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Interplanetary origin of intense geomagnetic storms (*Dst* < −100 nT) during solar cycle 23

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[1] We study the interplanetary causes of intense geomagnetic storms (*Dst* < −100 nT) that occurred during solar cycle 23 (1997–2005). It was 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 corotating interaction regions leading high speed streams. However, the relative importance of each of those driving structures was found to vary with the solar cycle phase. We divide the cycle in three phases (rising, maximum and declining) and explain the differences. We also discuss about the geoeffectiveness of each of the four main interplanetary driving structures. **Citation:** Gonzalez, W. D., E. Echer, A. L. Clua-Gonzalez, and B. T. Tsurutani (2007), Interplanetary origin of intense geomagnetic storms (*Dst* < −100 nT) during solar cycle 23, *Geophys. Res. Lett.*, *34*, L06101, doi:10.1029/2006GL028879.

1. Introduction

[2] *Gonzalez and Tsurutani* [1987] and *Tsurutani et al.* [1988] studied the interplanetary causes of intense geomagnetic storms (*Dst* < −100 nT) for the peak year of the maximum phase of solar cycle 21 and found that about half of the storms were associated with magnetic clouds and half with sheath field regions (following interplanetary shocks). Later, several authors have studied the geoeffectiveness of magnetic clouds for longer time intervals [*Gosling et al.*, 1991; *Echer et al.*, 2005] and of other interplanetary structures for several levels of intensity of magnetic storms [*Gonzalez et al.*, 1994, 1999; *Huttunen et al.*, 2002; *Gonzalez et al.*, 2002; *Richardson et al.*, 2002; *Tsurutani et al.*, 2003; *Echer and Gonzalez*, 2004; *Zhang et al.*, 2006; *Richardson et al.*, 2006; *Alves et al.*, 2006].

[3] In this letter we study the interplanetary causes of intense geomagnetic storms for the full interval of solar cycle 23, with particular interest in determining the relative importance of such causes as a function of the solar cycle-phase. For this purpose, we divided the cycle in three phases: (1) rising (R, 1997–1999), (2) maximum (M, 2000–2002.5) and (3) declining (D, 2002.5–2005). Here we do not try to study the association of interplanetary structures with their solar origin(s), due to the limited length of this letter and also due to the unsolved difficulties in the clear definition of such an association [e.g., *Dryer*, 1996].

2. Method of Analysis

[4] For this paper we have used the *Dst* data, published by the Solar Physics Interactive Data Resources (available at http://spidr.ngdc.noaa.gov/spidr/index.jsp) and the interplanetary data observed by the ACE and WIND satellites [*Stone et al.*, 1998; *Acuña et al.*, 1995].

[5] We have identified 87 intense storms (*Dst* < −100 nT) during solar cycle 23, for which we were interested in investigating their interplanetary causes. Figure 1 shows the yearly distribution of the peak *Dst* values of these storms as a function of the solar cycle.

[6] For the identification of the interplanetary causes we have followed the nomenclature and definitions given by *Burlaga et al.* [1987], *Tsurutani et al.* [1988, 1995], *Gonzalez et al.* [1999], and *Balogh et al.* [1999]. Table 1 gives the yearly distribution of the intense storms according to their interplanetary causes, in which, CIR stands for corotating interaction region (associated with a high speed stream), MC for a magnetic cloud (a common type of a ICME driver), "Sh + MC" for a sheath Bs (Bz southward) field followed by a magnetic cloud, SBC for a sector boundary crossing, "S compr MC" for a magnetic cloud compressed by a shock, and "Complex" for a case in which none of the other cases were identified. We are aware that Burlaga et al. and Tsurutani et al.'s methods of magnetic cloud identification may have, as yet, not been accepted as "universal" methods for such an identification. However, those methods have been fairly well accepted in the literature and most of the magnetic clouds identified for the present study are included in the lists of ICMEs independently obtained by *Cane and Richardson* [2003].

[7] The category of "sheath fields" corresponds to Bs fields in the sheath region that follow an interplanetary shock, without any other Bs structure following the sheath field region that could also be responsible for the development of the storm's main phase. Whereas in the category of "Sh + MC", a magnetic cloud (also with a Bs field), following the sheath region, was observed to be partly responsible for the development of the storm.

[8] The category of "ICMEs" (interplanetary coronal mass ejections [*Dryer*, 1994]) corresponds to several type of structures [e.g., *Tsurutani et al.*, 1988; *Gonzalez et al.*, 1999] that are not magnetic clouds, namely that they do not

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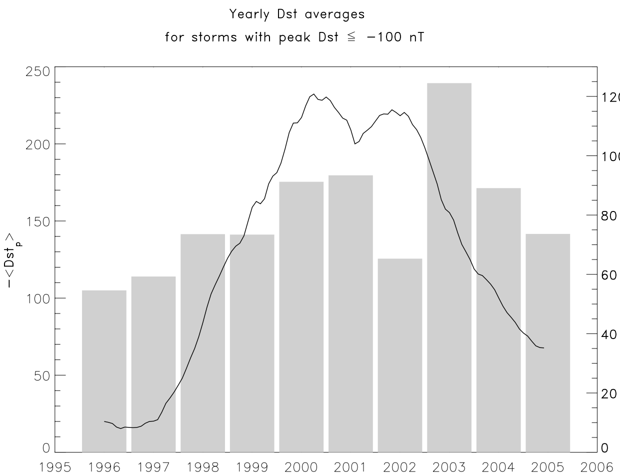

Figure 1. Yearly averages of peak *Dst* for intense storms during solar cycle 23.

have the typical signatures for magnetic clouds [*Burlaga et al.*, 1987].

3. Results

[9] One can see in table 1 that the four most common interplanetary structures responsible for the development of intense storms were the first four classes, namely CIR, MC, Sh + MC and Sh, with a total number in the cycle of 11, 21, 12, and 21 cases, respectively. Thus, from these, MCs and sheath fields were the most common driving structures. From Table 1 one can compute that those four most common structures represent a total of 75% of the interplanetary structures causing intense storms during solar cycle 23, with CIRs causing 13%, MCs 24%, sheath fields 24% and sheath + MCs 14% of the storms.

[10] The category of ICMEs, although in Table 1 has a relatively substantial contribution (8 cases), was not selected among the top driving structures, because as mentioned above, they correspond to several types of Bs structures that appear to be driving an interplanetary shock and, therefore, they do not belong to a single type of structure, as the selected top four structures do.

[11] In order to study the distribution of the four main interplanetary causes according to the selected solar cycle phases R, M, and D, we represented it with the histograms of Figure 2, in which the blue color stands for MCs, green for Sheath fields, red for Sh + MC, and black for CIRs.

[12] For the rising phase, one can observe in Figure 2 that more storms are due to magnetic clouds, second to sheath fields and third to the combination of sheath fields followed by magnetic clouds (CIRs represent only a minor contribution for this phase).

[13] For the maximum phase, more storms are associated with sheath fields, second with sheath fields followed by magnetic clouds and third with magnetic clouds (again for this phase too, CIRs represent a minor contribution).

[14] For the declining phase, more storms are related to magnetic clouds, second, CIRs, and third, sheath fields (a minor contribution is due to sheath fields followed by magnetic clouds).

[15] We discuss in the following section about the significance of these results.

[16] Figure 3 shows scattered plots of the peak *Dst* values as a function of their corresponding peak driving interplanetary electric field Ey (vBs) value (v stands for the solar wind speed and Bs for the southward component of the interplanetary magnetic field), for each of the selected four main interplanetary structures and for the three phases of the cycle.

[17] For the rising phase, Figure 3 shows that sheath fields are more geoeffective (bigger values of peak *Dst*). For the maximum phase, sheath fields followed by magnetic clouds appear to be more geoeffective, while for the declining phase, the more geoeffective ones are the magnetic clouds.

4. Discussion

[18] The yearly distribution of intense storms for solar cycle 23, as seen in the histograms of the peak *Dst* values of Figure 1, show the expected dual–peak distribution [*Gonzalez et al.*, 1990], with the first peak appearing at solar maximum and the second peak at the early part of the declining phase. From the information obtained in Figure 2, the first peak could be associated with sheath fields as the main driving structures, while magnetic clouds appear to be the main responsible structures for the second peak.

[19] As shown in Table 1, it is interesting to see that the four main interplanetary structures that caused intense geomagnetic storms during solar cycle 23 were those that have been previously discussed in the literature [e.g.,

Table 1. Interplanetary Structures That Caused Intense Geomagnetic Storms Per Year During Cycle 23[a]

Year/IP Structure	CIR	MC	Sh + MC	Sh	Slow MC	ICME	Sh + ICME	ICME + SBC	Sh + SBC	SC MC	ICME + CIR	Complex	Alfven Waves?
1997	-	1	2	1	1	-	-	-	-	-	-	-	-
1998	1	2	1	2	-	2	-	1	1	1	-	-	-
1999	-	2	-	1	-	1	-	-	-	-	1	-	-
2000	1	4	3	1	-	1	-	-	-	-	-	1	-
2001	-	2	2	6	1	1	1	-	-	-	-	-	-
2002	4	2	2	4	1	-	1	-	-	-	-	-	-
2003	2	2	-	2	-	-	-	-	-	-	-	1	-
2004	1	3	2	2	-	2	-	-	-	-	-	-	-
2005	2	3	-	2	2	1	-	-	-	-	-	-	1
Total[b]	11	21	12	21	5	8	2	1	1	1	1	2	1

[a]Abbreviations are CIR, corotating interaction region; MC, magnetic cloud; Sh+MC, sheath field followed by a magnetic cloud; Sh, sheath field; ICME, interplanetary coronal mass ejection; SBC, sector boundary crossing; SC MC, shock compressed magnetic cloud.

[b]The total number of storms is 87.

Tsurutani et al., 1995; *Gonzalez et al.*, 1999; *Tsurutani et al.*, 2006] as being the most common sources of intense storms, although these authors presented their results for separate phases (mainly maximum and declining) of the solar cycle. Further, Table 1 also shows that the two most common structures driving intense storms for the full solar cycle were magnetic clouds and sheath fields. These latter results are in agreement with those anticipated in the works by *Gonzalez and Tsurutani* [1987] and *Tsurutani et al.* [1988].

[20] As mentioned in section 2, it is important to point out that some times magnetic clouds may not clearly get identified within ICMEs [e.g., *Dryer*, 1996] just by following the methods suggested by *Burlaga et al.* [1987] and *Tsurutani et al.* [1988]. However, this is an observational problem associated with a single satellite observation that awaits for a future multi-satellite observation.

[21] One can see in Figure 2 that the three dominant interplanetary structures driving intense storms during solar cycle 23 vary according to the phase of the cycle, being magnetic clouds, then sheath fields, and then sheath fields followed by a magnetic cloud for the rising phase; sheath fields, then sheath fields followed by a magnetic cloud and then magnetic clouds for the maximum phase; and magnetic clouds, then CIRs and then sheath fields for the declining phase.

[22] Figure 2 also shows that magnetic clouds are the top dominant structures both for the rising as for the declining phases to drive intense storms, whereas sheath fields are the top dominant structures during solar maximum. Since intense sheath fields are associated with intense shocks, this latter result is in agreement with the expected intensification of CMEs during solar maximum [e.g., *Gonzalez et al.*, 1999].

[23] During the declining phase, another important and abundant interplanetary structure to drive intense storms are CIRs, as expected from the larger presence of the associated high speed streams during this phase of the solar cycle [*Tsurutani et al.*, 2006]. However, as discussed below, such structures are less geoeffective, leading only to storms with peak *Dst* values between −100 nT and −150 nT. Figure 2 also shows that CIRs have only a minor contribution during the rising and maximum phases.

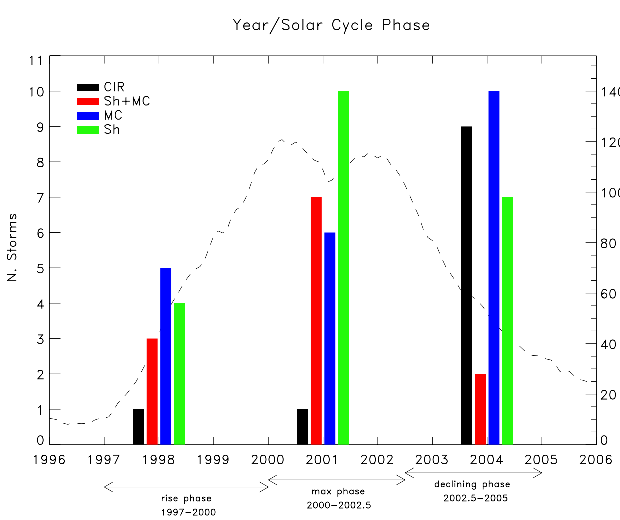

Figure 2. Distribution of the four main interplanetary structures causing intense magnetic storms according to the phase of the solar cycle 23.

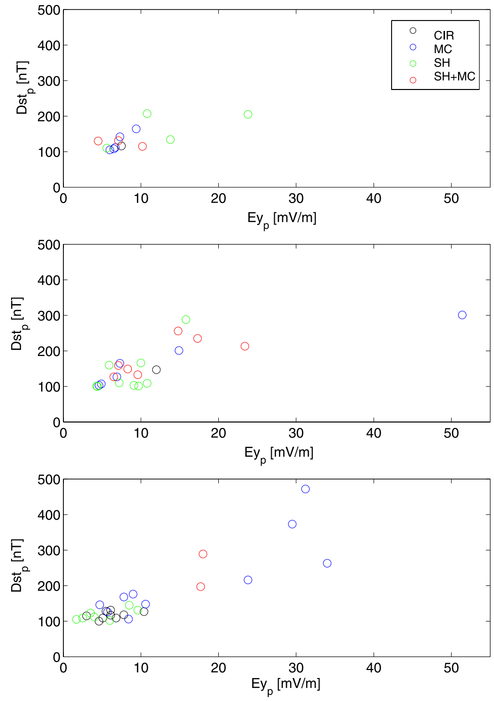

Figure 3. Relationship of peak *Dst* and peak Ey values for the four interplanetary structures in the three solar cycle-phases.

[24] *Richardson et al.* [2002] have studied the interplanetary sources of geomagnetic activity during the interval of 1972–2000, using the aa index and without restricting their studies to the class of intense geomagnetic storms. These authors have concentrated on the comparison of solar maximum and solar minimum conditions and, in general, for these parts of the solar cycle our results are in good agreement with theirs, namely that, during solar maximum the dominant interplanetary structures are associated with transients related with CMEs, whereas during solar minimum, high speed streams tend to contribute largely to the overall geomagnetic activity.

[25] Figure 3 shows the geoeffectiveness of the four main interplanetary drivers of intense storms. For the rising phase, although magnetic clouds are more abundant (as seen in Figure 2), the most geoeffective ones appear to be the sheath field structures (with largest *Dst* values). For the maximum phase, the most geoeffective structures seem to be sheath fields followed by magnetic clouds (with sheath fields being the most abundant ones from Figure 2); whereas for the declining phase, the most geoeffective structures are clearly magnetic clouds (also the most abundant ones from Figure 2).

[26] The *Dst* ranges associated with the four main interplanetary structures were: (1) nT for CIRs (−100, −147), (2) nT for MCs (−103, −472), (3) nT for sheath fields (−101, −288), and (4) nT for sheath fields+MCs (−115, −289). Thus, from these ranges, magnetic clouds were the most geoeffective structures and CIRs the least geoeffective ones. Further, in terms of geoeffectiveness leading to the

most intense storms, we had, for a selected threshold of peak *Dst* < -200 nT: CIRs with zero cases out of 11, MCs with 6 out of 21, sheath fields with 4 out of 21, and sheath fields+MCs with 4 out of 21 cases. Again, magnetic clouds were the most geoeffective ones.

[27] With respect to the results of Figure 3, we would like to have a better statistics in order to be more conclusive. This could be done by trying to extend the present study to other solar cycles.

[28] It is not worth to conclude about the statistical significance of the results shown in Figures 2 and 3 due to their limited number of events. However in order to improve this limitation and to also claim for more general results, it will be very interesting to try to extend the present study to other solar cycles.

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