V\rangle$) are similar (the differences, δ, are less than 10%) for both MCs and ICMEs. (Note that the differences are $\delta \equiv \frac{\mathrm{MC_{value}} - \mathrm{ICME_{value}}}{\mathrm{MC_{value}}} \times 100\%$.)

Figure 2 shows relationships between the intensity of geomagnetic storm (Dst_min) and different solar wind parameters (*i.e.*, V, N_p, V_th, B, $B_{z,\mathrm{min}}$, $VB_\mathrm{s,max}$, and ϵ_max). The left panels show the results for MCs and the right panels show the results for ICMEs. Linear correlation coefficients (c.c.s) are listed in the upper left corner of each panel, and the estimated Dst_min and linear fitting formulas are also listed, in the upper right corner. Table 3 summarized the yearly means of solar wind parameters for both MCs and ICMEs. Table 4 lists the c.c.s in detail. It is clear that the c.c.s for Dst_min *vs.* different solar wind parameters are higher for

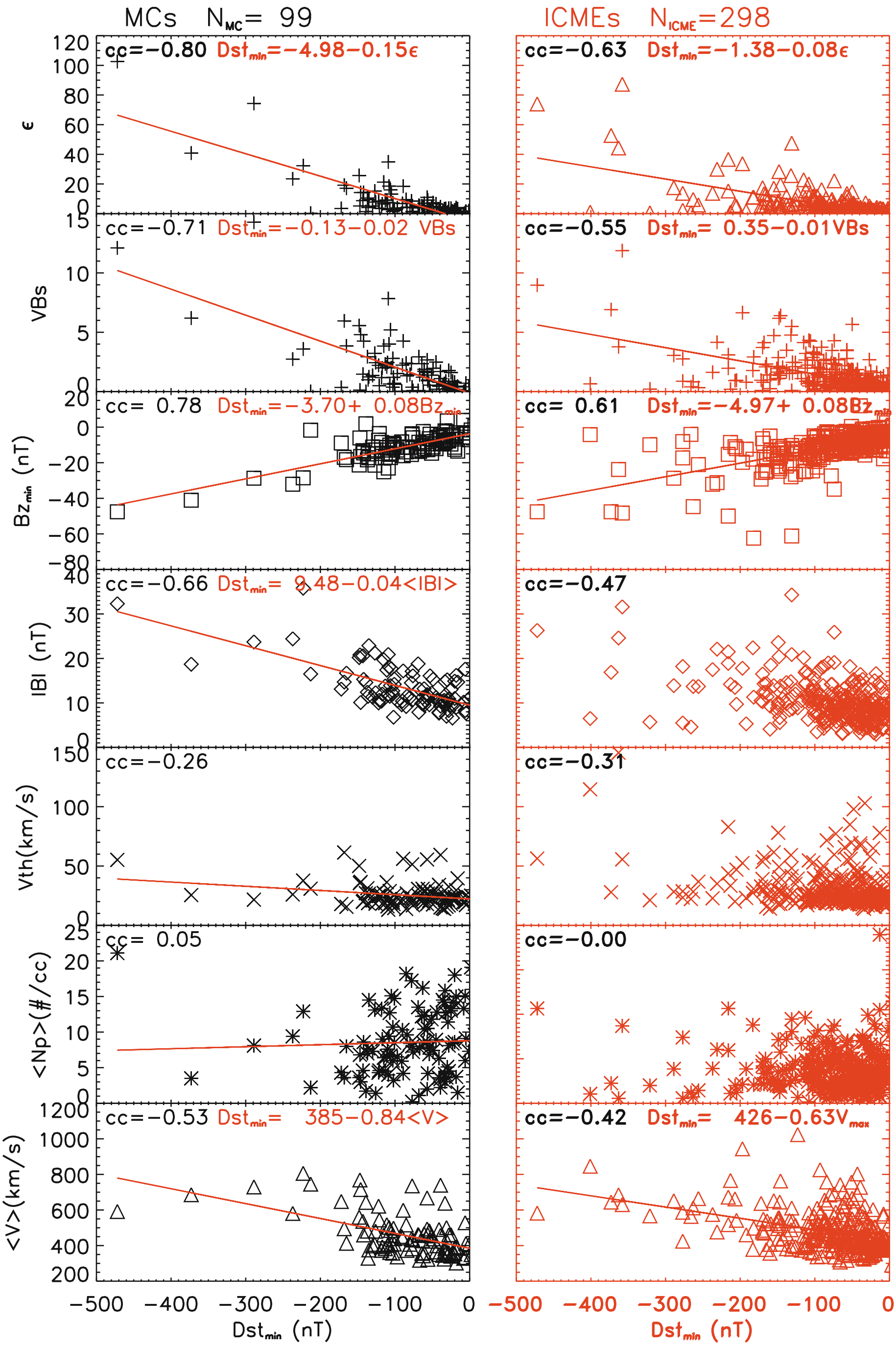

Figure 2 Relationships between the intensity of geomagnetic storm (Dst_{min}) and different solar wind parameters (V, N_p, V_{th}, B, $B_{z,min}$, $VB_{s,max}$, and Akasofu ϵ_{max}). The left panels show the results for MCs and right panels those for ICMEs.

Table 3 Summary the yearly means of solar wind parameters for both MCs and ICMEs.

Year	N_{Event}	$\langle V\rangle$	$\langle N_p\rangle$	$\langle V_{th}\rangle$	$\langle B\rangle$	$B_{z,\min}$	$Dst_{\min}$	Δt	$VB_{s,\max}$	$\langle\beta\rangle$
MCs										
1995	8	372	11.1	22.6	11.3	−7.9	−54.2	18.4	1.13	0.15
1996	4	354	13.4	22.4	9.6	−8.2	−26.2	28.0	0.65	0.18
1997	17	418	8.2	24.4	13.1	−10.0	−69.7	20.4	1.42	0.09
1998	11	420	10.4	18.7	13.0	−10.1	−70.0	25.1	1.66	0.08
1999	4	432	10.2	20.7	12.3	−8.2	−80.2	21.0	1.28	0.07
2000	12	487	7.4	22.8	14.3	−10.6	−92.1	20.2	1.07	0.07
2001	10	500	5.2	25.6	11.9	−8.7	−100.5	24.1	1.33	0.07
2002	10	466	7.3	28.0	12.9	−10.5	−71.9	20.4	1.03	0.08
2003	5	518	9.2	44.8	16.1	−20.8	−179.6	14.1	5.20	0.14
2004	7	600	6.9	32.3	20.5	−22.4	−187.9	17.4	5.13	0.04
2005	7	444	9.8	23.2	11.6	−10.3	−88.8	18.7	1.70	0.18
2006	6	438	9.9	25.2	13.7	−7.3	−33.0	13.6	0.96	0.14
ICMEs										
1996	4	357	13.0	22.2	9.1	−8.2	−26.2	29.3	0.65	0.22
1997	22	416	9.2	24.2	11.6	−11.2	−76.3	24.2	1.51	0.15
1998	35	433	9.5	26.1	10.7	−11.3	−68.8	33.7	1.15	0.19
1999	31	458	6.2	29.3	9.0	−11.2	−58.3	29.6	1.13	0.20
2000	47	470	8.2	26.0	9.6	−11.3	−73.0	29.9	1.21	0.27
2001	49	477	6.8	28.1	9.2	−10.9	−90.5	31.3	1.15	0.26
2002	26	451	7.0	36.5	11.2	−11.3	−76.8	31.2	1.11	0.20
2003	21	576	6.7	54.8	12.0	−11.0	−114.4	31.2	1.69	0.34
2004	21	521	4.8	37.3	10.1	−13.0	−106.0	31.0	1.91	0.32
2005	30	541	6.7	29.4	9.7	−11.0	−88.6	25.8	1.00	0.29
2006	12	474	6.2	25.1	9.4	−6.6	−51.2	21.3	0.93	0.14

the MC events than for the ICME events. (There is an exception, *i.e.*, the c.c. for solar wind thermal speed *vs.* $Dst_{\min}$ is smaller for MC events than for the ICME events, but both c.c.s are very poor: −0.25 for MCs and −0.30 for ICMEs.)

3. Discussion

ICMEs are defined in terms of a far larger number of possible physical indicators than are used for defining MCs (the parameters defined are listed in the Introduction), meaning perhaps 12 *vs.* four parameters, respectively, *i.e.*, a ratio of three times as many for ICMEs than MCs. The results of this study show that 85 out of 307 (or ≈ 28%) ICMEs appear to contain MCs, which is close to (and confirms) the earlier finding (30%) by Gosling (1990); but we found this result here by using considerably *larger data sets*. The frequency of the occurrence for ICMEs is ≈ three times that for MCs. The difference between the definitions of a MC and an ICME may be the principal reason for their occurrence frequencies being so different.

The results of this study (see Figure 1) show that most solar wind conditions inside both MCs and ICMEs are similar except the average event duration (Δt) and average proton

Table 4 Summary of linear correlation coefficients for $Dst_{\rm min}$ *vs.* various solar wind parameters.

	$\langle V\rangle$	$\langle N_{\rm p}\rangle$	$\langle V_{\rm th}\rangle$	$\langle \lvert B\rvert\rangle$	$\langle B_{z,\rm min}\rangle$	$\langle VB_{\rm s,max}\rangle$	$\langle \epsilon_{\rm max}\rangle$
$Dst_{\rm min}$ of MCs	−0.53	0.05	−0.26	−0.66	0.78	−0.71	−0.80
$Dst_{\rm min}$ of ICMEs	−0.42	0.00	−0.31	−0.47	0.61	−0.55	−0.63

plasma β ($\langle\beta\rangle$). But the correlation coefficient for $Dst_{\rm min}$ *vs.* different solar wind parameters are better for MCs than for ICMEs. For the 85 ICMEs which appear to contain MCs, their average duration ($\langle\Delta t\rangle$) is 32 h, which is slightly (8.1%) longer than the typical ICMEs duration ($\Delta t = 29.6$ h; see Table 2).

We have also found that six observed MCs are not listed in the ICME list made by Richardson and Cane (http://www.ssg.sr.unh.edu/mag/ace/ACElists/ICMEtable.html). The starting-times of these events were: 16 May 1997, 18 September 1997, 1 August 2000, 19 May 2002, 3 September 2002, and 10 July 2003. Table 5 summarizes the solar wind characteristics of these six MCs. The event durations, Δt, of these six individual events are 7.8, 60, 15.8, 19.5, 18.5 and 13 h, respectively; the estimated axial field magnitudes of the magnetic fields ($B_\circ$)* are 11.2,17.8, 18.1, 22.4, 14.4 and 13.9 nT; the average velocities are 490.7, 322.6, 459.8, 460.5, 349.4, and 356 km s^{-1}; and the quality ($Q_\circ$)* of the MCs are 3, 3, 3, 1, 2, and 3. ($Q_\circ$*, the estimated quality of the model fitting: $Q_\circ = 1, 2$ and 3 for good, fair and poor, respectively (see Appendix A of Lepping *et al.* (2006)).) For these six MCs, *i*) the speed (406.5 km s^{-1}) is $\approx 12\%$ lower than the average speed of the MCs$_{99\ \rm events}$ (455 km s^{-1}); *ii*) the magnetic field (10.5 nT) is $\approx 28\%$ weaker than the average (13.4 nT); *iii*) the $Q_\circ$s are relatively poor (only one is $Q_\circ = 1$, one is $Q_\circ = 2$ and four are $Q_\circ = 3$); and *iv*) the average proton density (9 cm^{-2}) is $\approx 18\%$ higher than the average (8.5 cm^{-2}), but $N_{\rm p,max}$ is $\approx 14\%$ higher than average $N_{\rm p,max}$. Probably the poor $Q_\circ$s, lower solar wind speeds, and weaker magnetic fields are the major reasons that the MCs cannot be identified as part of the ICMEs for these events. But the dominant factor is not obvious to us. And besides the above possible reasons, we have no other explanation as to why these MCs are not included in the ICME list. The results also show that Δt for ICMEs is 41% longer than for MCs; and β of the proton plasma for ICMEs is 123% larger than for MCs. What are the major factors which cause these two huge differences? Are they caused by the usual (natural) long durations for ICMEs, or the choice of our definition for the ICMEs?

We have also found that five ICMEs (out of 289) contain two MCs each. These ICMEs occurred starting on 6 November 1997, 6 January 1992, 19 March 2001, 9 November 2004, and 13 April 2006 with a Δt of 56, 45, 55, 51, and 16 h, respectively. The value of $\langle\Delta t\rangle$ for these five ICMEs is 44.6 h, which is 50% longer than that for a typical ICME, and two times longer than that for a typical MC. (Table 6 summarizes detailed information for these five ICMEs.) Four out of these five ICMEs have extremely long durations, *e.g.*, $\Delta t \geq 45$ h. At least two solar disturbances (or CMEs) are related to these ICME events, according to the study of Gopalswamy *et al.* (2007). MHD discontinuities separate the two MCs and apparently serve as their boundaries.

In contrast, there is only one MC incorporating two ICMEs, which occurred on 8 November 1998 with a Δt of 25.5 h, which is $\approx 24\%$ longer than that for a typical MC. This MC starts in the tail of the first ICME and ends in the middle of the second one. The huge differences between ICMEs and MCs might be caused simply by their different definitions. One important element in the definition of a MC is the lower value of β for the proton plasma (< 0.3 inside a MC). If an ICME intersects two MCs, it usually means that a region in the middle of the ICME contains high β solar wind material.

Table 5 MCs are not associated with ICME.

Event							Mean[a] 6 MCs	Mean[b] 99 MCs	δ[c] %
Year	1997	1997	2000	2002	2002	2003			
Month	05	09	08	05	09	07			
Day	16	18	01	19	03	10			
$\langle N_\mathrm{p}\rangle$ (cm^{-3})	3.6	10.5	4.5	4.2	19.1	12.2	9.0	8.6	18
$\langle V\rangle$ ($\mathrm{km\,s}^{-1}$)	490.7	322.6	459.8	460.5	349.4	356	406.5	455	−12
$\langle V_\mathrm{th}\rangle$ ($\mathrm{km\,s}^{-1}$)	34	26.8	32.5	30.7	25	20.6	28.3	25.3	11
$\langle B\rangle$ (nT)	7.9	11	10.9	11.7	11.4	9.9	10.5	13.4	−28
$N_{\mathrm{p,max}}$ (cm^{-3})	10.3	39.1	47.8	9.7	41.8	23	28.6	24.7	14
B_max (nT)	9.6	13.5	12.7	21.2	17.4	13.4	14.6	17.7	−21

[a] Averages of five MCs which are not associated with ICME.

[b] Averages of 99 MCs.

[c] δ ($\equiv \frac{\langle \mathrm{MC}_{6\ \mathrm{events}}\rangle - \langle \mathrm{MC}_{99\ \mathrm{events}}\rangle}{\langle \mathrm{MC}_{99\ \mathrm{events}}\rangle} \times 100\%$): difference between the averages of six non-ICME MCs and 99 MCs.

Table 6 The five ICMEs: each ICME contains two MCs.

Event						Mean 5 ICMEs	Mean 298 ICMEs	Mean 99 MCs
Year	1997	1998	2001	2004	2006			
Month	11	01	03	11	04			
Day	06	06	19	09	13			
Duration (hours)	56	45	55	51	16	44.6	29.6	20.5
$\langle N_\mathrm{p}\rangle$ (cm^{-3})	9.0	13.4	6.6	7.7	6.8	8.7	7.4	8.6
$\langle V\rangle$ ($\mathrm{km\,s}^{-1}$)	405.8	374.9	378.0	651.6	520.4	466.1	477.3	455.1
$\langle V_\mathrm{th}\rangle$($\mathrm{km\,s}^{-1}$)	26.5	22.1	15.6	28.3	26.7	23.8	30.6	25.3
$\langle B\rangle$ (nT)	11.2	14.2	14.4	13.9	18.2	14.4	10.1	13.4
$N_{\mathrm{p,max}}$(cm^{-3})	36.6	76.7	42.2	48.6	15.6	43.9	24.1	24.7
B_max (nT)	18.6	20.4	19.8	42.4	20.2	24.8	20.8	17.7

Table 7 Correlation coefficients between sunspot, CME, ICME, and MC.

	Sunspot	CME	ICME	MC
Sunspot	–	0.79	0.81	0.28
CME	–	–	0.69	0.03
ICME	–	–	–	0.45

Earlier studies of individual ICMEs show a trend of a slight decrease in average magnetic field strength from solar cycle minimum to maximum (Cane and Richardson, 2003). Cane and Richardson (2003) claimed that this is primarily related to the fact that the number of magnetic clouds decreased toward maximum. However, results of this study did not show this tendency; *e.g.*, see Figure 1. Table 3 shows yearly averages for various solar wind parameters. We found that the average magnetic field strength, $\langle B\rangle$, for the MCs has a dip in 1996 (to 9.6 nT) and a peak in 2004 (20.5 nT). In contrast, dips of $\langle B\rangle$ within ICMEs occurred in 1996 (9.1 nT), 1999 (9.0 nT), and 2001 (9.2 nT), and a peak in 2003 (12.0 nT). Note that the average field magnitude, $\langle B\rangle$, for ICMEs kept dropping since the peak of 2003. The lowest fraction of MCs occurred in 1999 (12%), and the largest fraction occurred in 1996 (100%). It is also interesting to note that in 1999 the number of ICME caused by geomagnetic storms was lowest because low latitude coronal hole flows dominated (Bothmer, 2003). The decreased value of $\langle B\rangle$ toward solar maximum is not held according to the results shown in Figure 1 and Table 3. Our results also show that the $\langle B\rangle$ peaks for ICMEs occurred in the ascending and declining phases of the solar cycle. However, the $\langle B\rangle$ peaks for MCs occurred in the declining phase, and $\langle B\rangle$ tends to increase with solar activity for solar cycle 23.

The frequency of occurrence of CMEs tends to track the solar activity cycle in both amplitude and phase (Webb and Howard, 1994). This result was confirmed by Wu, Lepping, and Gopalswamy (2006). An ICME is an interplanetary manifestation of a CME and such an event is the result of a large explosive event on the Sun of twisted magnetic field lines and so it also is a MC (see, *e.g.*, Burlaga *et al.*, 1981; Webb *et al.*, 2000). Therefore, it is important to try to understand the relationship between them. During the period of 1996 – 2006, the linear correlation coefficients for sunspot number *vs.* CME, ICME and MC are 0.79, 0.81, and 0.28, respectively; for CME *vs.* ICME and MC the c.c.s are 0.69 and 0.03; and for ICME *vs.* MC the c.c. is 0.45. CMEs and ICMEs are both well correlated with sunspot number, but MCs are not well correlated with sunspot number, CMEs, or ICMEs. Usually 12 possible physical parameters are utilized for identifying ICMEs. That is, different subsets of these 12 physical parameters are utilized for different ICMEs, making it harder to misidentify an ICME encounter than a MC encounter (with far fewer identifying parameters). Lepping and Wu (2010) point out that most of the ICME identifiers are independent of the closest approach distance, or at least weakly dependent on it, in contrast to the situation for MCs where a large closest approach distance may cause a significant selection effect. This may be one of the principal causes for a poor MC – ICME correlation.

In general, MCs have a better linear correlation than ICMEs for various solar wind parameters *vs.* geomagnetic storm intensity, Dst_{min}; *e.g.*, see Table 2. Specifically, $B_{z,\mathrm{min}}$, $VB_{\mathrm{s,max}}$, and ϵ_{max} are all well correlated with Dst_{min} for MCs (with c.c.s of 0.78, −0.71, −0.80, respectively), but they correlate poorly for ICMEs (0.61, −0.55, −0.63, respectively). Correlation coefficients for $\langle V\rangle$, $\langle N_{\mathrm{p}}\rangle$, $\langle V_{\mathrm{th}}\rangle$, and $\langle|B|\rangle$ *vs.* Dst_{min} are −0.52, −0.68, −0.25 and −0.68, respectively, for MCs. They are −0.42, 0.00, −0.31, and −0.47, respectively, for ICMEs.

For the mean values of different parameters, Figure 1 and Table 2 give the following statistical results. *i*) The value of β for the proton plasma is much smaller in MCs than in ICMEs. *ii*) ϵ, VB_{s}, B, and N_{p} (solar wind proton density) are larger in MCs than in ICMEs. *iii*) Thermal speed (V_{th}), V_{max}, B_{max}, and duration are smaller for MCs than for ICMEs. *iv*) Solar wind speed (V), maximum proton density ($N_{\mathrm{p,max}}$), $B_{z,\mathrm{min}}$, and Dst_{min} are similar (differences are less than 10%) for both MCs and ICMEs.

4. Conclusions

We compare the frequency of occurrences and the physical characteristics of ICMEs and MCs by using *in-situ* solar wind plasma (SWE/*Wind*) and magnetic field (MFI/*Wind*) observations made during solar cycle 23. We found that ≈ 28% of the ICMEs appear to contain MCs during 1996 – 2006, which agrees with the value of 30% found earlier by Gosling (1990), but which is lower than the value of 41% found by Bothmer and Schwenn (1995).

It is found that six MCs are not associated with ICMEs, which conflicts with the belief of many authors that MCs are usually a subset of ICMEs (see, *e.g.*, Gopalswamy, 2006). In addition, we also found that the solar wind conditions of MCs and ICMEs are usually similar (except for their duration and proton plasma β; both are smaller on average for MCs). The average duration of ICMEs (29.6 h) is 44% longer than for MCs (20.5 h). The average of $\langle\beta\rangle$ is 0.01 for MCs and 0.24 for ICMEs. The linear correlation between geomagnetic storm intensity ($Dst_{\min}$) and relevant solar wind parameters is better for MCs than for ICMEs. The significant differences in the definitions of MCs and ICMEs are consequential when identifying them.

The statistical results are found and listed as follows.

i) The average intensity of geomagnetic storms caused by MCs is stronger than that for ICMEs.
ii) The average magnitude of negative $B_{z,\min}$ is almost the same for MCs and ICMEs.
iii) The average solar wind speed of MCs is slower than that for ICMEs.
iv) The average magnitude of magnetic fields in MCs is higher than that in ICMEs.
v) The average thermal speed is lower in MCs than that in ICMEs.
vi) Maximum VB_{s} and ϵs are larger in MCs than those for ICMEs.
vii) For MCs, the solar wind parameters, $B_{z,\min}$, and $VB_{\mathrm{s,max}}$ correlate well with the geomagnetic storm intensity ($Dst_{\min}$).

By the strict definitions of ICMEs and MCs and the statistical comparisons carried out here we see that there are, indeed, marked differences between these two kinds of structures, including their occurrence frequencies, plasma β values, durations, and other solar wind parameters. The difference between the definitions of MCs and ICMEs may be the principal reason for these physical differences. We found recently that selection effects that depend on the observer's closest approach distance for MCs, but not being likely so strong for ICMEs, are an important factor in this regard. We stress that since ICMEs are, on average 44% longer in duration than MCs (listed above), different plasma parcels are being examined when these two structures are being compared analytically. This alone should be expected to significantly contribute to some of the physical differences between these two kinds of structures.

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