# Comparisons of Characteristics of Magnetic Clouds and Cloud-Like Structures during 1995-2012

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## Abstract

Using eighteen years (1995 - 2012) of solar wind plasma and magnetic field data (observed by the *Wind* spacecraft), solar activity (*e.g.* sunspot number: SSN), and the geomagnetic activity index (*Dst*), we have identified 168 magnetic clouds (MCs) and 197 magnetic cloud - like structures (MCLs), and we have made relevant comparisons. The following features are found during seven different periods (TP: Total period during 1995 - 2012, P1 and P2: first and second half period during 1995 - 2003 and 2004 - 2012, Q1 and Q2: quiet periods during 1995 - 1997 and 2007 - 2009, A1 and A2: active periods during 1998 - 2006 and 2010 - 2012). (1) During the total period the yearly occurrence frequency is 9.3 for MCs and 10.9 for MCLs. (2) In the quiet periods $<N_{MCs}>_{Q1} > <N_{MCLs}>_{Q1}$ and $<N_{MCs}>_{Q2} > <N_{MCLs}>_{Q2}$, but in the active periods $<N_{MCs}>_{A1} < <N_{MCLs}>_{A1}$ and $<N_{MCs}>_{A2} < <N_{MCLs}>_{A2}$. (3) The minimum *Bz* ($Bz_{min}$) inside of a MC is well correlated with the intensity of geomagnetic activity, $Dst_{min}$ (minimum *Dst* found within a storm event) for MCs (with a Pearson correlation coefficient, c.c. = 0.75, and the fitting function is $Dst_{min} = 0.90+7.78Bz_{min}$), but $Bz_{min}$ for MCLs is not well correlated with the *Dst* index (c.c. = 0.56, and the fitting function is $Dst_{min} = -9.40+ 4.58\, Bz_{min}$). (4) MCs play a major role in producing geomagnetic storms: the absolute value of the average $Dst_{min}$ ($<Dst_{min}>_{MC}$ = -70 nT) for MCs associated geomagnetic storms is two times stronger than that for MCLs ($<Dst_{min}>_{MCL}$ = -35 nT), due to the difference in the IMF (interplanetary magnetic field) strength. (5) The SSN is not correlated with MCs ($\langle N_{MCs} \rangle_{TP}$, c.c. = 0.27), but is well associated with MCLs ($\langle N_{MCLs} \rangle_{TP}$ , c.c. = 0.85). Note that the c.c. for SSN *vs.* $\langle N_{MCs} \rangle_{P2}$ is higher than that for SSN *vs.* $\langle N_{MCLs} \rangle_{P2}$. (6) Averages of IMF, solar wind speed, and density inside of the MCs are higher than those inside of the MCLs. (7) The average of MC duration (≈18.82 hours) is ≈20 % longer than the average of MCL duration (≈15.69 hours). (8) There are more MCs than MCLs in the quiet solar period, and more MCLs than MCs in the active solar period, probably due to the interaction between a MC and another significant interplanetary disturbance (including another MC) which could obviously change the character of a MC, but we speculate that some MCLs are no doubt due to other factors such as complex birth conditions at the Sun.

***Key Words: Magnetic Cloud, Magnetic Cloud-like-Structure, Geomagnetic Storm, Coronal Mass Ejection, Solar Activity, Solar Cycle***

## 1. Introduction

The magnitude, sign, and variation of the north-south component of the interplanetary magnetic field (IMF), *Bz*, when rendered in the geocentric solar-magnetospheric (GSM) coordinate system, plays a crucial role in determining the amount of solar wind energy that is transferred to the magnetosphere (*e.g.* Arnoldy, 1971; Tsurutani and Meng, 1972; Russell and McPherron, 1973; Akasofu, 1981; Akasofu *et al.*, 1985). There are three kinds of storms: i) great or intense storms: $Dst_{\min}$ (minimum *Dst*) of -100 nT or less ii) moderate storms: -50nT > $Dst_{\min}$ > -100 nT, and iii) weak storms: -30 nT > $Dst_{\min}$ > -50 nT according to the value of the geomagnetic activity index [*Dst*] (*e.g.* Tsurutani and Gonzales, 1997).

Magnetic clouds (MCs) are one of the most geoeffective (causing typically $Dst_{\min} \leq -30$ nT) interplanetary (IP) structures (*e.g.* Wu and Lepping, 2002a,b; 2008; 2011). In general, inside a MC is a region of high magnetic field strength, low proton temperature, low proton β, and smoothly changing (rotating) magnetic field (*e.g.* Burlaga *et al.*, 1981). Also important are magnetic cloud-like structures (MCLs). A MCL structure is found (initially as a candidate MC) by an automatic identification scheme (Lepping, Wu, and Berdichevsky, 2005) that uses the same criteria as for an MC, but the structure apparently is not *a simple force-free flux rope* after further examination. That is, strictly speaking, an MCL structure cannot be shown to be a flux rope by using the MC-fitting model developed by Lepping, Jones, and Burlaga (1990), although it appears *qualitatively* to be an MC according to the original definition of Burlaga et al. (1981) (see also Burlaga 1988, 1995). We consider this to be an operational definition. For example, the attempted model fitting may not properly converge (usually the main reason), or the estimated closest approach may show a value of close to, or greater than, 1.0, or the $\chi^2$ may be excessively large, or the estimated asymmetry may be unacceptably large, etc.; the details of a scheme for assessing quality of an MC fitting using the Lepping, Jones, and Burlaga (1990) fitting scheme are given by Lepping *et al.* (2006).

It would be very artificial (*i.e.* very subjective) to try to put a quality figure on an MCL-structure. Since our MC fit model cannot fit an MCL (which is part of the MCL's operational definition), we do not have the model's parameter output values for the quantities needed to assess quality of fit, as we do for MCs. For example, for *bona fide* MCs quality values of 1 (excellent), 2 (good), and 3 (poor) are assigned according to our prescription for quality-of-fit (given in Appendix A of Lepping *et al.*, 2006), which is based on various aspects of the fitting (various flags, direction of the MC's axis with respect to the Sun--Earth line, check on the reasonableness of the MC's radius, degree of asymmetry, value of the $\chi^2$ of the model fit, and similar considerations), but obtaining these is not possible for MCLs. If some other schemes were developed for the quality of MCLs, the resulting quality-values would have no relationship to the qualities derived for MCs from their prescription, and therefore could not be compared properly with those of MCs. Also, MCLs have such broad range of characteristics that to try to develop such a new quality-scheme for them would be exceedingly problematical.

On average, most MC events (≈ 90 % MCs) induce geomagnetic storms, and ≈ 39 % of MCs generate intense geomagnetic storms (*e.g.* Wu, Lepping, and Gopalswamy, 2006). Unlike MCs, only ≈ 49 % of MCLs generate geomagnetic storms, and only ≈ 8 % of MCLs generated intense geomagnetic storms (*e.g.* Wu, Lepping, and Gopalswamy, 2006). The average yearly occurrence rate is lower for MCs ($\langle N_{\mathrm{MCs}} \rangle = \approx 9.5$, where $N$ is the number of MCs) than it is for MCLs ($\langle N_{\mathrm{MCLs}} \rangle = \approx 13.6$, where $N$ is the number of the MCLs) per year for the period of 1995 - 2003 (Wu and Lepping, 2007).

Earlier studies (Wu, Lepping, and Gopalswamy, 2003, 2006) show that i) $<N_{MCs}>$ is not correlated with the occurrence frequency of solar coronal mass ejections (CMEs) [$<N_{CMEs}>$] nor with the Sunspot number (SSN), ii) the intensity of geomagnetic storms [$Dst_{min}$] for MC events is correlated well with both SSN and the $<N_{CMEs}>$, iii) the lowest occurrence rate of MCs occurred at solar minimum (Lepping *et al.* 2011), iv) the occurrence frequency of MCLs ($<N_{MCLs}>$) or that of the so-called joint set, MCs+MCLs ($<N_{MCs+MCLs}>$) is correlated well with both the SSN and the $<N_{CMEs}>$ for the period 1995 - 2003, and v) the initial finding that the Pearson correlation coefficient (c.c.) is better for SSN vs. $<N_{MCLs}>_{1995 - 2003}$ than for SSN *vs.* $<N_{MCs+MCLs}>_{1995 - 2003}$.

The *Wind* spacecraft has collected solar wind *in-situ* data for more than 19 years (1995 - 2013). It has covered two solar minima (years 1996 and 2008) and two maxima (years 2000 and 2012). This dataset provides a good opportunity for studying the effects of solar activity in various frameworks. In particular, it enables us to investigate various relevant parameters for MCs (or MCLs), the differences between MCs and MCLs, and the effects of solar activity on both MCs and MCLs. Data analysis and results are given in Section 2. Discussion and conclusions are given in Sections 3 and 4, respectively.

## 2. Data Analysis

Four data sets are used in this study. The first dataset, *Wind* solar wind plasma and magnetic field data, was obtained from the National Aeronautics and Space Administration (NASA, USA) *Wind* SWE and MFI teams (http://cdaweb.gsfc.nasa.gov/pub/data/wind). The second dataset, MCs for i) January 1995 to August 2003 is listed in Table 1 of Lepping *et al.* (2006), ii) January 2007 to December 2009 MCs are listed in Table 1 of Lepping *et al.* (2011), and iii)

2010-2012 MCs are listed in Lepping *et al.* (2012). The third dataset, MCLs for January 1995 to December 2012, is listed in Table 1.

Table 1. Solar wind parameters of MCLs that occurred during 1995 - 2012.

| CODE | YEAR | DOY1 $t_{start}$ | DOY2 $t_{end}$ | duration hours | $<B>$ nT | $<Np>$ $cm^{-3}$ | $<V>$ $km\ s^{-1}$ | $<Vth>$ $km\ s^{-1}$ | β | $BZ_{min}$ nT | $VBs_{max}$ nT | $Dst_{min}$ nT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 | 1995 | 91.69 | 92.13 | 10.57 | 8.6 | 7.7 | 386.8 | 17.9 | 0.07 | -9.35 | 6.7 | -42 |
| 002 | 1995 | 94.65 | 95.16 | 12.20 | 9.6 | 4.5 | 275.9 | 27.2 | 0.08 | -7.98 | 5.4 | -20 |
| 003 | 1995 | 181.92 | 182.51 | 14.20 | 10.3 | 8.2 | 426.5 | 21.6 | 0.09 | -6.80 | 7.6 | -56 |
| 004 | 1995 | 182.84 | 183.55 | 16.95 | 7.6 | 10.3 | 353.0 | 18.5 | 0.13 | -2.74 | 2.2 | -25 |
| 005 | 1995 | 258.66 | 259.12 | 11.15 | 11.0 | 11.2 | 427.5 | 21.1 | 0.10 | -4.26 | 6.0 | -48 |
| 006 | 1995 | 336.47 | 336.86 | 9.27 | 9.9 | 7.4 | 368.7 | 17.8 | 0.06 | -3.02 | 2.8 | -33 |
| 007 | 1996 | 357.47 | 357.86 | 9.37 | 6.6 | 4.1 | 403.7 | 33.4 | 0.23 | -6.22 | 4.1 | -33 |
| 008 | 1997 | 146.67 | 147.76 | 26.10 | 10.0 | 10.4 | 333.5 | 21.9 | 0.11 | -10.86 | 8.0 | -73 |
| 009 | 1997 | 300.64 | 301.23 | 14.18 | 7.3 | 4.8 | 449.3 | 20.8 | 0.10 | -7.38 | 5.0 | -60 |
| 010 | 1997 | 308.10 | 308.80 | 16.77 | 7.4 | 8.5 | 323.8 | 20.4 | 0.14 | -6.52 | 3.4 | -60 |
| 011 | 1997 | 319.00 | 319.83 | 19.93 | 7.9 | 5.1 | 338.3 | 23.0 | 0.10 | -5.76 | 3.4 | -60 |
| 012 | 1997 | 344.78 | 345.54 | 18.25 | 13.3 | 2.9 | 354.7 | 25.7 | 0.04 | -13.24 | 14.2 | -56 |
| 013 | 1997 | 364.74 | 365.22 | 11.53 | 12.5 | 4.4 | 369.9 | 38.9 | 0.10 | 0.83 | 2.4 | -38 |
| 014 | 1998 | 21.24 | 22.04 | 19.30 | 15.1 | 9.6 | 422.5 | 27.8 | 0.08 | -1.31 | 4.3 | -11 |
| 015 | 1998 | 29.96 | 30.96 | 24.03 | 8.0 | 8.4 | 374.5 | 17.6 | 0.09 | -7.86 | 5.4 | -55 |
| 016 | 1998 | 48.42 | 48.86 | 10.60 | 12.2 | 10.5 | 401.4 | 21.5 | 0.07 | -13.54 | 14.9 | -100 |
| 017 | 1998 | 49.14 | 49.50 | 8.65 | 17.3 | 18.2 | 390.0 | 29.1 | 0.11 | -9.65 | 13.6 | -43 |
| 018 | 1998 | 49.93 | 50.33 | 9.60 | 10.5 | 2.1 | 416.7 | 29.6 | 0.05 | -3.99 | 5.3 | -43 |
| 019 | 1998 | 99.25 | 99.67 | 10.17 | 7.5 | 4.4 | 320.3 | 22.3 | 0.10 | -4.22 | 2.4 | -8 |
| 020 | 1998 | 101.87 | 103.17 | 31.12 | 9.1 | 4.9 | 386.9 | 21.8 | 0.07 | -7.93 | 4.4 | -46 |
| 021 | 1998 | 105.54 | 105.97 | 10.30 | 7.1 | 6.0 | 323.4 | 19.4 | 0.10 | -2.31 | 3.1 | -5 |
| 022 | 1998 | 127.53 | 127.89 | 8.68 | 10.0 | 4.8 | 495.8 | 27.2 | 0.09 | 0.00 | 2.3 | -42 |
| 023 | 1998 | 176.98 | 177.32 | 8.15 | 13.0 | 9.9 | 472.0 | 31.3 | 0.13 | -14.13 | 13.6 | -55 |
| 024 | 1998 | 192.62 | 193.24 | 14.93 | 12.0 | 3.2 | 389.1 | 28.0 | 0.04 | -9.38 | 7.0 | -35 |
| 025 | 1998 | 218.07 | 218.49 | 10.13 | 13.1 | 19.5 | 387.5 | 22.8 | 0.13 | -18.32 | 22.6 | -138 |
| 026 | 1998 | 224.23 | 224.87 | 15.38 | 7.3 | 9.2 | 369.3 | 19.2 | 0.14 | -0.65 | 2.1 | -6 |
| 027 | 1998 | 225.63 | 226.22 | 14.33 | 8.4 | 2.8 | 335.0 | 22.6 | 0.05 | -4.06 | 3.1 | -12 |
| 028 | 1998 | 229.05 | 230.08 | 24.85 | 7.5 | 1.6 | 293.7 | 21.3 | 0.03 | -4.25 | 2.9 | -7 |
| 029 | 1998 | 239.24 | 239.87 | 15.12 | 14.1 | 2.7 | 608.1 | 48.6 | 0.07 | -14.72 | 35.2 | -67 |
| 030 | 1999 | 26.95 | 27.39 | 10.55 | 7.1 | 8.2 | 347.6 | 18.4 | 0.12 | -6.49 | 4.1 | 1 |
| 031 | 1999 | 44.89 | 45.70 | 19.45 | 8.9 | 6.1 | 438.9 | 26.0 | 0.12 | -8.22 | 8.3 | 1 |
| 032 | 1999 | 116.81 | 117.39 | 13.92 | 10.2 | 1.0 | 410.0 | 46.1 | 0.06 | -7.45 | 6.0 | 1 |
| 033 | 1999 | 153.98 | 154.94 | 23.05 | 9.2 | 5.3 | 427.8 | 26.8 | 0.11 | -0.52 | 1.8 | -6 |
| 034 | 1999 | 177.42 | 177.80 | 9.13 | 14.3 | 16.6 | 344.8 | 30.5 | 0.17 | -7.03 | 8.5 | -6 |
| 035 | 1999 | 266.56 | 266.90 | 8.15 | 6.9 | 2.1 | 524.5 | 22.5 | 0.05 | -3.51 | 3.2 | -27 |
| 036 | 1999 | 292.94 | 293.89 | 22.80 | 6.7 | 7.2 | 353.3 | 19.1 | 0.13 | -0.90 | 1.0 | -46 |
| 037 | 1999 | 294.40 | 294.82 | 10.08 | 18.8 | 8.5 | 464.4 | 39.8 | 0.08 | -12.48 | 20.6 | -46 |
| 038 | 1999 | 325.36 | 325.71 | 8.53 | 9.9 | 9.2 | 376.3 | 28.8 | 0.17 | -6.65 | 5.9 | -20 |
| 039 | 1999 | 326.09 | 326.56 | 11.28 | 12.6 | 6.2 | 460.9 | 30.7 | 0.09 | -4.29 | 4.6 | -20 |
| 040 | 1999 | 327.29 | 327.82 | 12.75 | 8.8 | 2.7 | 452.9 | 23.2 | 0.04 | -5.97 | 6.7 | -38 |
| 041 | 1999 | 327.92 | 328.30 | 9.20 | 11.0 | 5.0 | 452.5 | 23.8 | 0.06 | -4.07 | 5.7 | -38 |
| 042 | 1999 | 332.95 | 333.35 | 9.57 | 7.9 | 3.9 | 398.1 | 30.0 | 0.13 | -5.59 | 5.2 | 2 |
| 043 | 1999 | 333.58 | 334.03 | 10.78 | 8.4 | 6.9 | 378.1 | 27.5 | 0.16 | -4.26 | 5.4 | 2 |
| 044 | 1999 | 348.28 | 348.86 | 13.92 | 10.4 | 2.9 | 434.1 | 31.4 | 0.05 | -1.77 | 3.7 | -92 |
| 045 | 1999 | 360.35 | 361.00 | 15.60 | 8.2 | 6.2 | 411.3 | 28.5 | 0.17 | -3.92 | 6.4 | 10 |
| 046 | 2000 | 22.74 | 23.12 | 9.12 | 18.4 | 7.3 | 321.8 | 46.3 | 0.11 | -16.36 | 28.4 | -40 |
| 047 | 2000 | 24.21 | 24.78 | 13.68 | 16.8 | 5.8 | 347.1 | 51.4 | 0.12 | -14.38 | 25.7 | -40 |
| 048 | 2000 | 61.15 | 61.62 | 11.10 | 8.8 | 5.1 | 501.2 | 22.6 | 0.09 | -8.05 | 10.2 | -43 |
| 049 | 2000 | 68.60 | 69.06 | 11.05 | 8.2 | 5.2 | 439.5 | 34.8 | 0.19 | -6.65 | 5.4 | -40 |
| 050 | 2000 | 79.74 | 80.23 | 11.87 | 9.5 | 7.4 | 359.3 | 21.8 | 0.09 | -1.77 | 1.8 | -1 |
| 051 | 2000 | 88.41 | 89.74 | 31.92 | 8.6 | 1.7 | 385.8 | 31.3 | 0.05 | -5.37 | 3.6 | -60 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 052 | 2000 | 91.18 | 92.25 | 25.63 | 7.5 | 9.3 | 380.8 | 17.4 | 0.11 | -8.16 | 6.3 | -60 |
| 053 | 2000 | 128.10 | 129.28 | 28.30 | 9.6 | 6.8 | 390.6 | 20.3 | 0.08 | -2.09 | 3.1 | -6 |
| 054 | 2000 | 149.88 | 150.30 | 10.10 | 7.8 | 9.1 | 339.2 | 20.0 | 0.13 | -6.75 | 5.3 | -38 |
| 055 | 2000 | 190.58 | 191.12 | 12.95 | 6.9 | 3.9 | 374.0 | 28.3 | 0.15 | -5.40 | 3.0 | -44 |
| 056 | 2000 | 194.06 | 195.19 | 27.12 | 9.8 | 2.7 | 505.0 | 24.1 | 0.04 | -2.51 | 4.4 | -44 |
| 057 | 2000 | 223.80 | 224.33 | 12.60 | 13.6 | 3.6 | 425.1 | 20.5 | 0.03 | -24.83 | 44.6 | -106 |
| 058 | 2000 | 233.84 | 234.27 | 10.37 | 7.5 | 6.4 | 328.8 | 23.0 | 0.14 | -7.48 | 4.8 | -31 |
| 059 | 2000 | 236.73 | 237.10 | 8.87 | 11.0 | 5.5 | 300.6 | 26.9 | 0.08 | -0.83 | 1.6 | -20 |
| 060 | 2000 | 246.58 | 246.97 | 9.35 | 9.1 | 3.2 | 440.4 | 35.8 | 0.11 | -5.14 | 5.4 | -36 |
| 061 | 2000 | 248.92 | 249.48 | 13.45 | 8.4 | 8.7 | 404.0 | 23.4 | 0.15 | -4.37 | 3.8 | -36 |
| 062 | 2000 | 255.68 | 256.03 | 8.52 | 8.5 | 8.5 | 349.3 | 19.4 | 0.10 | -2.66 | 2.3 | 4 |
| 063 | 2000 | 262.78 | 263.16 | 9.12 | 8.0 | 1.7 | 685.6 | 37.6 | 0.08 | -5.25 | 14.4 | 4 |
| 064 | 2000 | 304.46 | 305.02 | 13.43 | 10.3 | 5.8 | 359.0 | 21.4 | 0.06 | -8.63 | 6.8 | -40 |
| 065 | 2000 | 332.86 | 333.21 | 8.48 | 7.6 | 7.7 | 544.5 | 25.4 | 0.18 | -4.37 | 6.3 | -46 |
| 066 | 2000 | 338.55 | 339.03 | 11.55 | 9.6 | 4.6 | 430.2 | 33.2 | 0.12 | -6.25 | 5.1 | -30 |
| 067 | 2000 | 362.01 | 362.54 | 12.70 | 8.6 | 6.0 | 402.4 | 20.3 | 0.08 | -5.99 | 4.2 | 2 |
| 068 | 2000 | 363.07 | 363.41 | 8.08 | 8.4 | 4.4 | 347.1 | 24.6 | 0.10 | -3.50 | 3.4 | -19 |
| 069 | 2000 | 364.80 | 365.24 | 10.62 | 8.8 | 5.6 | 375.1 | 20.2 | 0.07 | -7.46 | 3.9 | -19 |
| 070 | 2001 | 103.56 | 104.43 | 21.02 | 8.7 | 2.9 | 729.7 | 24.6 | 0.05 | -5.05 | 13.1 | -77 |
| 071 | 2001 | 108.72 | 110.24 | 36.40 | 8.0 | 3.9 | 441.4 | 22.5 | 0.07 | -4.89 | 9.1 | -114 |
| 072 | 2001 | 114.30 | 114.71 | 9.82 | 10.7 | 5.1 | 400.8 | 49.8 | 0.23 | -7.71 | 6.5 | -102 |
| 073 | 2001 | 114.96 | 115.42 | 11.05 | 8.2 | 3.4 | 430.7 | 33.8 | 0.13 | -5.49 | 5.0 | -102 |
| 074 | 2001 | 127.92 | 128.45 | 12.62 | 7.9 | 4.6 | 356.4 | 17.8 | 0.06 | -4.36 | 3.7 | -21 |
| 075 | 2001 | 129.71 | 130.45 | 17.95 | 7.8 | 5.4 | 444.4 | 17.4 | 0.06 | -8.35 | 6.8 | -76 |
| 076 | 2001 | 144.12 | 145.24 | 26.88 | 8.8 | 1.3 | 493.7 | 54.2 | 0.11 | -5.02 | 5.1 | -28 |
| 077 | 2001 | 157.88 | 158.41 | 12.78 | 7.3 | 6.0 | 383.1 | 25.5 | 0.16 | -4.39 | 3.3 | 3 |
| 078 | 2001 | 158.71 | 159.27 | 13.37 | 8.5 | 10.1 | 389.8 | 16.9 | 0.10 | -0.10 | 1.3 | -7 |
| 079 | 2001 | 170.03 | 170.59 | 13.43 | 16.0 | 1.5 | 420.9 | 54.1 | 0.04 | -1.38 | 6.2 | -7 |
| 080 | 2001 | 229.96 | 230.63 | 16.10 | 16.0 | 10.4 | 545.8 | 24.9 | 0.06 | -0.14 | 8.3 | -17 |
| 081 | 2001 | 257.03 | 257.44 | 9.83 | 13.2 | 11.1 | 422.7 | 29.6 | 0.14 | 2.15 | 0.4 | -17 |
| 082 | 2001 | 282.89 | 283.36 | 11.28 | 7.4 | 3.2 | 421.0 | 37.7 | 0.18 | -3.31 | 2.7 | -43 |
| 083 | 2001 | 300.06 | 300.60 | 12.97 | 7.6 | 2.1 | 389.5 | 25.1 | 0.06 | -6.13 | 4.9 | -27 |
| 084 | 2001 | 308.78 | 309.35 | 13.70 | 8.4 | 5.6 | 343.4 | 18.8 | 0.07 | -1.46 | 2.8 | -31 |
| 085 | 2001 | 320.08 | 320.45 | 8.88 | 15.8 | 10.6 | 338.0 | 38.2 | 0.14 | -7.49 | 8.0 | -31 |
| 086 | 2001 | 347.01 | 348.55 | 36.95 | 7.6 | 10.8 | 302.0 | 16.3 | 0.11 | -5.95 | 5.7 | -25 |
| 087 | 2001 | 350.44 | 351.16 | 17.27 | 9.3 | 4.2 | 499.2 | 36.4 | 0.15 | -6.31 | 6.6 | -25 |
| 088 | 2001 | 361.80 | 362.54 | 17.77 | 8.8 | 11.8 | 359.3 | 17.6 | 0.10 | -4.24 | 2.4 | -15 |
| 089 | 2001 | 362.66 | 363.21 | 13.23 | 7.5 | 15.3 | 361.9 | 14.3 | 0.12 | 0.85 | 0.6 | 3 |
| 090 | 2001 | 364.18 | 364.79 | 14.62 | 17.5 | 9.9 | 402.6 | 36.9 | 0.08 | -6.89 | 10.9 | 3 |
| 091 | 2002 | 1.35 | 2.37 | 24.58 | 7.1 | 3.3 | 425.6 | 28.1 | 0.11 | -4.79 | 4.9 | -48 |
| 092 | 2002 | 8.71 | 9.69 | 23.47 | 9.2 | 4.4 | 370.1 | 36.3 | 0.15 | -5.15 | 3.7 | -48 |
| 093 | 2002 | 9.74 | 10.11 | 8.88 | 7.8 | 5.4 | 347.5 | 30.9 | 0.18 | -6.06 | 3.9 | -48 |
| 094 | 2002 | 11.28 | 11.89 | 14.63 | 8.0 | 3.9 | 613.3 | 34.4 | 0.17 | -6.30 | 9.5 | -48 |
| 095 | 2002 | 61.87 | 62.36 | 11.77 | 10.3 | 5.5 | 397.6 | 37.4 | 0.16 | -3.96 | 4.0 | -48 |
| 096 | 2002 | 95.15 | 95.52 | 8.87 | 6.3 | 4.0 | 410.8 | 19.3 | 0.09 | -4.05 | 3.0 | -48 |
| 097 | 2002 | 102.03 | 102.58 | 13.28 | 9.6 | 8.4 | 436.8 | 21.2 | 0.09 | -8.88 | 7.1 | -10 |
| 098 | 2002 | 105.41 | 105.88 | 11.45 | 8.4 | 6.8 | 342.0 | 26.2 | 0.15 | -7.04 | 5.9 | -18 |
| 099 | 2002 | 116.58 | 116.99 | 9.90 | 8.4 | 5.0 | 394.7 | 26.2 | 0.11 | -7.45 | 6.0 | -8 |
| 100 | 2002 | 128.29 | 129.13 | 20.12 | 8.6 | 4.1 | 363.2 | 22.8 | 0.07 | -5.57 | 6.4 | -29 |
| 101 | 2002 | 143.11 | 143.49 | 9.13 | 15.2 | 13.0 | 441.9 | 36.5 | 0.15 | -9.41 | 26.7 | -24 |
| 102 | 2002 | 162.59 | 163.33 | 17.72 | 7.7 | 5.2 | 387.8 | 29.6 | 0.17 | -4.65 | 3.3 | -27 |
| 103 | 2002 | 216.84 | 217.59 | 18.00 | 8.1 | 5.2 | 447.1 | 32.1 | 0.18 | -3.39 | 4.2 | -102 |
| 104 | 2002 | 231.78 | 232.18 | 9.60 | 8.4 | 3.7 | 492.7 | 16.4 | 0.04 | -9.60 | 10.4 | -71 |
| 105 | 2002 | 251.92 | 253.53 | 38.57 | 9.0 | 3.8 | 456.5 | 22.2 | 0.05 | -6.66 | 6.2 | -79 |
| 106 | 2002 | 253.54 | 253.93 | 9.37 | 9.3 | 5.6 | 406.9 | 21.5 | 0.07 | -8.90 | 8.2 | -82 |
| 107 | 2002 | 266.10 | 266.68 | 13.92 | 8.1 | 2.0 | 404.2 | 29.6 | 0.06 | -3.41 | 2.7 | -15 |
| 108 | 2002 | 272.12 | 272.70 | 14.08 | 12.0 | 16.2 | 299.9 | 18.3 | 0.10 | 1.47 | 1.4 | 13 |
| 109 | 2002 | 276.73 | 277.84 | 26.60 | 10.5 | 5.7 | 413.6 | 23.6 | 0.07 | -11.91 | 12.0 | -146 |
| 110 | 2002 | 314.33 | 314.75 | 10.08 | 15.2 | 12.6 | 366.7 | 32.4 | 0.12 | 0.73 | 4.0 | -30 |
| 111 | 2002 | 321.64 | 323.01 | 33.03 | 9.5 | 6.0 | 389.3 | 21.2 | 0.07 | -9.19 | 8.1 | -30 |
| 112 | 2003 | 11.35 | 11.84 | 11.75 | 8.0 | 3.2 | 436.0 | 31.8 | 0.12 | -3.79 | 3.2 | 3 |
| 113 | 2003 | 13.75 | 14.21 | 10.85 | 10.8 | 7.2 | 394.0 | 23.5 | 0.07 | -8.43 | 5.5 | -1 |
| 114 | 2003 | 26.91 | 27.66 | 18.00 | 10.3 | 3.8 | 536.0 | 20.3 | 0.04 | -3.61 | 4.4 | -1 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 115 | 2003 | 31.79 | 32.71 | 22.12 | 10.4 | 0.9 | 468.4 | 63.3 | 0.09 | -3.48 | 6.2 | -1 |
| 116 | 2003 | 118.61 | 119.17 | 13.43 | 10.2 | 1.6 | 402.2 | 44.3 | 0.10 | -5.60 | 8.0 | -13 |
| 117 | 2003 | 129.52 | 129.94 | 10.08 | 8.4 | 2.0 | 757.6 | 43.7 | 0.12 | -7.63 | 10.2 | -13 |
| 118 | 2003 | 130.61 | 130.98 | 8.90 | 6.8 | 1.7 | 577.6 | 29.8 | 0.09 | -6.61 | 7.0 | -13 |
| 119 | 2003 | 196.40 | 196.82 | 10.08 | 8.7 | 4.1 | 566.4 | 29.2 | 0.11 | -7.12 | 10.5 | -31 |
| 120 | 2003 | 202.30 | 203.27 | 23.28 | 7.1 | 1.5 | 455.2 | 34.7 | 0.07 | -4.59 | 3.6 | -31 |
| 121 | 2003 | 206.46 | 206.92 | 11.02 | 9.2 | 13.5 | 320.1 | 18.4 | 0.13 | -3.54 | 3.1 | -31 |
| 122 | 2003 | 274.95 | 275.77 | 19.67 | 17.2 | 4.0 | 330.2 | 35.5 | 0.04 | -10.02 | 15.3 | -28 |
| 123 | 2004 | 79.02 | 79.44 | 10.05 | 7.1 | 6.5 | 326.1 | 25.0 | 0.17 | -6.28 | 3.5 | -20 |
| 124 | 2004 | 123.46 | 123.89 | 10.37 | 8.2 | 5.1 | 389.8 | 23.5 | 0.10 | -0.18 | 1.2 | -6 |
| 125 | 2004 | 149.50 | 149.90 | 9.68 | 7.7 | 6.3 | 391.2 | 29.5 | 0.14 | -7.37 | 5.0 | -17 |
| 126 | 2004 | 165.67 | 166.60 | 22.33 | 9.9 | 12.0 | 354.6 | 19.7 | 0.11 | -10.14 | 9.1 | -28 |
| 127 | 2004 | 177.49 | 178.38 | 21.42 | 8.4 | 2.7 | 332.9 | 26.0 | 0.06 | -0.64 | 1.2 | 2 |
| 128 | 2004 | 205.73 | 206.22 | 11.73 | 7.8 | 5.8 | 504.2 | 14.9 | 0.05 | -2.39 | 3.5 | -75 |
| 129 | 2004 | 230.62 | 230.96 | 8.07 | 10.7 | 8.6 | 342.4 | 22.2 | 0.08 | -9.63 | 7.5 | -13 |
| 130 | 2004 | 256.00 | 257.90 | 45.53 | 10.0 | 1.6 | 296.0 | 28.8 | 0.03 | -8.75 | 16.2 | -12 |
| 131 | 2004 | 315.10 | 315.70 | 14.38 | 20.0 | 6.1 | 699.4 | 22.7 | 0.02 | -28.65 | 96.3 | -289 |
| 132 | 2004 | 333.19 | 333.53 | 8.05 | 7.2 | 8.7 | 388.1 | 23.6 | 0.19 | -5.63 | 3.5 | -61 |
| 133 | 2004 | 345.22 | 345.89 | 16.15 | 8.3 | 6.9 | 416.2 | 23.0 | 0.12 | -3.72 | 2.5 | -42 |
| 134 | 2004 | 348.17 | 348.58 | 9.90 | 13.2 | 4.5 | 393.0 | 28.6 | 0.06 | -2.61 | 4.3 | -61 |
| 135 | 2004 | 362.68 | 364.11 | 34.35 | 7.4 | 4.9 | 441.1 | 19.5 | 0.07 | -7.07 | 5.7 | -60 |
| 136 | 2005 | 7.62 | 8.15 | 12.53 | 17.5 | 15.9 | 535.3 | 21.7 | 0.07 | -11.96 | 18.9 | -96 |
| 137 | 2005 | 8.86 | 9.41 | 13.17 | 9.0 | 4.6 | 467.1 | 18.4 | 0.05 | 2.70 | 0.5 | -50 |
| 138 | 2005 | 16.68 | 17.06 | 9.10 | 9.2 | 8.8 | 539.4 | 21.8 | 0.11 | -7.73 | 6.4 | -70 |
| 139 | 2005 | 47.51 | 47.98 | 11.28 | 12.5 | 8.1 | 390.3 | 29.8 | 0.10 | -8.26 | 13.0 | -55 |
| 140 | 2005 | 136.27 | 138.96 | 64.72 | 7.1 | 0.8 | 535.8 | 27.0 | 0.03 | -5.79 | 6.5 | -116 |
| 141 | 2005 | 149.28 | 149.70 | 10.08 | 16.6 | 8.1 | 475.4 | 26.9 | 0.06 | 1.44 | 5.4 | -46 |
| 142 | 2005 | 173.46 | 173.95 | 11.75 | 7.5 | 11.7 | 318.3 | 15.4 | 0.11 | -6.88 | 3.3 | -7 |
| 143 | 2005 | 192.63 | 193.35 | 17.30 | 10.1 | 3.5 | 424.9 | 24.4 | 0.05 | -8.95 | 9.3 | -85 |
| 144 | 2005 | 245.85 | 246.22 | 8.83 | 9.2 | 4.1 | 642.3 | 24.3 | 0.07 | -4.40 | 7.1 | -41 |
| 145 | 2005 | 347.00 | 347.55 | 13.02 | 7.0 | 2.5 | 408.3 | 28.2 | 0.09 | -3.86 | 2.3 | -85 |
| 146 | 2005 | 359.02 | 359.35 | 8.05 | 8.0 | 13.0 | 349.8 | 19.2 | 0.17 | -8.26 | 5.0 | -59 |
| 147 | 2006 | 25.17 | 25.68 | 12.25 | 7.8 | 3.7 | 413.8 | 19.9 | 0.06 | -3.59 | 7.3 | -1 |
| 148 | 2006 | 45.27 | 45.76 | 11.60 | 7.2 | 7.4 | 326.3 | 20.4 | 0.13 | -0.15 | 0.8 | 7 |
| 149 | 2006 | 191.83 | 192.72 | 21.35 | 10.4 | 10.5 | 367.7 | 21.6 | 0.11 | -0.73 | 2.5 | -23 |
| 150 | 2006 | 230.69 | 231.07 | 9.15 | 9.6 | 11.1 | 388.0 | 22.8 | 0.14 | -1.96 | 3.7 | -4 |
| 151 | 2006 | 232.59 | 233.37 | 18.70 | 8.9 | 2.4 | 401.6 | 21.1 | 0.03 | -1.99 | 2.6 | -41 |
| 152 | 2006 | 242.88 | 243.72 | 20.13 | 7.7 | 8.6 | 406.7 | 17.6 | 0.12 | -5.58 | 3.9 | -17 |
| 153 | 2006 | 243.87 | 244.26 | 9.22 | 7.3 | 6.0 | 380.9 | 24.8 | 0.15 | -4.60 | 2.9 | -34 |
| 154 | 2006 | 322.31 | 323.31 | 24.07 | 8.9 | 0.8 | 399.2 | 26.6 | 0.02 | -6.65 | 4.1 | -14 |
| 155 | 2006 | 323.41 | 324.15 | 17.67 | 8.0 | 2.7 | 395.9 | 24.2 | 0.06 | -3.47 | 2.8 | -5 |
| 156 | 2006 | 324.24 | 324.88 | 15.43 | 7.2 | 0.7 | 372.6 | 27.6 | 0.03 | -1.79 | 1.7 | -6 |
| 157 | 2006 | 333.71 | 334.45 | 17.75 | 11.2 | 8.2 | 410.1 | 19.8 | 0.06 | -10.07 | 9.4 | -74 |
| 158 | 2008 | 221.59 | 221.99 | 9.60 | 7.3 | 6.1 | 358.1 | 21.3 | 0.13 | -0.31 | 1.0 | 1 |
| 159 | 2010 | 38.96 | 40.23 | 30.68 | 8.8 | 5.1 | 360.6 | 23.8 | 0.07 | -3.54 | 2.9 | -23 |
| 160 | 2010 | 46.00 | 46.93 | 22.27 | 8.9 | 8.3 | 307.9 | 17.5 | 0.07 | -11.23 | 6.4 | -58 |
| 161 | 2010 | 68.68 | 69.31 | 15.03 | 7.9 | 7.4 | 366.1 | 21.0 | 0.11 | 0.07 | 1.2 | 0 |
| 162 | 2010 | 102.06 | 102.56 | 11.92 | 11.5 | 9.9 | 407.3 | 16.9 | 0.05 | -0.51 | 2.7 | -51 |
| 163 | 2010 | 138.18 | 138.65 | 11.35 | 6.7 | 6.2 | 358.0 | 22.3 | 0.16 | -5.98 | 3.2 | -31 |
| 164 | 2010 | 138.68 | 139.37 | 16.42 | 9.5 | 12.4 | 353.3 | 22.3 | 0.15 | 2.43 | 1.5 | -23 |
| 165 | 2010 | 204.89 | 205.36 | 11.25 | 9.2 | 9.4 | 379.0 | 25.4 | 0.14 | -0.35 | 1.8 | 2 |
| 166 | 2010 | 244.03 | 244.92 | 21.22 | 7.2 | 7.9 | 338.3 | 19.3 | 0.13 | -4.52 | 2.6 | -1 |
| 167 | 2010 | 258.14 | 258.65 | 12.38 | 8.4 | 7.4 | 366.2 | 26.0 | 0.16 | -0.53 | 1.7 | -23 |
| 168 | 2010 | 258.87 | 259.28 | 9.90 | 7.5 | 5.1 | 368.9 | 20.0 | 0.10 | -2.71 | 1.1 | -9 |
| 169 | 2011 | 75.48 | 76.54 | 25.40 | 7.3 | 3.7 | 381.6 | 26.5 | 0.11 | -3.85 | 2.3 | -1 |
| 170 | 2011 | 89.02 | 91.44 | 58.15 | 11.5 | 3.0 | 341.8 | 20.6 | 0.03 | -7.75 | 6.1 | -5 |
| 171 | 2011 | 113.32 | 114.46 | 27.35 | 7.8 | 4.0 | 398.3 | 23.0 | 0.08 | -4.17 | 2.2 | -8 |
| 172 | 2011 | 181.79 | 182.23 | 10.40 | 7.7 | 11.3 | 329.7 | 18.4 | 0.16 | -8.43 | 4.8 | -34 |
| 173 | 2011 | 279.55 | 280.01 | 11.12 | 10.5 | 8.8 | 371.2 | 23.2 | 0.10 | 0.20 | 2.3 | -12 |
| 174 | 2012 | 2.65 | 3.20 | 13.05 | 9.6 | 8.6 | 386.5 | 26.1 | 0.14 | -8.94 | 6.4 | -26 |
| 175 | 2012 | 22.89 | 24.07 | 28.25 | 7.2 | 5.3 | 428.1 | 22.2 | 0.11 | -11.78 | 17.0 | -73 |
| 176 | 2012 | 24.19 | 24.62 | 10.50 | 9.2 | 4.4 | 401.2 | 18.8 | 0.04 | -1.66 | 6.0 | -35 |
| 177 | 2012 | 45.86 | 46.71 | 20.32 | 8.4 | 5.3 | 384.4 | 17.0 | 0.05 | -8.67 | 6.4 | -62 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 178 | 2012 | 46.82 | 47.16 | 8.13 | 8.5 | 5.9 | 368.8 | 26.1 | 0.13 | -8.46 | 6.4 | -58 |
| 179 | 2012 | 60.30 | 60.98 | 16.53 | 7.0 | 6.1 | 452.5 | 20.4 | 0.11 | -2.06 | 2.3 | -7 |
| 180 | 2012 | 95.84 | 96.38 | 13.08 | 8.2 | 5.7 | 335.0 | 17.1 | 0.07 | -8.49 | 5.4 | -56 |
| 181 | 2012 | 96.77 | 97.93 | 27.85 | 9.6 | 9.8 | 340.8 | 23.0 | 0.13 | -9.68 | 7.1 | -14 |
| 182 | 2012 | 112.06 | 112.48 | 9.98 | 7.2 | 8.1 | 313.9 | 19.3 | 0.13 | -0.82 | 1.1 | 3 |
| 183 | 2012 | 125.14 | 125.79 | 15.52 | 7.5 | 4.0 | 318.1 | 20.7 | 0.07 | -2.68 | 1.9 | -8 |
| 184 | 2012 | 127.35 | 127.76 | 9.82 | 9.1 | 4.3 | 308.0 | 29.0 | 0.11 | -6.09 | 3.0 | -2 |
| 185 | 2012 | 155.00 | 155.47 | 11.12 | 8.7 | 8.2 | 331.7 | 15.2 | 0.05 | -8.09 | 4.9 | 2 |
| 186 | 2012 | 176.65 | 177.19 | 13.05 | 7.3 | 7.3 | 361.9 | 21.0 | 0.14 | -5.93 | 3.5 | 13 |
| 187 | 2012 | 211.69 | 212.05 | 8.75 | 8.4 | 6.1 | 355.3 | 27.7 | 0.16 | -4.00 | 3.6 | -4 |
| 188 | 2012 | 212.76 | 213.18 | 10.10 | 7.7 | 3.9 | 417.8 | 29.0 | 0.12 | -4.25 | 5.0 | -28 |
| 189 | 2012 | 231.81 | 232.34 | 12.82 | 11.1 | 8.4 | 386.1 | 20.6 | 0.07 | 3.83 | 1.3 | -25 |
| 190 | 2012 | 245.33 | 246.24 | 21.92 | 7.0 | 4.4 | 323.3 | 14.8 | 0.04 | -6.76 | 3.0 | -20 |
| 191 | 2012 | 246.25 | 247.39 | 27.40 | 7.8 | 9.3 | 312.3 | 18.6 | 0.12 | -8.64 | 7.8 | -76 |
| 192 | 2012 | 249.25 | 249.74 | 11.73 | 11.1 | 5.4 | 507.7 | 24.8 | 0.07 | -1.26 | 6.1 | -68 |
| 193 | 2012 | 250.10 | 250.66 | 13.58 | 9.7 | 2.1 | 424.2 | 20.9 | 0.02 | -5.05 | 2.6 | -35 |
| 194 | 2012 | 281.36 | 282.10 | 17.87 | 8.4 | 6.4 | 327.0 | 18.0 | 0.07 | -5.80 | 4.4 | -18 |
| 195 | 2012 | 282.72 | 283.65 | 22.25 | 15.4 | 4.5 | 393.5 | 20.8 | 0.03 | -15.98 | 21.0 | -111 |
| 196 | 2012 | 286.67 | 287.40 | 17.63 | 9.8 | 2.9 | 483.3 | 27.0 | 0.05 | -11.51 | 11.7 | -91 |
| 197 | 2012 | 305.99 | 307.14 | 27.63 | 11.2 | 10.1 | 342.9 | 16.4 | 0.04 | -11.84 | 9.7 | -62 |
| Average | | | | 15.69 | 9.6 | 6.3 | 404.8 | 25.6 | 0.10 | -5.70 | 6.7 | -35 |

From left to right of Table 1 are: (1) the code number of MCL, (2) the year that the MCL occurred, (3) the start time of the MCL, (4) the end time of the MCL, (5) the duration of the MCL (in hours) (6) the average of magnetic field, <*B*> (in nT), (7) the average of solar wind proton density, <*Np*> (in no/cc), (8) the average of solar wind velocity, <*V*> (in km $s^{-1}$), (9) the average of solar wind thermal speed, <*Vth*> (in km $s^{-1}$), (10) the average of plasma β, (11) the minimum Bz ($Bz_{min}$, in nT) within the MCL, (12) the maximum *VBs* ($VBs_{max}$) within the MCL, and (13) the related minimum *Dst* ($Dst_{min}$, in nT) within the MCL event.

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(a) MC on March 04, 1995 (b) MCL on January 07, 2005

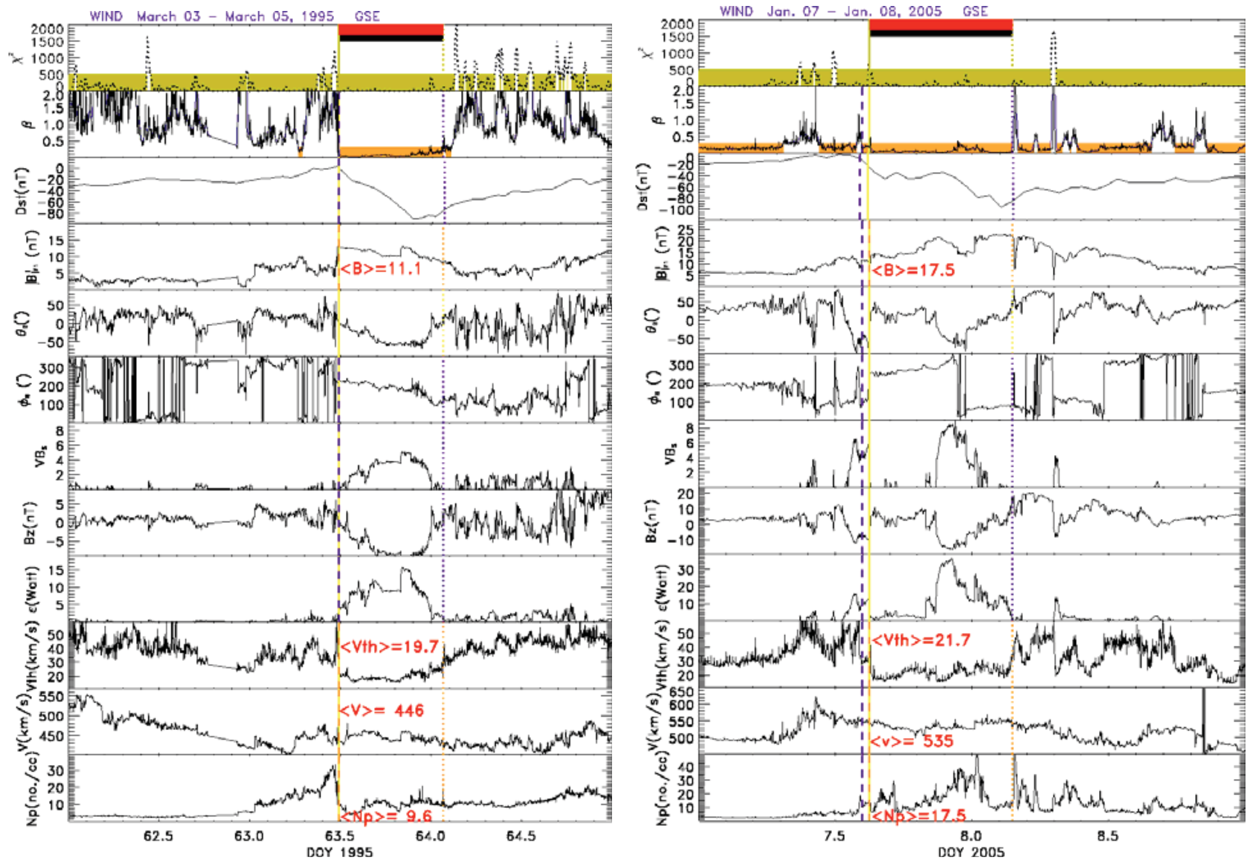


Figure 1. (a) An example of a magnetic cloud (MC) that was observed on 04 March 1995, and (b) a magnetic cloud-like structure (MCL) that was observed on 07 January 2005. From top to bottom: $\chi^2$ of quadratic fit to latitude of the field ($\theta_B$), running average of proton plasma β. *Dst*, magnetic field [*B*] in terms of magnitude [|B|], latitude [$\theta_B$] and longitude [$\phi_B$] in GSE coords., induced electric field [*VBs*], *Bz* of the field in GSE, solar-wind-magnetosphere energy coupling function [ε, see Akasofu, 1981], proton plasma thermal speed [*Vth*], bulk speed [*V*], and number density [*Np*]. The red-horizontal bar in the top panel represents the scheme's identification of the extent of this MC candidate (Lepping *et al.*, 2005). The vertical yellow-dashed line and blue-dotted line represent front and rear boundaries as found by an MC automatic identification model. Averages of *Np*, *V*, *Vth*, and B for MC/MCL are provided in red in each panel.

The fourth dataset, the *Dst*, was obtained from both the National Geophysical data Center, Boulder, Colorado, USA and Kyoto University, Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/dstdir/). The fifth dataset, the sunspot number (SSN), was provided by the World Data Center SILSO of the Royal Observatory of Belgium (ISN); and data access is provided by NOAA/NGDC.

### 2.1 Selection of MC and MCL Events

As well as using visual inspection, we used a program that can identify MC/MCL events automatically (Lepping, Wu, and Berdichevsky, 2005) to the magnetic field and plasma data, to search for MC/MCL candidates. Then we applied the least-squares MC model-fitting procedure (Lepping, Jones, and Burlaga 1990) to these candidates to verify the MCs and find their characteristics. Those events that are not *bona-fide* MCs are called MCLs. Figure 1 shows an example of an MC (left panel, Figure 1a) and an example of an MCL (right panel, Figure 1b). Both the MC and the MCL have induced a severe geomagnetic storm.

The $Dst_{\mathrm{min}}$ is slightly more intense for the MCL (≈ -100 nT) than for the MC (≈ -90nT), which is caused by a stronger $Bz_{\mathrm{min}}$ in the MCL. Figure 1a clearly shows that the MC is the result of an isolated solar disturbance (or event) that apparently did not interact with any other kind of interplanetary structure (*e.g.* heliosphere current sheet (*e.g.* Blanco *et al.*, 2011), co-rotating interaction region (*e.g.* Rouillard *et al.*, 2009), interplanetary coronal mass ejection (*e.g.* Temmer *et al.*, 2014), or interplanetary shock (*e.g.* Collier, Lepping, and Berdichevsky, 2007). The direction of the IMF changed smoothly from the front boundary to the end boundary of the MC, and an obvious shock occurred ≈0.5 day ahead of the MC’s front boundary and was apparently driven by the MC.

Figure 1b shows a different situation: there was no clear shock in front of the MCL, the direction of the IMF did not change smoothly, the peak of *B* was near the rear boundary of the

MCL, and several low-β structures (areas marked in orange on the second panel from top of Figure 1b) were either in the front or at the end of the MCL. It seems that the main body of the MCL may be interacting with another kind of interplanetary disturbance before the MCL (or MC) arrived at 1 AU.

In this study seven different periods will be studied according to solar activity (Total Period (TP) during 1995-2012, first and second half period during 1995 - 2003 (P1) and 2004 - 2012 (P2), Quiet periods during 1995 - 1997 (Q1) and 2007 - 2009 (Q2), and Active periods during 1998-2006 (A1) and 2010 - 2012 (A2)]. During 1995-2012 (TP), we have identified 168 MCs [Lepping et al., 2012] and 197 MCLs. Details of the related solar wind parameters of these 197 MCLs are listed in Table 1.

Figure 2a shows the yearly occurrence frequency of MCs ($N_{MCs}$, black-solid line) and MCLs ($N_{MCLs}$, red-dotted line). During 1995 - 2012 (total period, TP), the average occurrence rates of MCs and MCLs are $\langle N_{MCs}\rangle_{TP} = 9.3$ and $\langle N_{MCLs}\rangle_{TP} = 10.9$, respectively. Overall, in the lower solar activity periods more MCs are identified than MCLs. By contrast, more MCLs than MCs are identified in higher solar activity periods. For example, at solar minimum between Solar Cycles 22 and 23 (in 1996), 4 MCs are observed but only one MCL is found. At solar minimum between Solar Cycle 23 and 24 (or during 2007 - 2009) only one MCL was identified in 2008, and no MCL was found in 2007 or 2009. By comparison, 5, 1, and 12 MCs were identified in 2007, 2008, and 2009, respectively. Figure 2b shows the yearly averages of the geomagnetic storm intensities that were associated with the MCs or MCL events. On average, the intensity of storms [$Dst_{min}$] associated with MC events is stronger than for MCLs. (Note that a geomagnetic storm might be driven by an MC/MCL itself or by the upstream sheath fields of the structure (Lepping and Berdichevsky, 2000), if an upstream shock is present.) The average of $Dst_{min}$ ($<Dst_{min}>_{MC}$ = -70 nT) for MC-associated storms is almost two times stronger than that associated with the MCL events ($<Dst_{min}>_{MCL}$ = -35 nT) , when the total period is considered.

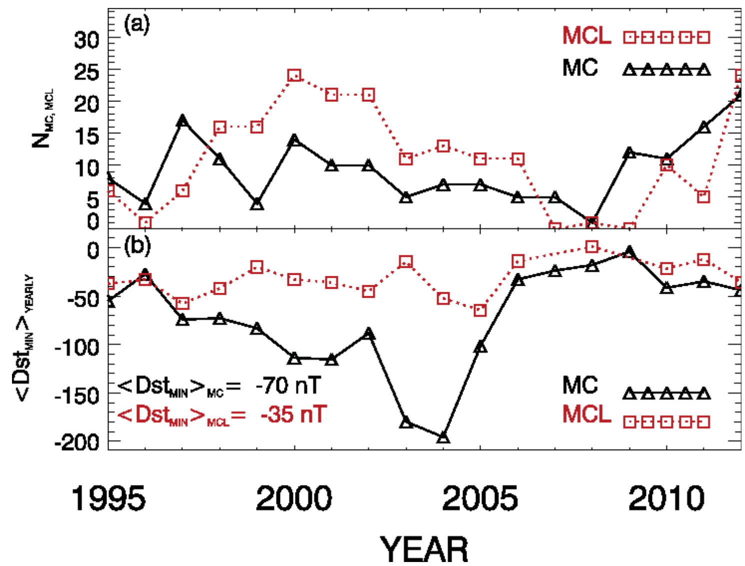


Figure 2. (a) Yearly occurrence frequency of magnetic clouds (MCs) and MC-like structures (MCLs), and (b) Yearly averages of the geomagnetic storm intensity [$<Dst_{min}>$] which is associated with either the MC or MCL events.

Figure 3 shows the yearly occurrence frequency of SSN, MCs, MCLs, and the joint set (MCs+MCLs) for 1995 - 2012. Correlation coefficients (c.c.s) between the SSN and the occurrence frequency of MCs, MCLs, and MCs+MCLs are 0.27, 0.85, and 0.74, respectively. This result is consistent with previous studies (*e.g.* Wu, Lepping, and Gopalswamy, 2006).

We catalog both MCs and MCLs in terms of yearly averages for different kinds of parameters. Figure 4 shows histograms of the characteristics for MCs and MCLs during 1995 - 2012. Figures 4(a - h) show solar wind density, velocity, thermal speed (or temperature), magnetic field, duration of MCs/MCLs, $Bz_{min}$, $\varepsilon_{max}$, and associated $Dst_{min}$. Overall, Figures 4(a - h) show that density is smaller, velocity is slower, thermal speed (or temperature) is higher, magnetic field is weaker, duration is shorter (or size is smaller), and $Bz_{min}$, $VBs_{max}$, and $Dst_{min}$ are all weaker for MCLs than for MCs.

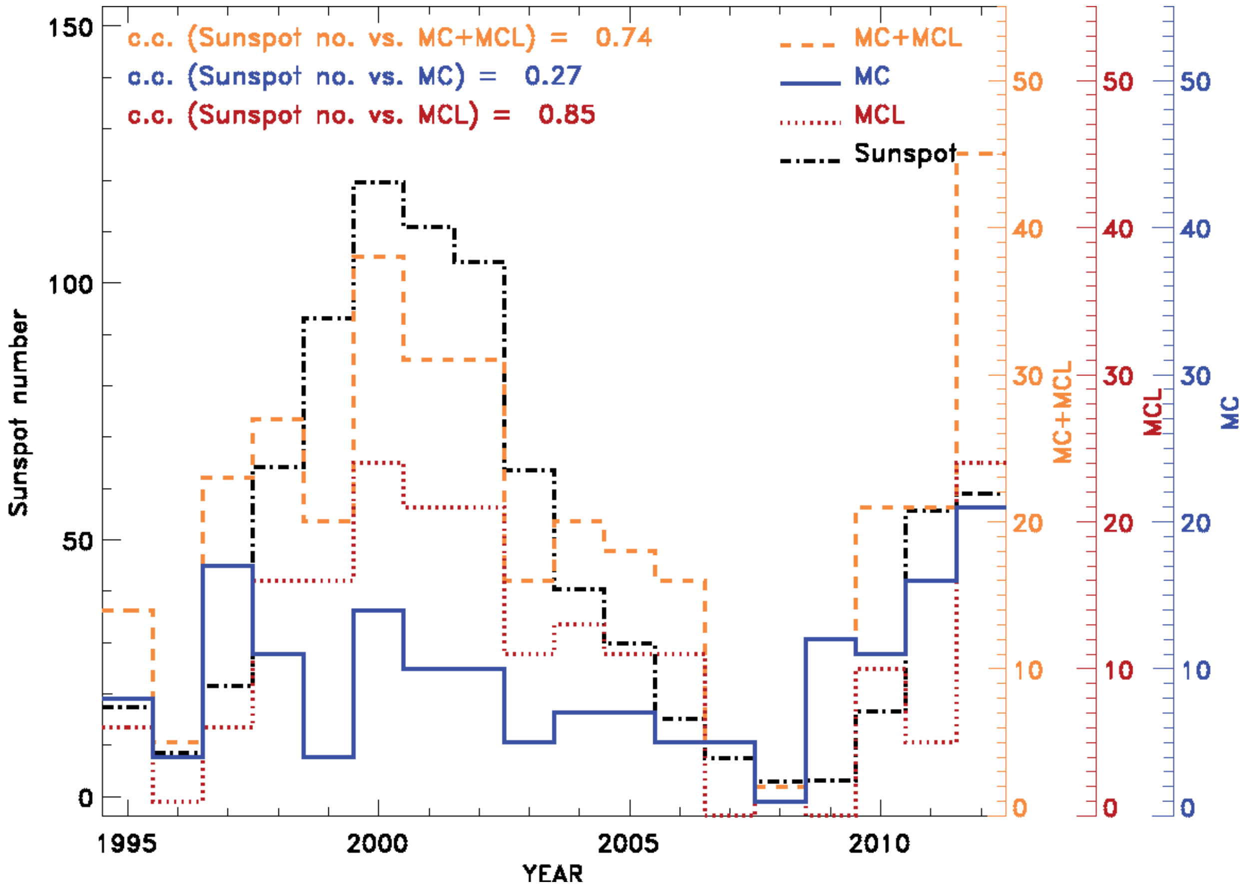


Figure 3. Yearly occurrence frequency of sunspot number (black-dot-dashed line), MCs (blue-solid line), MCLs (red-dotted line), and joint set (MCs+MCLs, orange-dashed line).

Figure 5 shows yearly averages of various solar wind parameters of MCs and MCLs that occurred during 1995 - 2012. Average values of parameters for MCs and MCLs (<MC> or <MCL>), are marked at the top of each panel in Figure 5, and they are also summarized in Table 2. Table 3 lists the averages of solar wind parameters of the MCs and MCLs that occurred in 1995 - 2012. On average, the speed of the MCs is ≈ 8 % faster than the speed of MCLs. The density of the MCs is 23 % higher than MCLs' density. The thermal speed (or temperature) of the MCs is ≈ 3 % lower than the thermal speed of the MCLs. The magnetic field of the MCs is ≈ 21 % stronger than that of MCLs.

Table 2. Yearly averages of solar wind parameters for MCLs (top) and MCs (bottom) that occurred during 1995 - 2012, and overall averages at bottom of each set.

| Year | $N_{MCL}$ | *B* | *Vth* | *V* | *Np* | β | ε | *VBs* | *Bx* | *By* | *Bz* | Δt [hrs] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1995 | 6 | 8.6 | 17.9 | 386 | 7.7 | 0.07 | 5.37 | 3.04 | -1.24 | 0.54 | -7.87 | 10.58 |
| 1996 | 1 | 9.6 | 27.2 | 275 | 4.5 | 0.08 | 2.43 | 0.61 | -7.43 | 2.42 | -1.61 | 12.20 |
| 1997 | 6 | 10.3 | 21.6 | 426 | 8.2 | 0.09 | 3.60 | 1.28 | -0.16 | -6.84 | -1.31 | 14.20 |
| 1998 | 16 | 7.6 | 18.5 | 353 | 10.3 | 0.13 | 0.61 | 0.06 | 1.73 | -6.19 | 2.19 | 16.95 |
| 1999 | 16 | 11.0 | 21.1 | 427 | 11.2 | 0.10 | 0.86 | 0.10 | -0.44 | 7.53 | 5.30 | 11.17 |
| 2000 | 24 | 9.9 | 17.9 | 368 | 7.4 | 0.06 | 1.31 | 0.10 | -2.68 | 8.68 | 1.89 | 9.28 |
| 2001 | 21 | 6.6 | 33.4 | 403 | 4.1 | 0.23 | 3.06 | 1.50 | 4.59 | -0.69 | -3.67 | 9.35 |
| 2002 | 21 | 10.0 | 21.9 | 333 | 10.4 | 0.11 | 4.36 | 1.82 | 2.93 | -3.24 | -5.42 | 26.08 |
| 2003 | 11 | 7.3 | 20.8 | 449 | 4.8 | 0.10 | 2.53 | 1.31 | 3.03 | -0.03 | -1.59 | 14.17 |
| 2004 | 13 | 7.4 | 20.4 | 323 | 8.5 | 0.14 | 1.31 | 0.55 | -2.11 | 5.75 | -0.92 | 16.78 |
| 2005 | 11 | 7.9 | 22.9 | 338 | 5.1 | 0.10 | 1.57 | 0.59 | 0.21 | 7.29 | -1.54 | 19.87 |
| 2006 | 11 | 13.3 | 25.7 | 354 | 2.9 | 0.04 | 9.60 | 3.09 | 4.98 | -7.15 | -8.59 | 18.25 |
| 2007 | 0 | 12.5 | 38.9 | 370 | 4.4 | 0.10 | 0.31 | 0.00 | 3.95 | 6.78 | 8.24 | 11.52 |
| 2008 | 1 | 15.1 | 27.8 | 422 | 9.5 | 0.08 | 0.44 | 0.01 | 11.34 | 3.12 | 7.47 | 19.30 |
| 2009 | 0 | 8.0 | 17.6 | 374 | 8.4 | 0.09 | 3.14 | 1.67 | 3.42 | -3.58 | -4.16 | 24.03 |
| 2010 | 10 | 12.2 | 21.5 | 401 | 10.5 | 0.07 | 9.73 | 3.44 | -3.80 | 5.31 | -8.32 | 10.60 |
| 2011 | 5 | 17.3 | 29.1 | 390 | 18.3 | 0.11 | 4.11 | 0.08 | 7.22 | -14.74 | 2.87 | 8.65 |
| 2012 | 24 | 10.5 | 29.8 | 416 | 2.1 | 0.05 | 0.37 | 0.07 | 3.02 | -4.17 | 7.41 | 9.60 |
| Average | | 9.6 | 25.6 | 405 | 6.3 | 0.10 | 2.56 | 0.72 | | | | 15.69 |

| Year | $N_{MC}$ | *B* | *Vth* | *V* | *Np* | β | ε | *VBs* | *Bx* | *By* | *Bz* | Δt [hrs] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1995 | 8 | 11.1 | 23.4 | 406 | 8.5 | 0.09 | 4.29 | 1.39 | 2.36 | 8.35 | -1.85 | 19.00 |
| 1996 | 4 | 10.4 | 22.3 | 443 | 10.3 | 0.21 | 6.73 | 2.21 | -5.75 | -0.82 | -4.49 | 17.00 |
| 1997 | 17 | 9.0 | 22.4 | 301 | 3.7 | 0.06 | 0.98 | 0.17 | -6.39 | 3.61 | 2.62 | 27.00 |
| 1998 | 11 | 8.3 | 19.6 | 333 | 15.1 | 0.18 | 0.32 | 0.06 | 5.54 | 1.14 | 3.53 | 10.50 |
| 1999 | 4 | 10.2 | 19.9 | 328 | 13.3 | 0.25 | 0.00 | 0.00 | 2.82 | 1.61 | 9.41 | 5.50 |
| 2000 | 14 | 9.5 | 22.4 | 359 | 12.3 | 0.17 | 4.02 | 1.70 | -2.79 | -5.86 | -4.41 | 22.00 |
| 2001 | 10 | 21.2 | 27.0 | 406 | 13.1 | 0.04 | 15.17 | 3.21 | 6.24 | -10.77 | -1.34 | 29.50 |
| 2002 | 10 | 10.6 | 24.7 | 398 | 12.7 | 0.21 | 1.57 | 0.19 | 5.63 | 7.44 | 1.72 | 17.00 |
| 2003 | 5 | 10.1 | 22.4 | 368 | 15.9 | 0.17 | 1.75 | 0.65 | -2.92 | 6.15 | 1.82 | 40.00 |
| 2004 | 7 | 11.0 | 22.4 | 353 | 18.1 | 0.19 | 2.38 | 0.78 | -2.39 | 7.71 | 0.90 | 17.00 |
| 2005 | 7 | 6.6 | 23.0 | 345 | 8.4 | 0.23 | 1.72 | 0.88 | 2.21 | -4.03 | -2.37 | 22.50 |
| 2006 | 5 | 10.4 | 21.6 | 349 | 11.4 | 0.11 | 1.21 | 0.26 | -4.35 | 6.04 | 3.08 | 32.48 |
| 2007 | 5 | 14.5 | 20.2 | 437 | 13.3 | 0.05 | 8.41 | 2.31 | -5.04 | -7.13 | -1.57 | 21.00 |
| 2008 | 1 | 7.9 | 24.8 | 456 | 1.1 | 0.03 | 5.49 | 2.93 | 3.76 | -0.71 | -6.46 | 15.00 |
| 2009 | 12 | 18.7 | 31.1 | 462 | 13.6 | 0.17 | 0.19 | 0.08 | 2.39 | 1.82 | 16.38 | 13.50 |
| 2010 | 11 | 11.5 | 29.0 | 360 | 12.8 | 0.20 | 2.56 | 0.61 | 6.12 | -5.37 | 1.09 | 40.00 |
| 2011 | 16 | 19.8 | 26.6 | 461 | 6.3 | 0.06 | 21.47 | 3.88 | -7.40 | 11.34 | -7.03 | 16.00 |
| 2012 | 21 | 7.8 | 34.0 | 489 | 3.7 | 0.21 | 1.07 | 0.45 | 0.00 | -4.73 | 2.47 | 7.80 |
| Average | | 12.3 | 24.8 | 440 | 8.1 | 0.11 | 5.78 | 1.37 | | | | 18.82 |

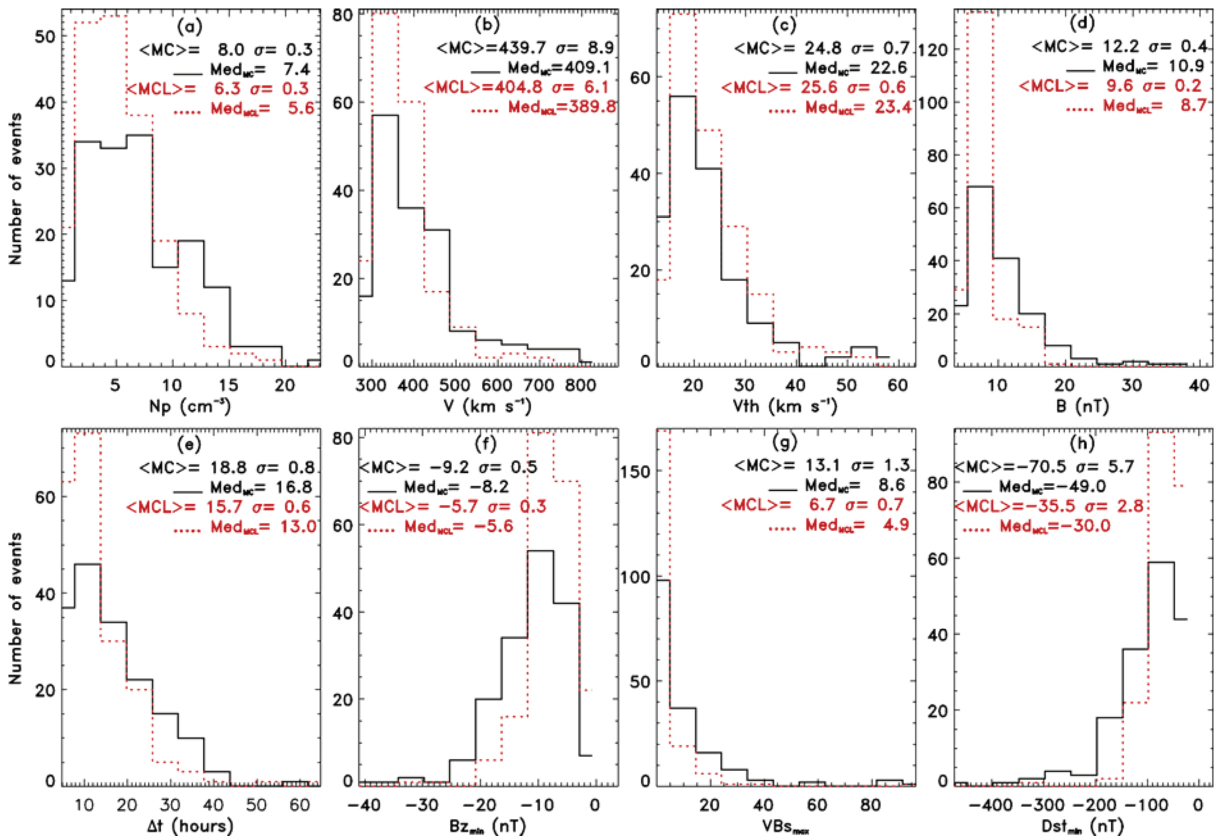


Figure 4. Histograms of solar wind properties for MCs and MCLs during 1995 - 2012. Black-solid lines and red-dotted lines represent MCs and MCLs, respectively. Values of the mean (<MC> or <MCL>), standard deviation [σ], and median [Med] for both MC and MCL are marked at the top of each panel.

Table 3. Averages of solar wind parameters of MCs and MCLs that occurred in 1995 - 2012

| | *N* | *Np* | *V* | Vth | *B* | β | $Bz_{min}$ | ΔT | $Dst_{min}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | [$cm^{-3}$] | [$km\ s^{-1}$] | [$km\ s^{-1}$] | [ nT] | | [ nT] | [Hours] | [nT] |
| MCs | 9.3 | 8.00 | 440 | 24.8 | 12.2 | 0.11 | -9.2 | 18.84 | -70 |
| MCLs | 10.9 | 6.29 | 405 | 25.6 | 9.6 | 0.10 | -5.7 | 15.69 | -35 |
| Ratio [%] MCLs/MCs | 117 | 77 | 92 | 103 | 79 | 91 | 62 | 83 | 50 |

Average proton plasma β for MCs is 9 % higher than that for MCLs. Average $Bz_{min}$ for MCs is 38 % stronger than it is for MCLs. Average duration [ΔT] of the MCs is 17 % longer than it is for MCLs. Overall, the solar wind parameters for the MCLs are weaker (or smaller) than they are for MCs, except the occurrence frequency: $\langle N_{MCLs}\rangle_{TP}$ is ≈17 % higher than for

$<N_{MCs}>_{TP}$. Table 3 shows the averages of solar wind parameters for both MCs and MCLs, and $<N_{MCs}>_{TP}$ and $<N_{MCLs}>_{TP}$.

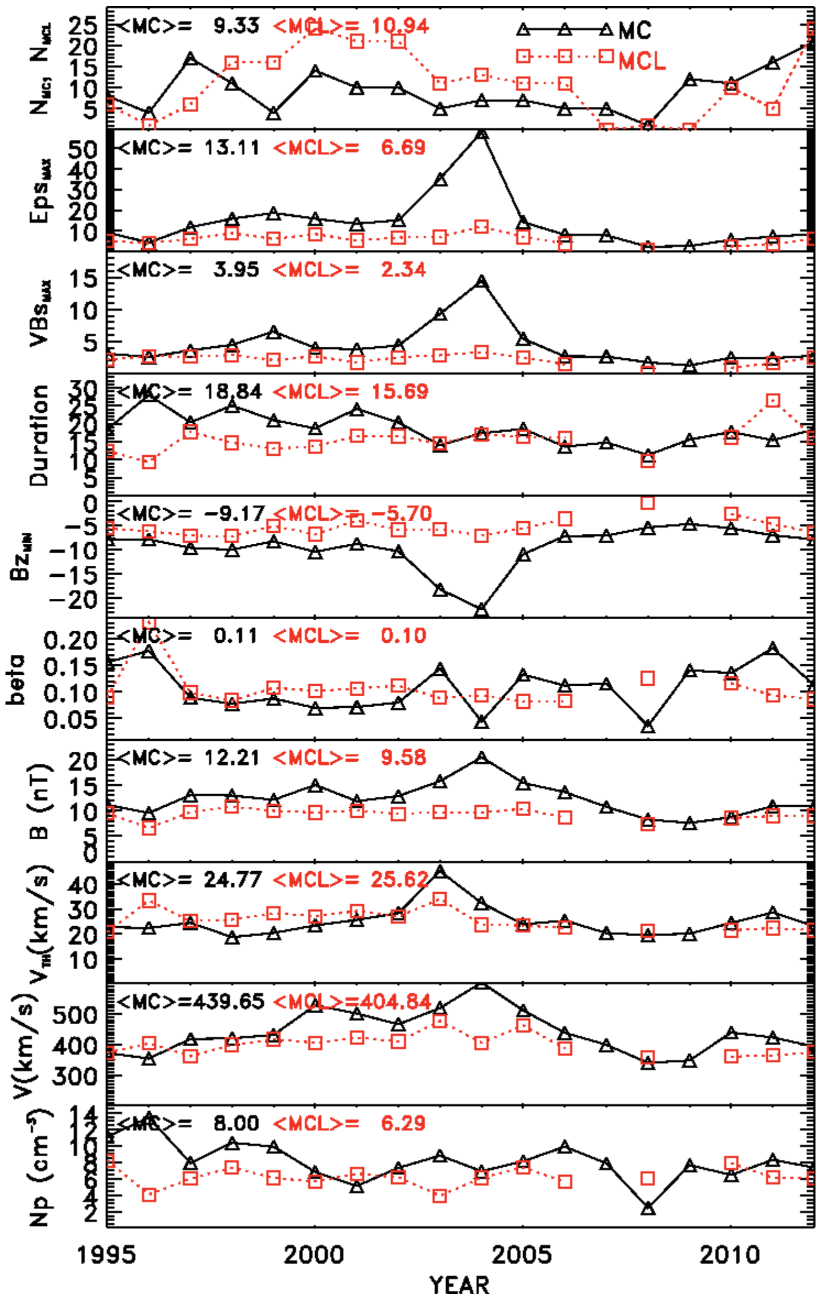


Figure 5. Yearly averages of solar wind parameters within an MC (black-solid-triangle lines) and an MCL (red-dashed-square lines) identified during 1995 - 2012.

## 3. Discussion

The results of this study show that the yearly occurrence frequency of MCL, $<N_{MCL}>_{TP}$ =10.9, is higher than that for MCs, $<N_{MC}>_{TP}$ =9.3. This is consistent with our previous study (Wu, Lepping, and Gopalswamy, 2006). $<N_{MCL}>_{P1}$ is ≈ 31 % higher than $<N_{MC}>_{P1}$. $<N_{MC}>_{TP}$ is 9.3, which is almost the same as $<N_{MC}>_{P1}$ (= 9.5). $<N_{MC}>_{TP}$ is 2 % less than $<N_{MC}>_{P1}$. In contrast, only 75 MCLs were identified during 2004 - 2012 (P2): $<N_{MCL}>_{yearly}$ dropped ≈ 39 % (*i.e.* $<N_{MCL}>_{P1}$ = 13.6 and $<N_{MCL}>_{P2}$ = 8.3). This is caused by the extremely low occurrence rate of MCLs during 2007 - 2009; no MCL was found in 2007 or 2009, and only one MCL occurred in 2008.

### 3.1 *What Caused the Extremely Low $<N_{MCL}>$ Rate During 2007 - 2009?*

This study shows some interesting results: $<N_{MC}>_{yearly}$ is *higher* than $<N_{MCL}>_{yearly}$ in the low solar activity period (*e.g.* 1995 - 1997, 2007 - 2009 or Q1, Q2), but $<N_{MC}>_{yearly}$ is *lower* than $<N_{MCL}>_{yearly}$ in the high solar-activity period (*e.g.* 1998 - 2006, 2010 - 2012 or A1, A2). In the solar minimum (or the low solar activity period), the solar wind was quieter and the heliospheric current sheet (HCS) was flatter, and fewer solar disturbances (*e.g.* coronal mass ejections, CMEs or solar flares, filaments …etc.) were ejected than in the high solar-activity period (periods A1 or A2). A solar disturbance can propagate all the way to the Earth without interacting with a HCS or any other solar disturbance (*e.g.* an ICME) during the solar minimum. Therefore, MCs have a higher chance of keeping their original characteristics at 1 AU in the minimum periods than at the maximum ones. At solar maximum, more solar disturbances were ejected from the Sun, and the tilt angle of the HCS was larger than at solar minimum. (Note, the tilt angle of the HCS is larger at solar maximum than at the solar minimum (*e.g.* Riley *et al.*, 2011)). Therefore, while MCs propagate all the way to 1 AU, the chance is higher for MCs to interact with another kind of solar wind disturbance. The interaction between an MC and another solar disturbance can obviously change the character of a MC. For example, the average duration of the MCs is reduced, the orientation of the magnitude field was changed after the interaction, and an MC may become an MCL after possible interactions with other structures (*e.g.* heliosphere current sheet (*e.g.* Blanco *et al.*, 2011), co-rotating interaction region (*e.g.* Rouillard *et al.*, 2009), interplanetary coronal mass ejection (*e.g.* Temmer *et al.*, 2014), or interplanetary shock (*e.g.* Collier, Lepping, and Berdichevsky, 2007)). Therefore, we expect there to be more MCs than MCLs in the quiet solar period, and more MCLs than MCs in active solar period. This does not mean, however, that MCLs are produced only by interactions with other interplanetary structures (more on this in Section 3.5)

In contrast, the chances are higher for an ICME to interact with a HCS or another CME at solar maximum, and this may result in a shorter ICME (which can become an MCL). Hence, at solar maximum more MCLs than MCs were identified, but the opposite is true at solar minimum. This may also explain why there was an anomaly with regard to $\langle N_{\mathrm{MC}} \rangle$ in 1997 ($N_{\mathrm{MC}}$ =17) and 2009 ($N_{\mathrm{MC}}$=12): In both cases $N_{\mathrm{MC}}$ is higher than in its previous year and also one year after (See Table 2). In the solar active periods (1998 - 2006 and 2010 - 2012), due to the higher CME rate and a non-quiet background solar wind, the rate of interaction between ICMEs and HCS is higher. This caused $\langle N_{\mathrm{MCL}} \rangle_{\mathrm{A1,A2}}$ to be greater than $\langle N_{\mathrm{MCs}} \rangle_{\mathrm{A1,A2}}$, and the average duration of MCLs to be shorter than that for the MCs.

Our previous study (See Figure 1 of Lepping and Wu, 2011) showed that the occurrence frequency of MCs in two adjacent solar minima was symmetric: 8, 4, 17 MCs were found in 1995, 1996, 1997; and 5, 1, 12 MCs were found in 2007, 2008, 2009, respectively. However, MCLs have no such relationship: 11, 0, 8 MCLs were identified in 1995, 1996, 1997, respectively; and 0, 1, 0 MCL was found in 2007, 2008, 2009, respectively.

An interaction between two solar wind structures will usually change the characteristics of those structures. Observations show that a CME--CME interaction could accelerate the slow CME and decelerate the fast CME (Temmer *et al.*, 2014). A fast CME overtaking a slow CME could result in an enhancement of radio emissions (Gopalswamy *et al.*, 2001). Using global three-dimensional magnetohydrodynamic (MHD) simulation, a CME-CME interaction has been studied for the famous Halloween epoch during October - November 2003 (*e.g.* Wu *et al.*, 2007; 2012). ICME erosion could proceed while the ICME is propagating from the Sun into the heliosphere, which has been studied by using both MHD simulation (*e.g.* Manchester *et al.*, 2014) and observations (*e.g.* Ruffenach *et al.*, 2012). The interaction between MCs and the heliospheric current sheet at 1 AU has been observed by a single spacecraft (*e.g.* Blanco *et al.*, 2011). These kinds of interactions may erode the characteristics of the MCs.

### 3.2 Anomaly of Occurrence Frequency of MCs/MCLs

Using the first nine years of data (1995 - 2003), our earlier studies showed that the occurrence frequency of MCs appeared to be unrelated to the sunspot number, but both the occurrence frequency of MCLs and the joint set (MCs+MCLs) were well correlated with sunspot number (*e.g.* Wu, Lepping, and Gopalswamy, 2003, 2006). Any apparent inconsistencies can be explained by the following.

This study, for which we use twice as long a data set (1995 - 2012) as our earlier study study (Wu, Lepping, and Gopalswamy, 2006) and which covers two solar minima, gives results consistent with the previous study. In order to understand the relationship between SSN and

$N_{MCs}$, $N_{MCLs}$ , and the joint set [$N_{MCs}$+$N_{MCLs}$], the plots (SSN *vs*. <$N_{MCs}$, $N_{MCLs}$, or $N_{MCs+MCLs}$ >$_{yearly}$) for different periods (PT, P1, and P2) are shown, *i.e.* Figures 6a, d, g is for 1995 - 2012, Figures 6b, e, h is for 1995 - 2003, and Figures 6c,f,i is for 2004 - 2012. The correlation coefficients (c.c.) and $N_{TOTAL}$ are denoted at the top of each panel. Detailed information is listed in Table 4. Note that since 2003, *Wind* has collected solar wind data for eleven more years, ten of which are included here. This provides a good opportunity for performing a statistical study for a longer interval (*e.g.* approximately twice as long as the previous study of Wu, Lepping, and Gopalswamy (2006)). Both P1 and P2 periods cover one solar maximum, one solar minimum, and one ascending phase.

Table 4. Correlation coefficients (cc) between yearly SSN and occurrence frequency of MCs, MCLs, and the joint set during different solar activity periods.

| | PT[1] | P1[2] | P2[3] | Q1+Q2[4] | A1+A2[5] | Q3+Q4[6] | A3+A4[7] |
|---|---|---|---|---|---|---|---|
| c.c. for SSN *vs*. $N_{MC}$ | 0.27 | 0.13 | 0.72 | 0.62 | 0.16 | 0.39 | 0.48 |
| c.c. for SSN *vs*. $N_{MCL}$ | **0.85** | **0.97** | 0.71 | **0.84** | **0.71** | **0.83** | **0.66** |
| c.c. for SSN *vs*. $N_{MC}$ +$N_{MCL}$ | 0.74 | 0.84 | **0.81** | 0.81 | 0.55 | 0.77 | 0.47 |

[1]1995 - 2012.[2]1995 - 2003(P1). [3]2004 - 2012(P2). [4]1995 - 1997(Q1) and 2007 - 2009(Q2). [5]1998 - 2006(A1) and 2010 - 2012(A2). [6]1995 - 1998(Q3) and 2006 - 2010(Q4). [7]1999 - 2005(A3) and 2011 - 2012(A4).

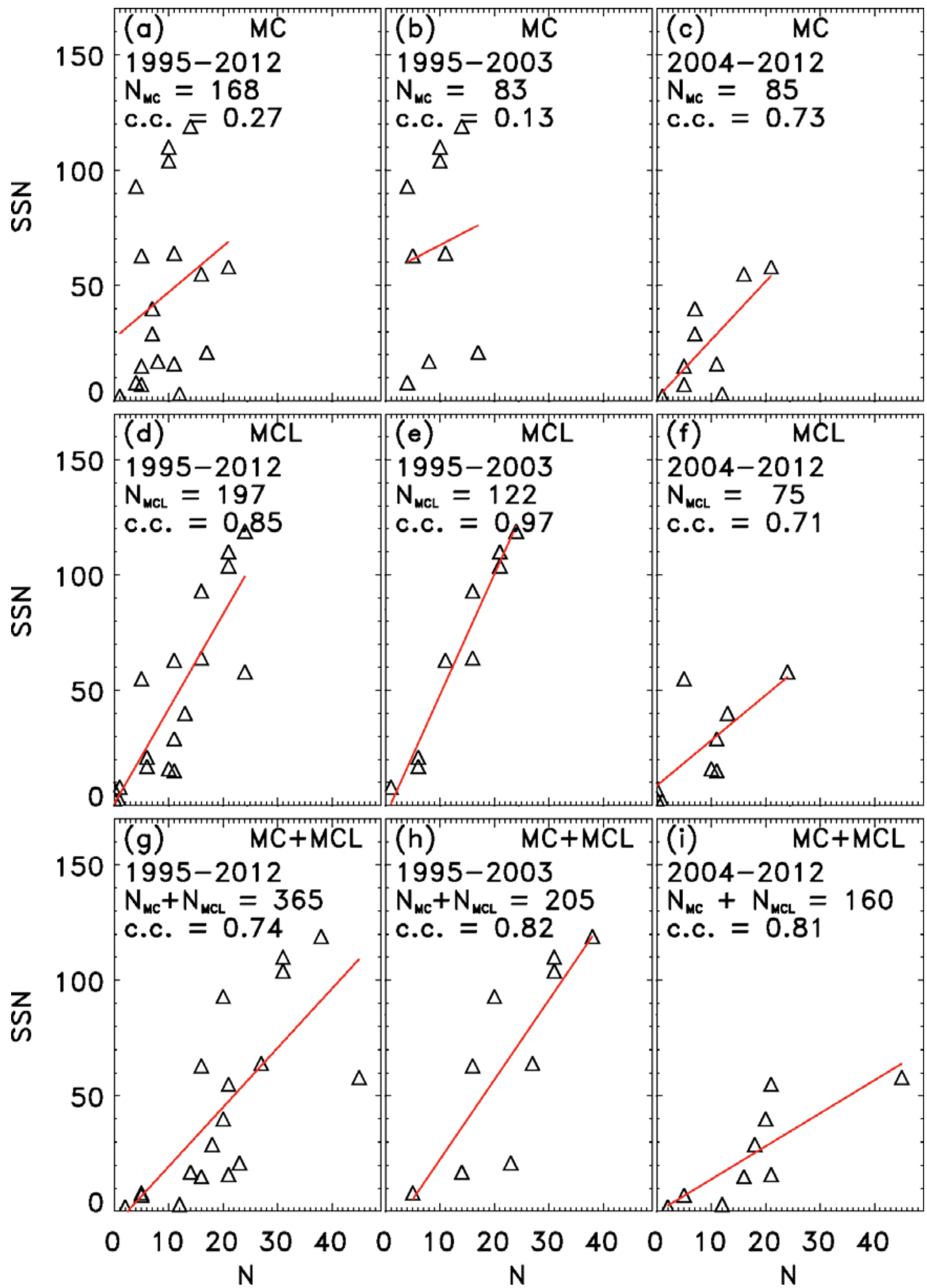


**Figure 6.** Distribution for SSN *vs.* $N_{MC}$, $N_{MCL}$, and $N_{MC+MCL}$ in different periods: 1995 - 2012 (a, d, g), 1995 - 2003 (b, e, h), and 2004 - 2012 (c, f, i). Correlation coefficients (c.c.) and total number of $N_{MC}$, $N_{MCL}$, and $N_{MC+MCL}$ are denoted in the top of each panel.

The c.c.s for SSN *vs.* $N_{MC}$ were poor, *i.e.* 0.13 and 0.27, for the periods of 1995 - 2003 and 1995 - 2012, respectively, but the c.c. was good for the period of 2004 - 2012 (*i.e.* 0.72). The poor correlations for P1 and PT are due to the low occurrence rate in the solar maximum of Cycle 23 (in 2000) and the anomaly in 1997 (unusual high rate compared with the nearby period). During 2004 - 2012, the anomaly in 2009 does not cause a low correlation for SSN *vs.* $N_{MC}$ because the occurrence rates are also high during 2010 - 2012. We do not know the reason for the high $N_{MC}$ during 2010 - 2012. Understanding this requires further investigation and is beyond the scope of this study. All other c.c. values in Table 4 are significant. The c.c. for SSN *vs*. $N_{MCL}$ decreased 27 %, from 0.97 to 0.71 for the periods of 1995 - 2003 and 1995 - 2012, respectively. The decrease of c.c. for SSN *vs.* $N_{MCL}$ may be due to the zero occurrence frequency in both 2007 and 2009, or the low c.c (0.71) during 2004 - 2012.

It would be useful to know the relationship between solar activity (*e.g.* solar minima/active periods) and the occurrence frequency of MCs/MCLs. In Table 4, Columns 5 and 6 list the c.c.s of SSN *vs.* $N_{MC}$, $N_{MCL}$, and $N_{MC}$+$N_{MCL}$ for different solar activate periods: Q1+Q2 and A1+A2. The c.c. is clearly higher for quiet periods than for active periods. In order to find the trend of solar activity *vs.* occurrence frequency of MC/MCL, we extended the minima to five years: Q3 for 1995 - 1998 (note no *Wind* data are available for 1994), and Q4 for 2006 - 2010; and reduced the active periods: A3 for 1999 - 2005 and A4 for 2011 - 2012. For MCLs, the c.c. is better in quiet periods than in active periods. But for MCs, the c.c. is higher in active periods than in quiet periods (See Columns 7 and 8).

For MCLs, the best c.c. (0.97) occurred during 1995 - 2003. During 1995 - 2012, the c.c. is 0.85 which is also higher than for the quiet periods (*e.g.* Q1+Q2 or Q3+Q4). For MCs, the cc is better in Q1+Q2 than in A1+A2, but the c.c. in A3+A4 is higher than in Q3+A4. There is no clear tendency of c.c. for $N_{MC}$ *vs.* SSN. In addition, the best c.c. for SSN *vs.* $N_{MC}$ is in P2. Therefore, it is clear that $N_{MCL}$ and ($N_{MC}$ +$N_{MCL}$) are strongly associated with solar activity, but $N_{MC}$ alone shows a complicated relationship with solar activity, and, in fact, it is quite poor when the full *Wind* interval is considered.

For the join set ($N_{MC+MCL}$), the c.c. dropped ≈ 11 %, *i.e.* from 0.82 (1995 - 2003) to 0.74 (1995 - 2012), which may be due to the low correlation of SSN *vs.* $N_{MCL}$. Note that the c.c. for SSN *vs.* $N_{MC}$ increased dramatically for the period 2004 - 2012 (c.c. = 0.73) which increases the c.c. for $N_{MC+MCL}$ *vs.* SSN to 0.81 (See Figures 6g, h, i, and Table 5). This appears to solve the dilemma as to why the c.c. for SNN *vs.* $N_{MCLs}$ is higher than it is for SSN *vs.* the joint set during 1995 - 2003.

### 3.3 Relationship between the Southward Magnetic Field and Geomagnetic Storms

The southward interplanetary magnetic field (IMF) plays a major role in geomagnetic activity (*e.g.* Tsurutani *et al.*, 1988). The strength of the southward IMF (*Bz* or *Bs*) in MC events is well correlated with geomagnetic storm intensity [$Dst_{min}$] (*e.g.*Burlaga *et al.*, 1981; Tsurutani *et al.*, 1988, Wu and Lepping, 2002a, b, 2005).

Our earlier study shows that the average of the magnetic field magnitude in MCs, $<B>_{MC}$ was 12.9 nT and $<Bz_{min}>_{MC}$ was -10 nT, and for MCLs these averages were $<B>_{MCL}$ = 9.8 nT and $<Bz_{min}>_{MCL}$= -5.7 nT during 1995 - 2003. The average of $Dst_{min}$ for MC ($<Dst_{min}>_{MCL}$) was -90 nT and $<Dst_{min}>_{MCL}$ was -35 nT during 1995 - 2003 (Wu *et al.*, 2006). The average durations were 21.1 and 15.0 hours for MCs and MCLs, respectively for that same period. This strongly implies that the shorter *Bz*-south interval in MCLs is generally the reason that they are less geoeffective (Wu, Lepping, and Gopalswamy, 2006).

Table 5. Various solar wind parameters of MCs (Top Set) and MCLs (Bottom Set) in different periods.

| Period | 1995 - 2012 | 1995 - 2003 | 2004 - 2012 |
|---|---|---|---|
| $N_{MC}$ [a] | 168 | 83 | 85 |
| $\langle N_{MC} \rangle_{yearly}$ [b] | 9.3 | 9.2 | 9.4 |
| $\langle Bz_{min} \rangle_{MC}$ [c] (nT) | -9.2 | -10.0 | -8.3 |
| $\langle Dst_{min} \rangle_{MC}$ [d] (nT) | -70.5 | -91.1 | -54.4 |
| $\langle B \rangle_{MC}$ [e] (nT) | 12.2 | 13 | 11.4 |
| c.c. ($Dst_{min}$ *vs.* $Bz_{min}$ )$_{MC}$ [f] | 0.71 | 0.54 | 0.81 |
| | | | |
| $N_{MCL}$ [a] | 197 | 122 | 75 |
| $\langle N_{MCL} \rangle_{yearly}$ [b] | 10.9 | 13.6 | 8.3 |
| $\langle Bz_{min} \rangle_{MCL}$ [c](nT) | -5.7 | -5.9 | -5.4 |
| $\langle Dst_{min} \rangle_{MCL}$ [d] (nT) | -35.5 | -34.8 | -36.5 |
| $\langle B \rangle_{MCL}$ [e] (nT) | 9.6 | 9.8 | 9.2 |
| c.c. ($Dst_{min}$-$Bz_{min}$)$_{MCL}$ [f] | 0.56 | 0.47 | 0.66 |

[a] Total number of MCs or MCLs, [b] yearly occurrence rate of MCs or MCLs, [c] average of $Bz_{min}$ within an MC or MCL, [d] average of $Dst_{min}$ associate with an MC/MCL event, , [e] average of *B*, and [f] c.c. (correlation coefficients) for $Dst_{min}$ *vs.* $Bz_{min}$

In this study, we have extended the period of interest to 18 years (1995 - 2012). Various solar wind parameters of MCs and MCLs in different periods are listed in Table 5. The averages of B are 12.2 nT and 9.6 nT for MCs and MCLs, respectively, which represent 5 %

and 2 % decreases compared to the first nine year period that we had studied. However, the averages of geomagnetic storm intensity [$<Dst_{min}>_{TP}$] for MCs ($<Dst_{min}>_{MC}$ = -70.5 nT) and MCLs ($<Dst_{min}>_{MCL}$ = -35 nT) dropped by 22.5 % and 2 %, respectively. The inconsistent change of $<Dst_{min}>$ *vs.* $< Bz_{min}>$ is due to the fact the geomagnetic activity is mainly caused by the southward magnetic field (*e.g.* Wu and Lepping, 2002a,b, 2005), not just field intensity.

The averages of $Bz_{min}$ for MCs [$<Bz_{min}>_{MC}$] and MCLs [$<Bz_{min}>_{MCL}$] are -10.0 nT and -5.9 nT, respectively, during 1995 - 2003. In the period 1995 - 2012, $<Bz_{min}>_{MC}$ is -9.2 nT and $<Bz_{min}>_{MCL}$ is -5.7 nT. From 1995 - 2003 to 1995 - 2012, $<Bz_{min}>_{MC}$ dropped by 10 % and $<Bz_{min}>_{MCL}$ dropped by 5 %, but $<Dst_{min}>_{MC}$ dropped by ≈ 23 % and $<Dst_{min}>_{MCL}$ dropped by ≈2 %. This implies that the relationship between $Bz_{min}$ and $Dst_{min}$ is non-linear.

Figure 7 shows the distribution of geomagnetic $Dst_{min}$ and $Bz_{min}$ for both MCs (top panels) and MCLs (bottom panels) during 1995 - 2012 (left panels), 1995 - 2003 (middle panels), and 2004 - 2012 (right panels), respectively. The red-straight lines are the linear fitting functions for the estimates of $Dst_{min}$ *vs.* $Bz_{min}$. The fitted function for the $Dst_{min}$ linear estimation is shown in the top of each panel, and the c.c. for $Dst_{min}$ *vs.* $Bz_{min}$ is given below the fitting function. The total number of MCs [$N_{MCs}$] or MCLs [$N_{MCLs}$] is shown above of each panel. Averages of $Bz_{min}$ ($<Bz_{min}>$), $Dst_{min}$ ($<Dst_{min}>$), and the yearly occurrence frequency ($<N_{MC}>$, $<N_{MCL}>$, *i.e.* the *average* number of events per year) are also denoted in the left lower corner. For MCs, the c.c.s for $Dst_{min}$ *vs.* $Bz_{min}$ are 0.71, 0.54, and 0.87 during the periods of 1995 - 2012, 1995 - 2003, and 2004 - 2012, respectively. For MCLs, the c.c.s ($Dst_{min}$ *vs.* $Bz_{min}$) are 0.56, 0.47, and 0.66 for the same periods. The MCs' c.c. is relatively high (c.c. = 0.87) for the period of 2004 - 2012, and the $Dst_{min}$'s linear fitting function, $Dst_{min} = 0.90+7.78Bz_{min}$ (MC), can be used to estimate the intensity of a geomagnetic storm that is associated with a MC.

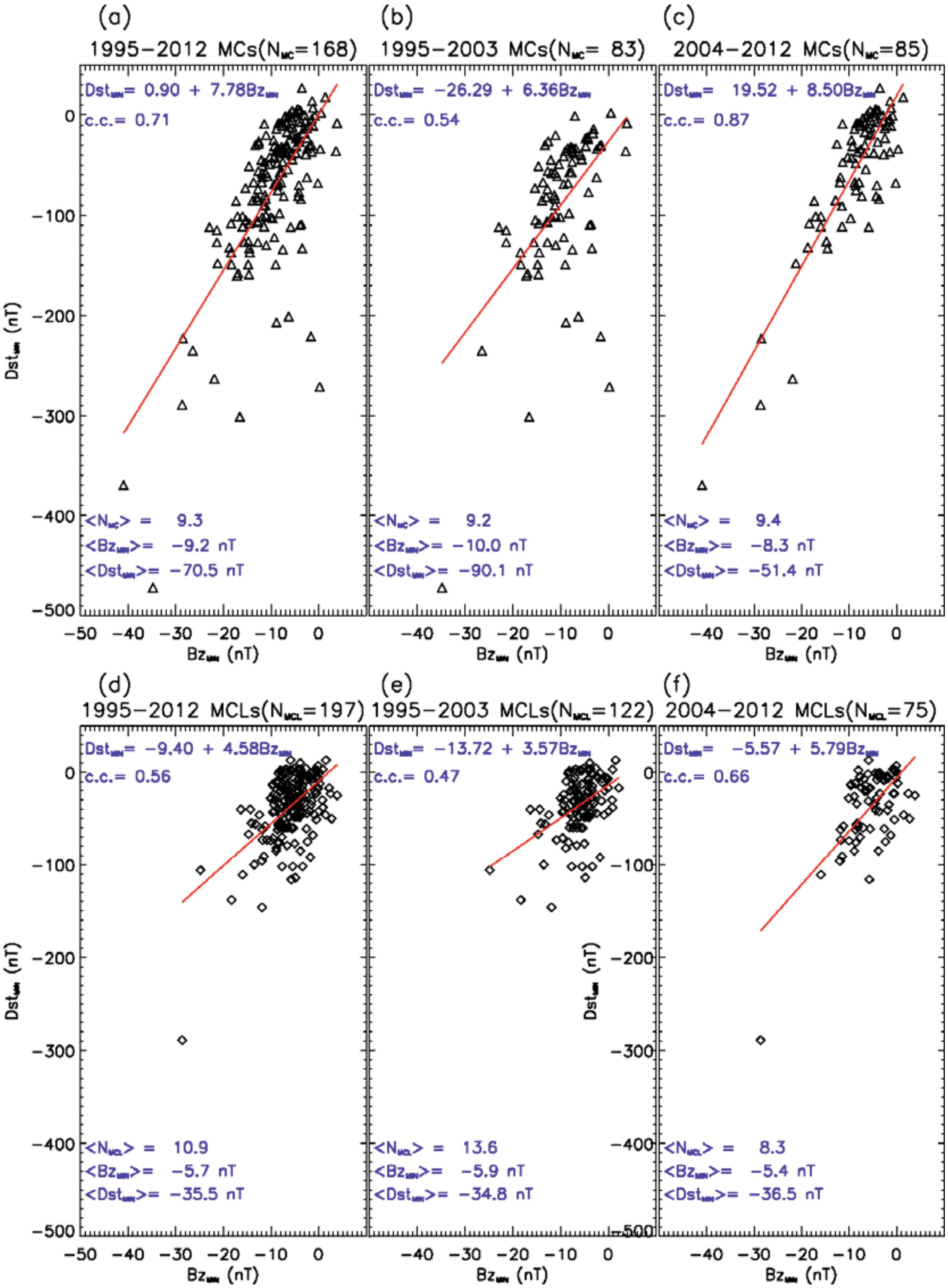


**Figure 7.** Distribution of geomagnetic storm intensity ($Dst_{\mathrm{min}}$) and minimum $Bz$ ($Bz_{\mathrm{min}}$) for both MCs (top panels) and MCLs (bottom panels) during 1995 - 2012 (left panels), 1995 - 2003 (middle panels), and 2004 - 2012 (right panel), respectively. $Dst_{\mathrm{min}}$'s linear fitting function and the c.c.s are denoted at the top of each panel, respectively. The averages of $<N_{MC\ or\ MCL}>$, $<Bz_{\mathrm{min}}>$, $<Dst_{\mathrm{min}}>$ are denoted on the bottom of each panel.

**Anomaly of Solar Wind Parameters for the MCs/MCLs**

The yearly average values for $VBs_{max}$ and $\mathcal{E}_{max}$ (see second and third panels of Figure 5) for the MCs in 2003 and 2004 are quite high compared to those for the periods during 1995 - 2002 and 2005 - 2012. The peak values for both types occurred in 2004. This explains why the minimum of $<Dst_{min}>$ occurred in 2004 (see top panel in Figure 2), since $Dst_{min}$ was well correlated with $VBs_{max}$ and $\mathcal{E}_{max}$ (*e.g.* Wu and Lepping, 2002a, b). The peak of solar wind speed and magnetic field also occurred in 2004, which caused the peaks for $VBs_{max}$ and $\mathcal{E}_{max}$ to occur in 2004. (Note that from the middle of 2003 *Wind* went behind the Earth's bow shock and remained there for approximately nine months.)

Averages of solar wind speed for MCs during 2000 - 2005 are faster than those during 1995 - 1999 and 2006 - 2012 (*i.e.* the "surrounding periods"; see the second panel from the bottom in Figure 5). During 2000 - 2005, the strength of $Bz_{min}$ is also higher than for the "surrounding periods." (Note that $Bs$ is proportional to $|Bz_{min}|$, if $Bz_{min}$ is less than zero.) Since both $VBs_{max}$ and $\mathcal{E}_{max}$ depend on the combination of solar wind speed and $Bz_{min}$, $<Dst_{min}>_{yearly}$ is also lower than for the "surrounding periods."

3.4 MC Fitting Model

The MC fitting model used in this study is a well developed and tested model. It has been used to fit all known *Wind* MC candidates (at least 400 events). Other flux-rope fitting models may be better (or worse) than our model as applied to some specific MC events. We do not know which model is the best among them for any given event, since other models have been used for only a limited number of events. We believe that it would be informative if all models were tested for a large number of events. We certainly do not know how the results would differ for different models, but this would be an interesting subject for future study. Some differences are bound to arise, because the results are, to some extent, model dependent. Even the estimated ratio of the number of MCs to MCLs is expected to differ from model to model.

We think an operational definition of an MCL structure, which is provided in the Introduction, is sufficient for our analysis. However, it might be helpful to provide a few speculative remarks on the nature of MCLs, or similarly, to try to answer the question “why do they exist?” MCLs are complicated, generally even more so than MCs. However, since we use a similar starting point for MCLs in our identification of them (by the auto ID program; see Lepping, Wu, and Berdichevsky, 2006), as we do for MCs themselves, most MCLs are very likely to be related to MCs. We believe that an MCL is any one of the following: i) a magnetic field structure resulting from the Sun’s attempt to eject what was to be an MC, but with complex conditions that distort it, or ii) the conditions at the Sun were not properly force-free, or iii) an MC starting at the Sun in respectable form (*i.e.* one that we ordinarily would have recognized as an MC with our usual procedures) that later becomes seriously distorted through interaction(s) with other solar wind structures, as mentioned above, or iv) two or more MCs that interact with each other in the interplanetary medium distorting one or all into MCL(s) states. Or we could have combinations or these, of course. Items i) and ii) are restricted to solar birth effects and iii) and iv) are “interaction” effects. At this point we have not been able to distribute our existing set of MCLs among these “causes.” It should be also stressed also other researchers, using different MC fitting models, but otherwise attempting to use our means of identifying MCLs, would no doubt find a different number of MCL events for any fixed interval and therefore would find a different ratio of $N_{\mathrm{MCs}}/N_{\mathrm{MCLs}}$. Their results, although expected to be different from ours, hopefully would not be too different. It remains to be investigated.

## 4. Conclusions

The main results of this study are given by the following.

- Average occurrence rates are ≈9.3 for MCs and ≈10.9 for MCLs for the total period, 1995 - 2012.
- In the lower solar activity period (1995 - 1997, 2007 - 2009), the occurrence rate of MCs is higher than that for MCLs.
- In the higher solar activity period (1998 - 2006, 2010 - 2012), the occurrence rate of MCs is lower than that for MCLs.
- $<N_{\text{MCLs}}>_{\text{Quiet period}} < <N_{\text{MCs}}>_{\text{Quiet period}}$ is caused by the lower interaction rate between MC and HCS, and other interplanetary disturbances.
- $<N_{\text{MCLs}}>_{\text{Active period}} > <N_{\text{MCs}}>_{\text{Active period}}$ is caused by higher interaction rate between MC and HCS, and other interplanetary disturbances.
- The occurrence rate of visually determined MCs is not related to the SSN during 1995 - 2012 or 1995 - 2003, but they are well correlated during 2004 - 2012.
- During the Total period $<N_{\text{MCLs}}>_{\text{TP}}$ and $<N_{\text{MCs+MCLs}}>_{\text{TP}}$ are well correlated with the SSN, but $<N_{\text{MCs}}>_{\text{TP}}$ is not well correlated with the SSN.
- The average duration of an MC over the Total period (18.82 hours) is typically longer than that of an MCL (15.69 hours).
- The average geomagnetic storm intensity associated with the MCs is stronger than that for the MCLs over the Total period.
- Stronger MC storms follow solar maximum, but MCLs do not show such a trend.
- The average solar wind speed is faster within MCs than within MCLs.
- The average absolute value of $Bz_{\text{min}}$ is more intense within MCs than within MCLs.
- The anomaly of unusually high $N_{\text{MC}}$ in 1997 and 2009 was caused by the lower interaction rate in 1997 (or 2009) and higher interaction rate in 1998 (or 2010) between MCs and other solar wind structures.

The relationship between MCs' $Bz_{\text{min}}$ and geomagnetic storm intensity is high (c.c = 0.71) during the total period. The $Dst_{\text{min}}$'s linear fitting function [$Dst_{\text{min}} = 0.90+7.78Bz_{\text{min}}$] could be used to predict the storm intensity once the $Bz_{\text{min}}$ of an MC is determined. This relationship may be useful for space weather predictions.

There are more MCs than MCLs in the quiet solar period, and more MCLs than MCs in the active solar period, probably due to the interaction between an MC and another significant interplanetary disturbance (including another MC) which could obviously change the character of an MC, but we speculate that some MCLs are no doubt due to other factors such as complex birth conditions at the Sun.

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