Geoeffectiveness of interplanetary shocks, magnetic clouds, sector boundary crossings and their combined occurrence

E. Echer and W. D. Gonzalez

Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil

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[1] The aim of this work is to study the geoeffectiveness of interplanetary shock waves, magnetic clouds, heliospheric current sheet sector boundary crossings, and the combinations of these interplanetary structures. Both single and compound structures have their geoeffectiveness evaluated, considering the percentage of moderate and intense magnetic storms (Dst ≤ -50 nT) that followed each event. With this criteria, it was found that, on average, around 57% of the interplanetary shocks, 26% of the sector boundary crossings, 77% of the magnetic clouds, 80% of magnetic clouds at sector boundaries, 60% of interplanetary shocks at sector boundaries, 81% of magnetic clouds driving shocks, 83% of magnetic clouds compressed by high speed streams, and 100% of magnetic clouds driving shocks and located at sector boundaries are geoeffective. Thus, compound interplanetary magnetic structures were found to be more geoeffective than single interplanetary magnetic structures. *INDEX TERMS:* 2134 Interplanetary Physics: Interplanetary magnetic fields; 2139 Interplanetary Physics: Interplanetary shocks; 2164 Interplanetary Physics: Solar wind plasma; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Echer, E., and W. D. Gonzalez (2004), Geoeffectiveness of interplanetary shocks, magnetic clouds, sector boundary crossings and their combined occurrence, *Geophys. Res. Lett.*, *31*, L09808, doi:10.1029/2003GL019199.

1. Introduction

[2] The prime cause of intense geomagnetic storms (Dst ≤ -100 nT) is the occurrence of strong (Bz ~ -10 nT) and long-duration ($\Delta t \sim 3$h) southward interplanetary magnetic fields (IMF), allowing a more effective energy transfer between solar wind and magnetosphere through the magnetic reconnection mechanism [*Dungey*, 1961; *Gonzalez and Tsurutani*, 1987; *Gonzalez et al.*, 1994, 1999]. These intense and long-duration southward magnetic fields may have their origin in the interplanetary ejecta, for example in magnetic clouds, or they may occur in the sheath region, behind the shock, caused by draping effects or by pre-existing southward magnetic fields amplified by shock compression [*Gonzalez et al.*, 1999]. The sources of southward interplanetary magnetic field are then known to be due to different solar wind structures and could also be due to the interaction between them.

[3] In this work a statistical analysis of the geoeffectiveness of interplanetary shock waves (S) - period 1973–2000, magnetic clouds (MC) - period 1966–2001, heliospheric current sheet sector boundary crossings (SBC), period 1957–2001, and their combined occurrence is performed. The geoeffectiveness of each structure is quantified in this work by the number of intense and moderate geomagnetic storms that followed each one.

2. Methodology

[4] In this work, the geomagnetic activity was classified in strength levels using Dst criterion [*Gonzalez et al.*, 1994]. The classification scheme is shown in Table 1. The hourly Dst index was obtained from the World Data Center for Geomagnetism, Kyoto.

[5] A list of shocks was compiled using events reported in the literature [*Abraham-Shrauner and Yun*, 1976; *Borrini et al.*, 1982; *Cane*, 1985; *Sheeley et al.*, 1985; *Volkmer and Neubauer*, 1985; *Richter et al.*, 1986; *Cane et al.*, 1987; *Gonzalez and Tsurutani*, 1987; *Marsden et al.*, 1987; *Mihalov et al.*, 1987; *Gosling et al.*, 1990; *Woo and Schwenn*, 1991; *Richardson and Cane*, 1993; *Bravo and Pérez-Enríquez*, 1994; *Bothmer and Schwenn*, 1998; *Bravo and Blanco-Cano*, 1998], and from the International Solar-Terrestrial Physics Program -ISTP Solar Wind Catalogue Candidate Events (http://www-spotf.gsfc.nasa.gov/scripts/swcat/Catalog_events.html). Within the period 1973–2000, 574 shocks were selected. The first years of solar wind observations, 1964–1972, had very sparsely sampled solar wind data, thus this period was not used. It was also observed that a very low number of shocks occurred during 1983–1993, because of a smaller number of solar wind observations during this period.

[6] A list of sector boundary crossings was obtained from the Wilcox Solar Observatory, internet homepage: http://quake.Stanford.EDU:80/~wso/SB/SB.html, derived from several sources and using the Svalgaard's criterion [*Svalgaard*, 1976] to characterize a sector boundary. The Wilcox's list was updated with OMNI database in the period 1993–2001. A total of 1229 sector boundary crossings were identified within the period 1947–2001. Among these SBC, 946 occurred after 1957 (when Dst index is available) and were used in this work.

[7] A magnetic cloud list was also compiled from events reported in literature [*Klein and Burlaga*, 1982; *Marsden et al.*, 1987; *Bothmer and Rust*, 1997; *Bothmer and Schwenn*, 1998; *Bravo and Blanco-Cano*, 1998; *Crooker et al.*, 1998; *Bravo et al.*, 1999; *Blanco-Cano and Bravo*, 2001] and from the magnetic clouds table on-line, internet homepage: http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html,2002. From these references, magnetic cloud events were checked through visual inspection of OMNI database solar wind

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Table 1. Classification of Geomagnetic Activity in Intensity Levels Following Dst Criterion

Geomagnetic Activity Level	Dst
Intense	Dst ≤ −100 nT
Moderate	−100 < Dst ≤ −50 nT
Weak	−50 < Dst ≤ −30 nT
Quiet	Dst > −30 nT

plasma and magnetic field parameter curves and using the criterion that MC should present high magnetic field intensity, smooth rotation in the Z or Y direction and low beta proton, a total of 149 MCs were extracted to this study.

[8] The corresponding Dst minimum (peak) value in a period of until 3 days after each structure identified in the lists was used to characterize the geoeffectiveness of each structure. These lists were also used in order to search for periods when two or three of these structures occurred conjointly in the solar wind. A detailed description of this methodology as well as the complete list of the events studied can be found in *Echer* [2003] or by request to the authors.

3. Results and Discussion

[9] Figure 1 shows the percentage of interplanetary shocks, sector boundary crossings, and magnetic clouds followed by each geomagnetic activity level. It is seen that 22% of the shocks were followed by intense geomagnetic activity, 35% by moderate and around 42% by weak and quiet geomagnetic activity. These results imply that around 57% of shocks are geoeffective, i.e., a moderate or an intense storm follows them. The statistical distribution of geomagnetic activity levels after shocks was also determined for solar maximum and solar minimum epochs. Several years around a solar maximum or minimum were chosen to determine these epochs. Since solar cycle is asymmetric, i.e., the ascending phase is shorter than the descending phase, it was decided to include 3 years before a solar minimum and 2 years after. For solar maxima epochs, the selection was 3 years before maximum and 3 years after. The results for solar maximum and minimum were observed to be very similar (not shown). Thus, statistically, when a shock is detected, there is a probability of around 57% that it would be followed by a moderate or intense geomagnetic storm. Nevertheless, these global results could not be observed in individual years or periods. Other statistical results have shown that around 50% of shocks were geoeffective during 1978–1979 maximum [*Gonzalez et al.*, 1999] or 64% during 2000 maximum [*Echer*, 2003]. These results indicate that the percentage of shocks causing intense and moderate activity varies for individual years, which seems to be caused by different structures during each solar cycle phase and also by differences in solar ejecta characteristics during each solar cycle maximum. Mechanisms associated to shock geoeffectiveness are well known, such as the compressed/shock fields in the sheath region. It is also known that faster ejecta, which are more likely to drive shocks, have higher magnetic field intensity and are potentially more geoeffective [*Gonzalez et al.*, 1999].

[10] In the second panel in Figure 1 the statistical distribution of geomagnetic activity after sector boundary crossings is shown, for the period 1957–2001. It can be seen that around 6% of SBCs are followed by intense, 20% by moderate, 25% by weak and 49% by quiet geomagnetic periods. When considering the IMF polarity reversal direction, no significant difference in the geoeffectiveness was observed between away/toward and toward/away transitions [*Echer*, 2003]. For different solar maximum and minimum periods, however, it was found that the percentage of SBCs followed by intense activity varies from 1% to 6% during different solar minima and from 7 to 14% during different solar maxima. Nevertheless, no significant difference was observed during the same solar activity epoch for both types of polarity reversal direction. The percentage of intense activity in the whole Dst data set from 1957–2001 is around 1.2%. Moderate and weak geomagnetic activity during the whole 1957–2001 period corresponds to 6.2 and 13.0% of the values, while for SBCs they are 20.0 and 25.0% of the events, respectively. Thus, the fact that SBCs are observed to be geoeffective in 26% of the events is a significantly higher result when compared to the whole Dst dataset (7% of Dst values are moderate or intense for the entire

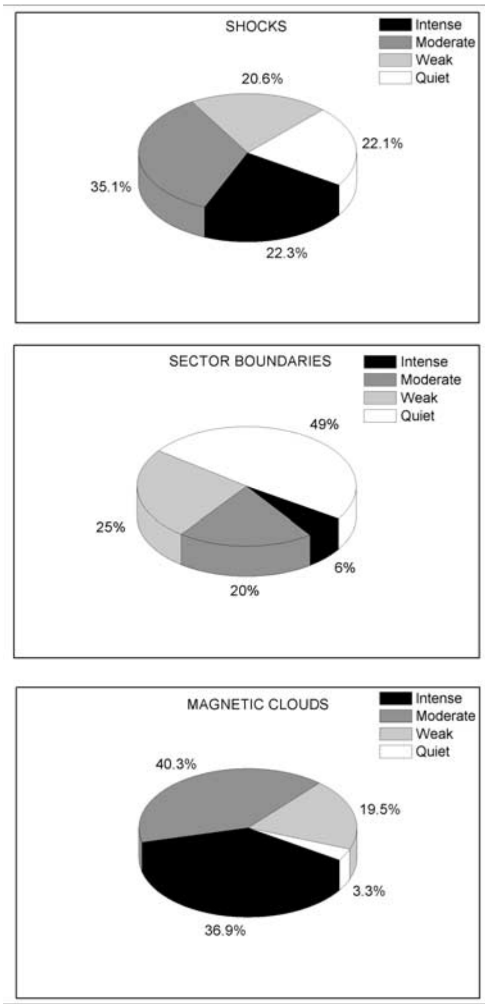

Figure 1. Sector Graphs of the percentage of interplanetary shocks (top panel), sector boundary crossings (middle panel) and magnetic clouds (bottom panel) followed by each geomagnetic activity strength level.

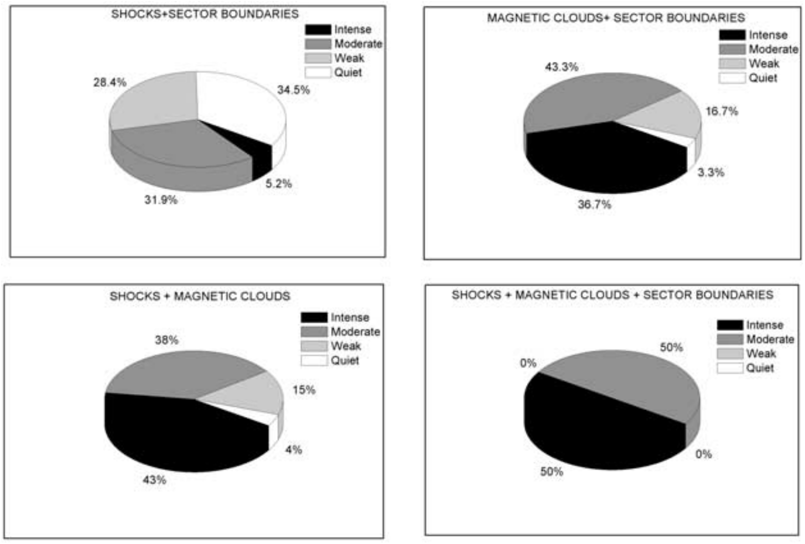

Figure 2. Sector graphs of the percentage of the combined occurrence of interplanetary shocks and sector boundaries (top panel on the left), magnetic clouds and sector boundaries (top panel on the right), shocks and magnetic clouds (bottom panel on the left) and shocks, magnetic clouds and sector boundaries (bottom panel on the right) followed by each geomagnetic activity strength level.

period of 1957–2001). According to *Bothmer and Schwenn* [1991], strong IMF deflexions out of ecliptic are usually occurring during SBCs. Also the presence of a high-speed corrotating stream after a SBC is usual [*Bothmer and Schwenn*, 1991], and that might cause geomagnetic activation though magnetospheric compression and/or IMF compression.

[11] The third panel in Figure 1 shows the magnetic cloud geoeffectiveness. Around 37% of magnetic clouds are followed by intense activity, 40% by moderate, 20% and 3% by weak and quiet activity, respectively. This result confirms the very well known high geoeffectiveness of magnetic clouds [*Gonzalez et al.*, 1999]. It is found in this study that around 77% of all magnetic clouds are geoeffective. The geoeffectiveness was also determined according to the magnetic cloud polarity (rotation in Y or Z direction). It was found that 66.5% of NSY_+ (rotation north-south in Z direction with Y axial field eastward) magnetic clouds, 83.0% of NSY_- (Y westward), 80.0% of YS (rotation in Y direction, with Z axial field southward), 73.0% of SNY_+, and 85.5% of SNY_- magnetic clouds are geoeffective. These results might be an indication for a slight preference of SN clouds and Y_- being more geoeffective. The properties of each magnetic cloud class agree with their geoeffectiveness, with SNY_- having the highest percentage of southward magnetic field, while NSY_+ clouds have the lowest percentage of southward magnetic field [*Echer*, 2003].

[12] *Klein and Burlaga* [1982] did not find a significant difference in the storm intensities according with the magnetic cloud type. However, *Zhang and Burlaga* [1988] reported that SN clouds could be more effective. *Vieira et al.* [2002] have found that NS clouds need more energy injection time to reach the same geomagnetic activity level of SN clouds. A possibility is also that SN and YS clouds are having their geoeffectiveness increased due to pre-existing sheath southward fields. From the results obtained in this study, it seems that NSY_+ clouds are statistically less geoeffective than other kind of clouds.

[13] Figure 2 shows the percentage of compound structures: shocks + sector boundaries (S/SBC), magnetic clouds + sector boundaries (MC/SBC), shocks + magnetic clouds (S/MC) and shocks + magnetic clouds + sector boundaries data sets (S/MC/SBC). Top panel on the left gives the percentage of S/SBC events followed by each magnetic activity level. In the period studied, 117 shocks were found at SBC (1973–2000). It is seen that the percentage of intense values are similar, 5% against 6% for the SBC set. However, for moderate geomagnetic activity there is a higher number of S+SBC events (32%) that are geoeffective than for SBC events (20%). The S/SBC set is geoeffective in 37% of events against 26% of SBC.

[14] From the 149 MCs set, 30 were identified at SBCs. Upper panel on the right in Figure 2 shows that around 37% of MC/SBC events are followed by intense magnetic activity, 43% by moderate, 17% by weak and 3% by quiet periods. This distribution is similar to the MC set, differing only because of a slightly higher number of moderate events (43% against 40%). The combination of possible warped magnetic fields by the SBC seems to be increasing the number of MC producing moderate storms in relation to weak/quiet events, but the field of SBC is not enough to increase the number of intense storms. It is found that 80% of MC + SBC events are geoeffective, a number slightly higher than the MC events (77%).

[15] Lower left panel in Figure 2 shows the distribution of magnetic clouds that were fast enough to drive a shock. From the whole 149 MC set, 127 occurred in the period after 1973 (coincidental with the shock events list) and 76 of them were found to be associated with a shock. Results show that 43% of MC + S are followed by intense magnetic activity, 38% by moderate, which leads to a total of 81% of magnetic clouds that are fast enough to drive a shock are geoeffective. This number is again slightly higher than the

whole data set for MC (77%) and MC/SBC (80%). This result, particularly the higher number of MC followed by intense storms (43% against 37%) is explained by previous works, which had shown that faster magnetic clouds are more geoeffective because both of their high ejecta fields and due to draping/shock effects [*Gonzalez et al.*, 1999].

[16] The number of magnetic clouds driving shocks and at sector boundary was found to be 12. The statistics of magnetic activity levels following these events are shown in the lower right panel of Figure 2. It is seen that, for this small data set, 100% of events are geoeffective, with 50% driving intense and 50% driving moderate magnetic activity. Although this particular dataset is small, it might indicate that this combination of high speed clouds at sector boundaries could be particularly geoeffective, perhaps due the presence of multiple southward IMF structures, which implies that, before the ring current has decayed significantly to the pre-storm level, a new major particle injection occurs, leading to a further development of the ring current with the Dst index decreasing for a second time [*Vieira et al.*, 2002]. These IMF southward structures could be due to the SBC deflected fields, sheath and ejecta fields, or, since CIRs are usually observed near SBC, due to sheath, ejecta and CIR fields.

[17] Additionally, the number of magnetic clouds that were followed by a high-speed stream (co-rotating or ejecta) was searched visually in OMNI plots and 18 events were found unambiguously to be compressed in their rear by high speed streams. From this MC set, it was found that around 39%, 44% and 17% were followed by intense, moderate and weak magnetic activity, respectively. Thus magnetic clouds compressed by high speed streams are geoeffective in 83% of the events, a result higher than the magnetic cloud whole set (77%), as expected due to the compression effects [*Gonzalez et al.*, 1999].

4. Conclusions

[18] The geoeffectiveness of a large number of interplanetary shocks (574), sector boundary crossings (946) and magnetic clouds (149) was evaluated through the Dst peak value after the structure (within an interval of 3 days). It was found that around 57% of the interplanetary shocks, 26% of the sector boundary crossings, 77% of the magnetic clouds are followed by intense or moderate geomagnetic activity. Additionally, 80% of magnetic clouds at sector boundaries, 60% of interplanetary shocks at sector boundaries, 81% of magnetic clouds driving shocks, 83% of magnetic clouds compressed by high speed streams and 100% of magnetic clouds driving shocks and located at sector boundaries were found to be geoeffective.

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E. Echer and W. D. Gonzalez, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil. (eecher@dge.inpe.br; gonzalez@dge.inpe.br)