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Characteristics of Magnetic Clouds and Interplanetary Coronal Mass Ejections which Cause Intense Geomagnetic Storms

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ABSTRACT

We present the results of a statistical data analysis of the geo-effectiveness of non-magnetic-cloud interplanetary coronal mass ejections (ICMEs) and compare them with those of magnetic-cloud (MC) interplanetary coronal mass ejections observed during solar cycle 23. (The term ICME as used here will refer to a non-MC ICME.) The starting point of this investigation is the set of intense geomagnetic storms ($Dst_{\min}$ ≤ -100 nT) of solar cycle 23 between 1996 and 2005. We also compare the solar source locations of the ICMEs with those of the MCs. The source locations of the solar disturbances are, on average, closer to the Sun-Earth line for the MCs than for the ICMEs. There is an anomaly for the location of the related solar sources: no event came from the region between the solar equator plane and 10°S (south) of that plane. The primary results are listed as follows. The average duration of these MCs is slightly longer (~7%) than that of ICMEs. The average geomagnetic storm intensity for the MCs is higher than that for the ICMEs and CIRs formed by high-speed streams from coronal holes, especially for the events associated with X class flares. The relevant average magnetic field component, i.e., $|Bz_{\min}|$, is more intense within the MCs than within the ICMEs. The average solar wind speed is similar for both MCs and ICMEs. Maximum solar wind speed is higher within ICMEs than within MCs. Maximum solar wind proton density is higher for MCs than for ICMEs.

Key words: Magnetic cloud, Interplanetary coronal mass ejection, Geomagnetic storm, Solar flare, Corotating interaction region

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1. INTRODUCTION

A magnetic cloud (MC) is defined as a region of a high strength magnetic-field, low proton temperature, low proton β, and smoothly-changing (rotating) magnetic field (Burlaga et al. 1981). Magnetic clouds are often preceded by upstream sheaths in which the plasma is usually hot and dense and the magnetic field is extremely turbulent (e.g., Tsurutani and Gonzalez 1997, and reference therein). The front "boundary" of the sheath may be a shock, a shock-like structure, a pressure pulse or a sharp rise in density, temperature, or velocity. About 1/4 of observed MCs have no upstream pressure pulse/shock, but all have a density increase (e.g., Wu and Lepping 2002). It is now generally believed that MCs are an important subset of ICMEs (interplanetary coronal mass ejections) or are contained within them, since ~90% of MCs drove geomagnetic storms with $Dst_{\min}$ (minimum Dst observed during a geomagnetic storm) ≤ -30 nT (e.g., Wu et al. 2003, 2006; Wu and Lepping 2007, 2008). Conversely, Wu and Lepping (2011) recently reported that six MCs are not associated with ICMEs by investigating 91 MCs and 307 ICMEs occurred in the period between 1996 and 2006. The average occurrence rate of MCs is ~9.5 MCs yr^{-1} for the period 1995 - 2003 (e.g., Lepping et al. 2006; Wu et al. 2006; Wu and Lepping 2008) but dropped slightly to ~8.6 for the period 1995 - 2006 (Wu and Lepping 2011). The average occurrence rate is higher for ICMEs (~29.6/year) than for MCs for the period of 1996 - 2005 (e.g., Richardson and Cane 2010), within which 78% or 231 out of 296 ICMEs drove geomagnetic storms with $Dst_{\min}$ ≤ -30 nT. Gopalswamy (2006) compared the properties of

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MCs and non-cloud ICMEs in general. Here we attempt to compare MCs-associated with non-MC-associated ICMEs for cases that cause strong geomagnetic storms. For simplicity, the term ICME as used henceforth will refer to a non-MC-associated ICME; and the term MC as used henceforth will refer to a MC-associated ICME.

Studying the interplanetary causes of intense geomagnetic storms (*Dst* < -100 nT) during solar cycle 23 (1997 - 2005), Gonzalez et al. (2007) found that the most common interplanetary structures leading to the development of an intense storm were: magnetic clouds, sheath fields, sheath fields followed by a magnetic cloud and co-rotating interaction regions leading high speed streams. Zhang et al. (2007) studied 88 major (or intense) geomagnetic storms with $Dst_{min} \leq$ -100 nT over the period of 1996 - 2005 caused by MCs, ICMEs and co-rotating interaction regions (CIRs). They found (1) 60%, 27%, and 13% of the major geomagnetic storms were caused by a single coronal mass ejection (CME)/ICME, multiple CMEs/ICMEs, and coronal holes or CIRs, respectively; (2) 63%, 12%, 13%, and 12% of major geomagnetic storms were related to solar active regions, quiet-Sun regions, coronal holes, and no signature areas, respectively; and (3) the locations of solar source regions were cataloged according to active region and quiet Sun. More than 87% [60% + 27% in above item (1)] of major geomagnetic storms are caused by either MCs or ICMEs. This motivates us to investigate if there are any distinguishing properties of ICMEs and MCs that caused the major geomagnetic storms. In this study, we separate the causes of major geomagnetic storms into three groups: MC-related, ICME-related, and CIR-related. There are three kinds of geomagnetic storms which are cataloged by the driving sources: (1) "sheath storm" wherein a geomagnetic storm is primarily driven by the southward IMF in the sheath region, and Dst_{min} occurred within sheath region; (2) "ejecta storm" such that a geomagnetic storm is primarily driven by the southward IMF in the ejecta (MC or ICME) region, and Dst_{min} occurred within ejecta region; and (3) "two-step storm" demonstrating that a geomagnetic storm is primarily driven by the southward IMF in both the sheath and ejecta regions, and Dst_{min} occurred within the ejecta region. If the magnetic fields are southward both in regard to the sheath and solar ejecta, a two-step main phase storm can result (e.g., Gonzalez et al. 2001). A two-step storm is defined as a storm in which a *Dst* decrease (induced by the southward fields in the sheath) does not fully recover to the pre-storm level before a second *Dst* decrease (induced by the southward fields in the solar ejecta) follows (e.g., Kamide et al. 1998) We will investigate the differences between these three kinds of storms.

2. DATA AND ANALYSIS

Four data sets are used in this study. (1) 88 intense geomagnetic storms (with $Dst_{min} \leq$ -100 nT which occurred from 1996 to 2005) as taken from Zhang et al. (2007). Information on Solar source locations, interplanetary shocks, interplanetary structures, e.g., MCs, ICMEs, or CIRs are included. A storm may be associated with a single MC/ICME, a complex solar wind flow produced by multiple interacting ICMEs (e.g., Yermolaev and Yermolaev 2008), the sheath itself, or the combination of the sheath with ICMEs/MCs wherein the sheath is the region between an interplanetary shock and an ICME. (2) The MCs are adopted from Lepping et al. (2006), and are listed in http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html, and from Huttunen et al. (2005). (3) The ICMEs are adopted from Richardson and Cane (2010). If an ICME was not identified as an MC (or not covering the near region of a MC within a few hours), we list it as a non-MC ICME. Finally, (4) solar wind plasma and magnetic field data (from the WIND or ACE spacecraft) are provided by the NASA Space Physics Data Facility (http://vho.nasa.gov/mission/wind/swe_gsfc/ and http://vho.nasa.gov/mission/wind/mfi/).

2.1 The Association Between CMEs and ICMEs

It is a complex task to determine the association between ICME and CME (e.g., Eselevich et al. 2009). In this study, we picked 88 events which were identified by Zhang et al. (2007). They used an interactive process with multiple steps which contains three major steps: (1) find all candidate front-side halo CMEs within a 120-hour-long search window before the arrival time of the ICME-driven shock; (2) reduce the search window by estimating the CME transit time based on in situ solar wind velocities at the location of shock arrival; and (3) for each remaining candidate CME in the search window, consider whether the CME speed at the Sun is consistent with the 1 AU transit speed implied by an association with the 1 AU shock/ICME and with the in situ solar wind speed [More detail information can be found in previous study by Zhang et al. (2007)].

2.2 Identification of Solar Source Locations

It is usually straightforward to identify the solar source of an ICME, but the results are sometimes ambiguous. For example, Wang et al. (2011) found that 231 CMEs source locations cannot be identified due to poor data, and 325 CMEs have no evident eruptive signatures in the field of view of EIT as a result of investigating 1078 Large Angle and Spectrometric Coronagraph (LASCO) CMEs listed in Coordinated Data Analysis Workshop (CDAW) catalog during the interval of 1977 - 1998.

The source locations for the studied events are adapted from a previous study (Zhang et al. 2007). First, they find a front side halo (full or partial) CME at a reasonable earlier time which depends on the transit time of the CME from the

Sun to the Earth (e.g., Webb et al. 2000; Zhang et al. 2003). Then, they use a cause-and-effect relationship between solar wind IP events to help justify the finding. In this study 88 ICMEs have been shown to cause severe geomagnetic storms when they passed the Earth. The relationship between CMEs and ICMEs is described in the above section.

There are three ways to identify the locations of solar sources (ejecta) according to Zhang et al. (2007). They are by: (1) using observations from the SOHO spacecraft wherein CMEs near the Sun are observed by the LASCO C2 and C3 coronagraphs which have fields of view of 2 - 6 solar radii (R_s) and 4 - 30 R_s, respectively; (2) identifying the surface features of CMEs in the source region with observations from the SOHO Extreme-Ultraviolet Imaging Telescope (EIT) which takes images of the Sun's corona over the full disk up to 1.5 R_s altitude; and (3) using traditional synoptic data, daily NOAA solar event reports which include data on soft X-ray flares, filament eruptions, and active regions.

3. RESULTS

Figure 1 shows the solar source locations of 43 MCs and 32 ICMEs causing intense geomagnetic storms. CIRs caused 13 intense storms, which are not shown in Fig. 1. Most events occurred within a 30° latitude of the solar equator.

For solar sources located in the northern hemisphere, the average latitudes are 8°N for MCs and 14°N for ICMEs, and the average longitudes are 4°W for MCs and 12°W for ICMEs. For solar sources located in the southern hemisphere, the average latitudes are 21°S (MCs) and 14°S (ICMEs), and the average longitudes are 15°W (MCs) and 10°W (ICMEs). The average latitude of source locations for ICMEs (~14°) is higher than for MCs (~11°). The average source longitude of ICMEs is 10°W, compared to 7°W for MCs (see also Table 1). The σ's (σ: standard deviation) for MCs are 2.87° for latitude and 5.03° for longitude, and the σ's for ICMEs are 2.48° for latitude and 3.08° for latitude. The larger σ of latitude and longitude for MCs are caused by two abnormal events which are located at S58W05 and S20W85.

Figure 2 shows *Dst* distributions of storms caused separately by MCs, ICMEs, and CIRs. The averages of Dst_{min} (<Dst_{min}>) are -175, -161 and -129 nT for the events caused by the MCs, ICMEs, and CIRs, respectively. The spread in values, measured by σ, are 13.6, 11.6, and 14.4 nT for the MCs, ICMEs, and CIRs, respectively. The median Dst_{min} values are -142, -147, and -116 nT for MCs, ICMEs, and CIRs, respectively. Table 2 also summarizes these values. It is clear that, on the average, the MC storms are a bit stronger (~9%) than the ICME storms. Figure 3 shows distributions of solar wind properties of ICMEs and MCs (see Table 3). Most solar wind properties are similar for MCs and ICMEs, except for their magnetic fields. The average speeds of MCs and ICMEs are very similar (less than 1% difference), but the median speed of ICMEs is ~14% higher.

Table 4 summarizes the flare association of MC and ICME events. There are 27 ICMEs and 28 MCs that have associated flares, and the <Dst_{min}> driven by those MCs (-198 nT) is ~18% higher than that associated with the ICMEs (-168 nT). The σ's are 100 nT for MCs and 67 nT for ICMEs. In addition, the <Dst_{min}> driven by flare-associated MCs (-198 nT) is ~13% higher than that for all MCs (-175 nT). For the 27 ICMEs related with flares, one event was related to a B class flare; 9 events were related to a C class flare; 6 events were related to an M class flare; and 12 events were related to an X class flare. For the 28 flare related MCs events, nine events were related to a C class flare; 8 events were related to an M class flare; and, 12 events were related to an X class flare. Forty one percent (41%) of ICMEs and 29% of MCs, related to intense storms, were associated with X class flares. This explains why the average speed (V_{max}) of the ICMEs was higher than that for the MCs because CME speeds are correlated with X-ray flare size (Yashiro et al. 2005).

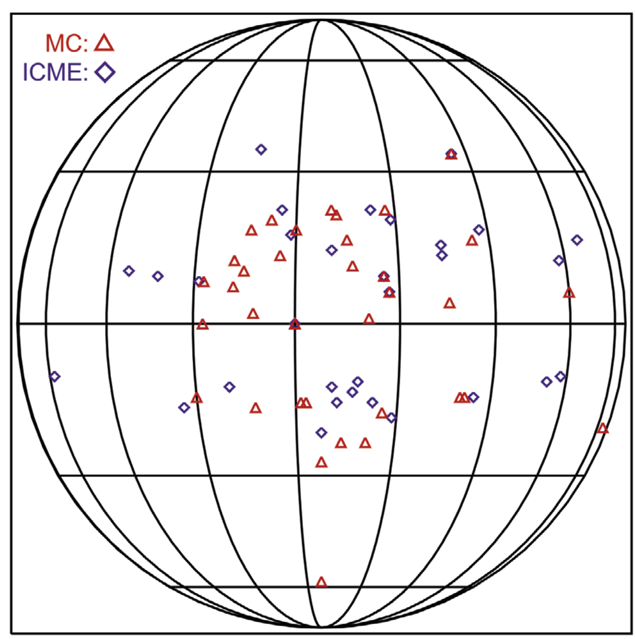

Fig. 1. Solar source locations for MCs (triangles) and non-magnetic-cloud ICMEs (diamonds) the grid spacing is 20° in latitude and longitude.

Table 1. Averages of solar source locations for MCs and ICMEs.

Source location	MC	σ^a	ICMEs	σ^a
Latitude	11°	2.87°	14°	2.48°
Longitude	7°W	5.03°	10°W	3.08°

a: σ - standard deviation.

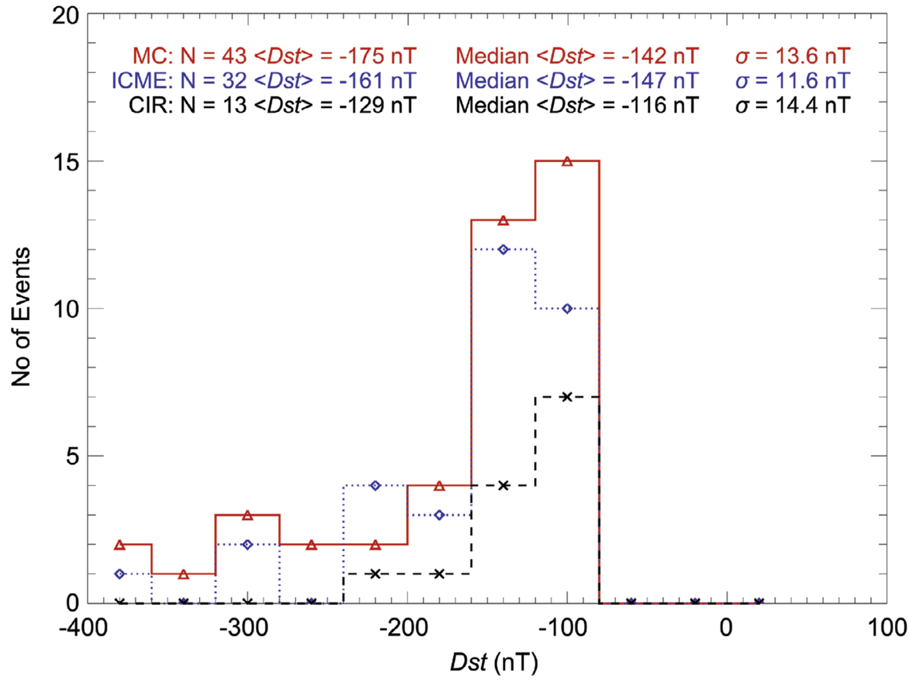

Fig. 2. Histograms of storm Intensity (Dst_{min}) for MCs (triangles), ICMEs (diamonds), and CIRs (crosses) for the period 1996 - 2005 in which, *Np* (max) and *V* (max) are the peak proton density and velocity within MCs, ICMEs, or CIRs.

Table 2. Averages of Intensity for intense geomagnetic storms caused by MCs, ICMEs, and CIRs during the interval of 1996 - 2005.

	MCs (43)	ICMEs (32)	CIRs (13)
< Dst_{min} > (nT)	-175	-161	-129
Median Dst_{min} (nT)	-142	-147	-116
σ^a (nT)	13.6	11.6	14.4

a: σ - standard deviation.

4. DISCUSSION

About 85% of major (or intense) geomagnetic storms are related to either MCs or ICMEs (e.g., Zhang et al. 2007). The other significant cases of such storms are CIRs. Among these three sources of intense geomagnetic storms, MCs are the most important: (1) about ~50% of intense geomagnetic storms are caused by MCs; and, (2) the intensity of MC storms is greater than that for ICME storms.

The average magnetic field at Earth's orbit of the storm-producing MCs (14 nT) is ~27% larger than that for ICMEs (11 nT). Average speed is almost the same (less than 1% difference) for both types: 498 km s^{-1} (MCs) and 500 km s^{-1} (ICMEs). This result consists with long-term statistical study for the general population by Yermolaev et al. (2010) who investigated more than 20 years worth of solar wind data (1976 - 2000). However, the median speed of ICMEs (535 km s^{-1}) is faster than that for MCs (469 km s^{-1}). This speed relation is consistent with projection effects. Storm-effective MC sources are much closer to the disk center, so the associated CMEs have intense projection effects compared to those originating at larger central meridian distances (see Gopalswamy et al. 2007). Specifically, the median speed for ICMEs is ~14% higher than that for MCs. Since the average source location for ICMEs is further away from the Sun-Earth line than that for MCs (e.g., see Fig. 1 and Table 1), more energy for ICMEs to propagate to the Earth is required. For intense storms which are related to solar flares, there is a greater percentage of ICMEs (41%) than MCs (29%) related to X class flares, but the intensity of geomagnetic storms for MCs (<Dst_{min}> ~-264 nT) is higher than that for ICMEs (<Dst_{min}> ~-181 nT). Therefore, the average speed for ICMEs is higher than that for MCs because the energy input from the solar source for ICMEs is stronger than that for MCs. The average Bz_{min} is stronger within MCs (-21 nT) than within ICMEs (-17 nT) which also supports the above features. The average duration is longer for MC-associated events (1.34 days) than for ICME-associated events (1.12 days). It is interesting to note that the average magnetic field strength of our MCs is ~30% higher than that for the general population (e.g., Gopalswamy 2006; Yermolaev et al. 2010), stressing the importance of field strength in causing storms. Again, the stronger magnetic fields in MCs than in ICMEs also show the importance of solar source locations for MCs.

Both Fig. 1 and Table 1 show clearly: (1) most solar sources occurred within 30° of the solar equator, with one exception, which is the MC-associated event that occurred

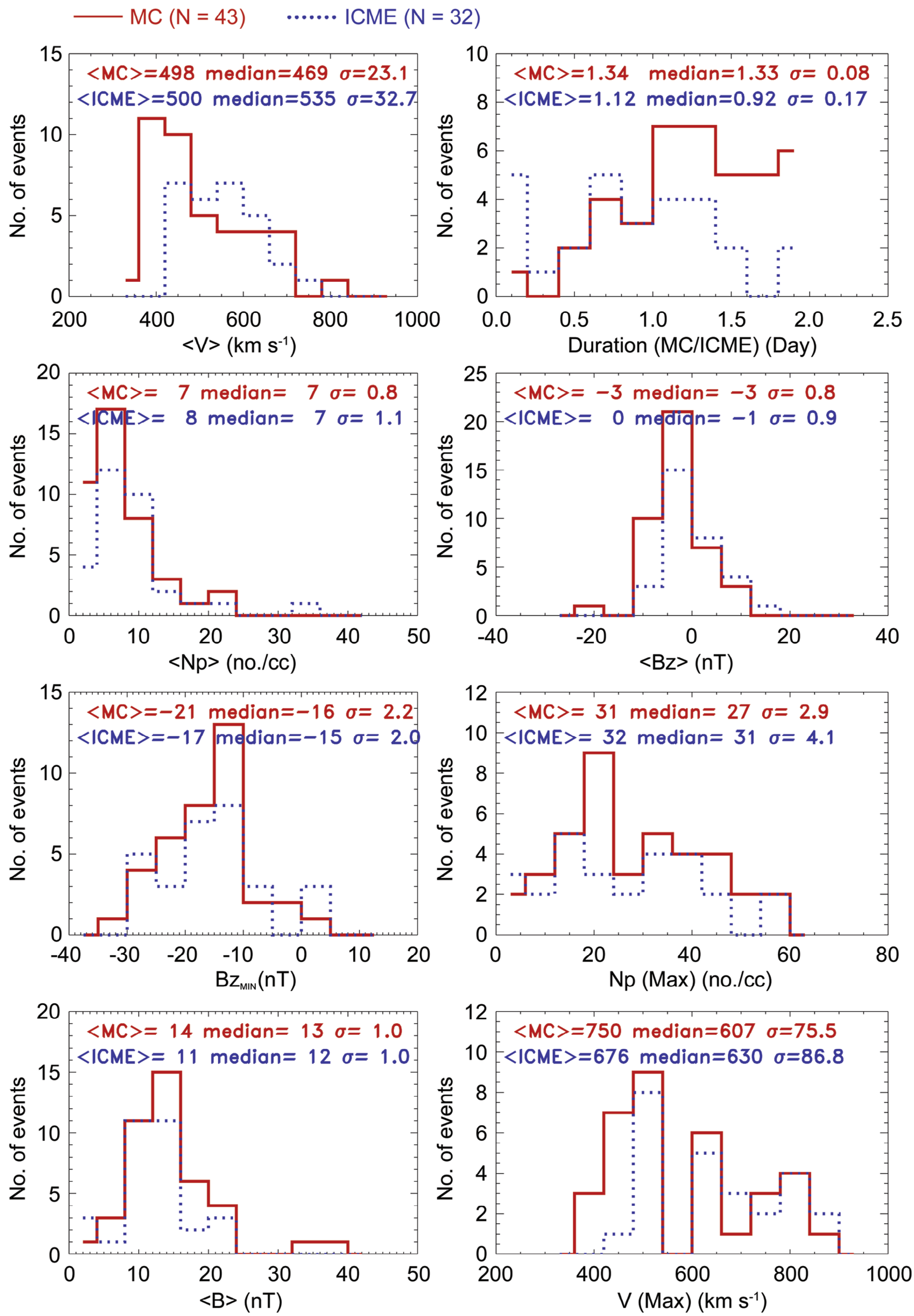

Fig. 3. Histograms of solar wind properties for storm-related MCs and ICMEs.

Table 3. Solar wind properties of MCs and ICMEs which caused intense geomagnetic storms during the interval of 1995 - 2005.

	MCs Average	ICMEs Average	MCs Median	ICMEs Median	MCs σ^a	ICMEs σ^a
Duration (Days)	1.34	1.12	1.33	0.92	0.08	0.17
B (nT)	14	11	13	12	1.0	1.0
$Bz_{min}{}^{b}$ **(nT)**	-21	-17	-16	-15	2.2	2.0
Np^{c} **(cm^{-3})**	7	8	7	7	0.8	1.1
$Np_{max}{}^{d}$ **(cm^{-3})**	31	32	27	31	2.9	4.1
V^{e} **(km s^{-1})**	498	500	469	535	23.1	32.7
$V_{max}{}^{f}$ **(km s^{-1})**	750	676	607	630	75.5	86.8
$\langle Bz \rangle^{g}$ **(nT)**	-3	0	-3	-1	0.8	0.9

Notes: a: σ - standard deviation (nT); b: Minimum Bz within a MC/ICME; c: average Np within a MC/ICME; d: maximum Np within a MC/ICME; e: average V within a MC/ICME; f: maximum V within a MC/ICME; and g: average Bz within a MC/ICME.

Table 4. Flare association.

	MCs	ICMEs	CIRs
Storms	49%	36%	15%
$\langle Dst_{min} \rangle$ **(nT)**	-175	-161	-129
Storms associated with Flares	28	27	
$\langle Dst_{min} \rangle$ **(nT)**	-198	-168	
σ **(nT)**	100	67	
X Class (no. of events)	8	11	
$\langle Dst_{min} \rangle$ **(nT)**	-264	-181	
σ **(nT)**	100	86	
M Class (no. of events)	11	6	
$\langle Dst_{min} \rangle$ **(nT)**	-206	-164	
σ **(nT)**	104	55	
C Class (no. of events)	9	9	
$\langle Dst_{min} \rangle$ **(nT)**	-129	-159	
σ **(nT)**	42	54	
B Class (no. of events)	0	1	
$\langle Dst_{min} \rangle$ **(nT)**		-138	

at 58°S; and (2) more sources were in the north than in the south which probably reflects the asymmetry in the locations of major active regions during solar cycle 23 (e.g., Richardson and Cane 2005; Riley et al. 2006). The solar source locations of ICMEs related to "intense storms" were on average further away from the Sun-Earth line than those of the MCs. This implies that on average the observing spacecraft were closer to the center of the solar ejecta for the MCs than for the ICMEs. The following average features show this effect. (i) The intensity of the magnetic field is stronger for MCs than for ICMEs; (ii) maximum $|Bz_{min}|$ is stronger within MCs than within ICMEs; and (iii) the duration is longer for MCs than for ICMEs. The effects of items (i) and (ii) are directly connected with criteria of selection for MC and non-MC events. Note that the average duration of MCs is about ~19% longer than that for ICMEs, but the median duration is ~45% longer for MCs than for ICMEs. This implies that there are more shorter-duration ICMEs than MCs, but some ICMEs are much longer than MCs.

There is an anomaly in the locations of the related solar sources; no event came from the region between the solar equator plane and 10°S (south) of that plane. This feature was not observed by studying general cases over the interval 1996 - 2003 [e.g., see Fig. 9 of Gopalswamy (2006)]. The butterfly diagram of sunspot numbers might explain why this anomaly happened; there were no active regions near the solar equator. In any case, it is a mystery that the anomaly is only just south of solar equatorial plane. The solar heliospheric current sheet (HCS) might be present within this region. An interaction might have taken place between the HCS and the solar ejecta. For example, performing global three-dimensional magnetohydrodynamic numerical simulations, Wu et al. (2007b) studied this kind interaction which occurred during solar minimum for the well known event of May 12, 1997 [see Fig. 2 of Wu et al. (2007b)], and during solar maximum for solar events of October 25 - 28, 2003 [see Figs. 1 - 2 of Wu et al. (2007a)]. Figure 2 of both Wu et al. (2007a and b) show that the shape of the ICME was distorted, and the characteristics of ICME might have been destroyed after interacting with the HCS. This might explain why there was no solar source within this region of ejecta which drove intense geomagnetic storms. This requires further investigation in detail by performing data analysis or numerical simulation which are considered to be beyond the scope of this paper.

Gopalswamy (2006) compared the properties of 85 MCs and 109 shock-driving ICMEs that occurred during 1996 - 2003. Figure 4 of Gopalswamy (2006) shows the following differences between MCs and shock-driving IC-

MEs: (1) magnetic field, solar wind speed, and solar wind proton density within MCs are higher than within shock-driving ICMEs; (2) thermal speed is lower within MCs than within shock-driving ICMEs; and (3) the average duration for shock-driving ICME events is longer than that for MCs. This study investigated major (intense) geomagnetic storms which occurred from 1996 to 2005, slightly longer than the period studied by Gopalswamy (2006). The following features are found in this study: (i) the average magnetic field strength for the events associated with MCs is higher than that associated with ICMEs which is consistent with the findings of Gopalswamy (2006). (ii) the average duration is higher for MCs (~32.2 hr) than for ICMEs (~26.9 hr). The results of Gopalswamy (2006) show that the average duration of shock-driving ICMEs (~38.8 hr) is much longer than that of MCs (~20.9 hr). The currently studied events are associated with major geomagnetic storms which might require a long duration southward interplanetary magnetic field to drive down the value of *Dst* (e.g., Wu et al. 2006). This is consistent with the average duration of the MCs for the major (intense) geomagnetic storms being much longer than the average duration of the MCs that occurred during the interval of 1996 - 2003.

Characteristics of magnetic clouds (MCs), magnetic cloud-like structures (MCLs), and interplanetary coronal mass ejections (ICMEs) have been studied and compared, previously. For example, using WIND in-situ solar wind plasma and magnetic field data with a one-minute resolution, Wu and Lepping (2007) compared the characteristics of MC and a magnetic cloud-like structures (MCL) for events which occurred over the period of 1995 - 2003. The average duration of the cloud passage was between 14.9 and 21.0 hours with associated $Dst_{\min}$ being -45, and -91 nT for MCLs and MCs, respectively. The average plasma beta was 0.1 for both MCLs and MCs. Wu and Lepping (2008) also compared the geo-effectiveness of MCs, MCLs and interplanetary (IP) shocks for the period 1995 - 2003. The associated $Dst_{\min}$ was -91, -45, -74.6, and -66 nT for MCs, MCLs, IP shocks with MCs/MCLs and IP shocks without MCs/MCLs, respectively. Recently, using OMNI hourly data, Yermolaev et al. (2010) studied the occurrence rate and geo-effectiveness of large-scale solar wind structures for the time interval of 1976 - 2000. The average duration for MCs and ICMEs was 25 and 29 hours, respectively. The associated geomagnetic activity ($Dst_{\min}$) was -52.1 and -21.1 nT. The average beta value was 0.016 and 0.31, respectively. More recently, Wu and Lepping (2011) performed a statistical study of MCs and ICMEs that occurred in solar cycle 23 (1996 - 2006). They found an average duration was 20.6 hours for the MCs and 29.6 hours for the ICMEs that they studied. Their associated $Dst_{\min}$ were -86.4 and -79.7 nT, and average beta values were 0.0972 and 0.242, respectively. All these previous studies suggest: (1) MCs are the most important storm-causing structures, (2) the duration is shorter for MCs than for ICMEs, and (3) the plasma β is smaller for MCs than for ICMEs.

In this study, we investigate the characteristics of MC-associated ICMEs and non-MC associated ICMEs for the events followed by severe geomagnetic storms ($Dst_{\min}$ < -100 nT). The average of the related $Dst_{\min}$ is -175 and -161 nT for MC-associated and non-MC-associated ICMEs, respectively. This result is consistent with previous studies as discussed above. The average duration is 1.34 and 1.12 days (or 32.2 and 26.9 hours) for MC- and non-MC-associated ICME events, respectively. Since all the events are associated with ICMEs, the one that contains a MC (two or more MCs) is likely to be more geo-effective. The difference between MCs and ICMEs, where changing field characteristics and low β_p are emphasized for the MCs, is one of the major reasons for the difference of their average characteristics (Wu and Lepping 2011).

Lepping et al. (2011) identified 18 MCs for the period 2007 - 2009. The average duration of MCs (15.2 hours) is shorter [by 49%, (15.2 -29.6)/29.6 × 100% = -49%] than that found in the previous solar cycle (1995 - 1997) which is 29.6 hours. Recently, Kilpua et al. (2012) introduced a new terminology; the "ICME-like structure" is used for ICMEs with a small flux-rope. The small flux-rope previously discussed has been described by Feng et al. (2008). Kilpua et al. (2012) found that the duration of a typical ICME-like structure is less than 10 hours [see Table 1 in Feng et al. (2008) or Kilpua et al. (2012)], and its magnetic field is weak (< 7 nT). Kilpua et al. (2012) identified a total of 85 ICMEs during the period 2007 - 2010. The durations of ICMEs are 19.8, 22.4, and 25.9 hours for the periods of January 2007 - June 2008, July 2008 - June 2009, and July 2009 - December 2010, respectively. The overall duration of ICMEs is 23.9 hours [= (19.8 × 11 + 22.4 × 38 + 25.9 × 50)/(11 + 38 + 50)] according to data listed in Table 4 as listed by Kilpua et al. (2012). The average duration of ICMEs (23.9 hours) is about 36% [= (23.9 - 15.2)/23.9] longer than that for MCs (15.2 hours). This is slightly 5% (= 36% - 31%) larger than the typical period [~31% = (29.6 - 20.5)/29.6] found for the cycle 23 during 1995 - 2006.

5. CONCLUSIONS

We investigated all intense geomagnetic storms which had $Dst_{\min}$ ≤ -100 nT during the interval of 1996 - 2005. We found that magnetic clouds are the most important interplanetary structures with respect to inducing intense geomagnetic storms. The main results of this study are: (1) there are ~49%, 36%, and 15% of the intense geomagnetic storms caused by MC-associated ICMEs, non-MC-associated ICMEs, and CIRs, respectively, (2) the average duration of these MCs is slightly longer (~19%) than that of the ICMEs, (3) the average geomagnetic storm intensity for the MCs is higher than that of the ICMEs or CIRs, especially for events associated with X class flares, (4) the solar source locations are closer to the Sun-Earth line for the MCs than for the ICMEs, (5) the average magnetic field strength and $Bz_{\min}$ are stronger within MCs than within ICMEs, (6) the average solar wind speed is similar for both MCs and ICMEs, and (7) both average and maximum solar wind proton density are higher for ICMEs than for MCs.

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