Terrestrial Response To Eruptive Solar Flares: Geomagnetic Storms

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Abstract

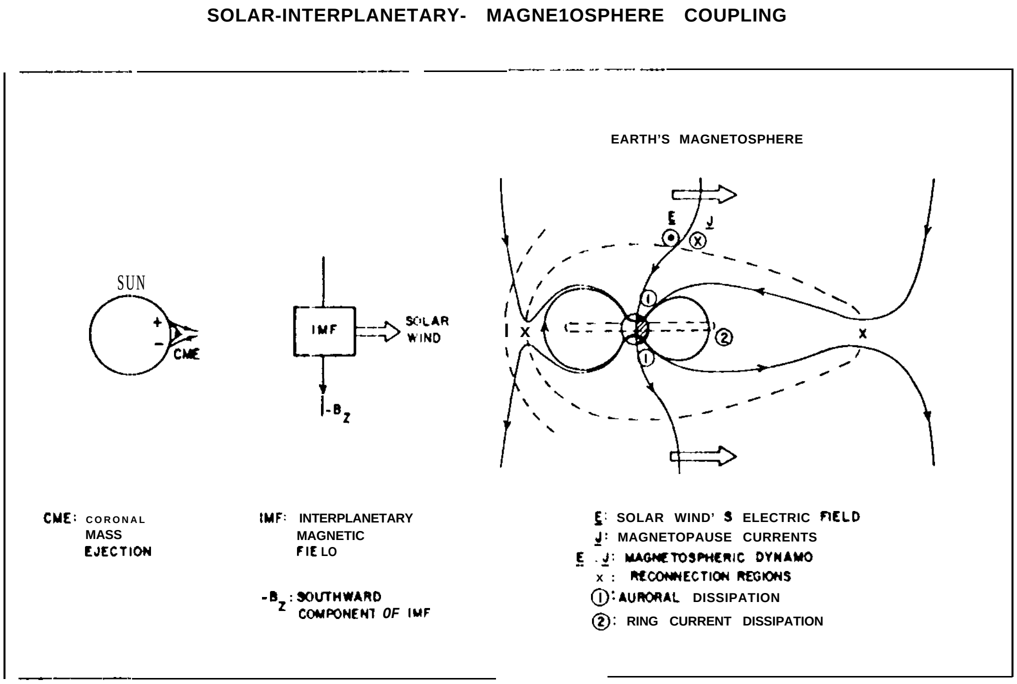
During the interval of August 1978- December 1979, 56 unambiguous fast forward shocks were identified using magnetic field and plasma data collected by the ISEE-3 spacecraft. Because this interval is at a solar maximum we assume the streams causing these shocks are associated with coronal mass ejections and eruptive solar flares. For these shocks we shall describe the shock- storm relationship for the level of intense storms ($Dst < -100$ nT). Then, we will discuss the interplanetary structures that are associated with the large-amplitude and long-duration negative B_z fields, which are found in the sheath field and/or driver gas regions of the shock and are thought to be the main cause of the intense storms.

We will also present for the solar physicist a summary of the interplanetary /magnetosphere coupling functions, based on the magnetopause reconnection process. We will end by giving an overview of the long-term evolution of geomagnetic storms such as those associated with the seasonal and solar cycle distributions.

1. Introduction

Because the emphasis of this review is to discuss the origin of geomagnetic storms in eruptive flares and, since the latter are claimed to be closely associated with coronal mass ejections (Z. Svestka, private communication) and fast forward shocks to them (e.g. Sheeley *et* al., 1985), we reduce our task to the study of the association of geomagnetic storms with interplanetary shocks.

Recent studies by Gonzalez and Tsurutani (1987), Tsurutani *et al.* (1988, 1991) and Gosling *et* al. (1991) indicate that the category of storms having the largest association with interplanetary shocks are the most intense ones. This level of storm intensity can be expressed by the storm index threshold $Dst < -100$ nT. Gonzalez and Tsurutani (1987), Tsurutani *et* al. (1988, 1991) anti Gonzalez *et* al. (1989) have shown that the main interplanetary feature associated with intense storms, accompanying the shocks, is the presence of a large-amplitude (< -10 nT), long-duration (> 3 hours) and negative B_z component of the IMF. Thus this review also concentrates on the origin of this type of B_z fields and on its quantitative interaction with the magnetosphere which leads to the development of the storms.



SOLAR-INTERPLANETARY- MAGNE1OSPHERE COUPLING

Figure 1. Schematic of the solar-interplanetary-magnetosphere coupling during solar maximum years at which a coronal mass ejection (CME) is the most important solar source for the interplanetary and magnetospheric disturbances.

Figure 1 shows schematically the solar-interplanetary -magnetosphere coupling for eruptive flares. At the sun the main ingredient is the CME, whereas at the interplanetary medium the main responsible feature for the development of the storm is the presence of a southward IMF carried by the solar wind. At the magnetosphere this southward field reconnects with the geomagnetic field leading to an effective momentum and energy transfer via a magnetospheric dynamo. In this figure two of the most important dissipation regions within the magnetosphere are indicated, the auroral and the ring current regions. The former refers to the substorm process, for which the level of intensity is monitored by the auroral electrojet index AE, and the latter refers to the storm process itself with its intensity monitored by the storm index Dst.

2. Interplanetary Shocks and Magnetic Storms

The ISEE-3 satellite, situated in a halo orbit around the L_1 libration point (at approximately 240 earth radii in front of the earth), measured 56 unambiguous fast forward shocks during the interval of August 16, 1978 to December 28, 1979 (e.g. Tsurutani and Lin, 1985). From these 56 shocks it was reported by Gonzalez and Tsurutani

(1987) that only nine preceded (within typical time lags) the occurrence of an intense geomagnetic storm (Dst < –100nT). Thus from the predictive point of view one can say that about 14% of the interplanetary shocks during solar maximum are expected to lead to the development of intense storms.

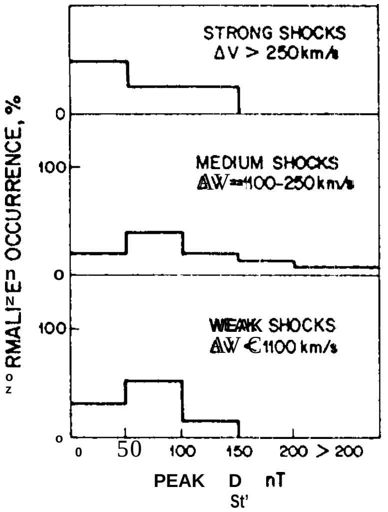


Figure 2. Normalized occurrence of interplanetary shocks for the interval August 1978- December 1979, observed by ISEE-3, as a function of the storm intensity (given by peak Dst). They are shown for three selected shock-strength intervals (strong, medium and weak). Taken from Gonzalez and Tsurutani, 1987,

On the other hand, since nine of the intense storms that occurred within this studied interval were associated with shocks, one can also say that during solar maximum 90 % of the intense storms are expected to be associated with fast forward shocks within 1 AU. A similar conclusion was arrived at by Gosling *et* al. (1991).

With respect to any influence of the shock's strength in the intensity of the resulting storm, it has long been known (e.g. Akasofu and Chapman, 1963) that there is no association at all. Figure 2 (taken from Gonzalez and Tsurutani, 1987) illustrates this point where it is shown that both weak and strong shocks have equal chances to lead to magnetic storms of any intensity.

3. Sources of Southward IMF Fields for Intense Storms

Gonzalez and Tsurutani (1987) reported that all ten intense storms (Dst <-100 nT) that occurred during the ISEE-3 studied interval had associated with them large-amplitude (< –10 nT), long-duration (>3 hours) negative B_z fields in the interplanetary medium.

Figure 3 shows one example of such an association for the day August 28, 1978. This figure illustrates the fast forward shock event that was observed at 02:00 UT of day 27, the compressed (and heated) sheath field region lasting to approximately 18:25

UT of day 27 and also a driver gas region lasting to approximately 12:00 UT of day 28. In this case, the $-B_z$ event is associated with the driver gas for which a magnetic cloud (with rotation in the B_y component) was observed (Gonzalez *et al.*, 1990*a*).

Figure 3 also shows the occurrence of a high-intensity, long-duration and continuous auroral activity (HILDCAA) event as shown by the horizontal bar in the AE panel. Tsurutani and Gonzalez (1987) and Tsurutani *et* al. (1990) associated these HILDCAA events with the simultaneous occurrence of large amplitude Alfvenic fluctuations and argued that magnetic reconnection between the southward field of these fluctuations and the geomagnetic field is responsible for the magnetospheric energization.

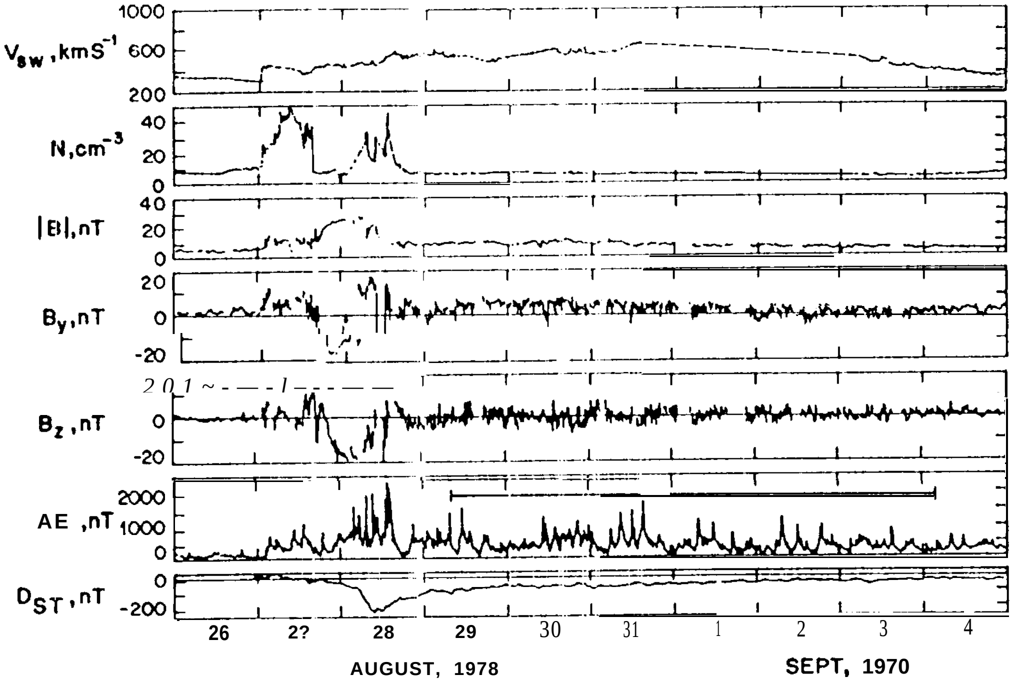
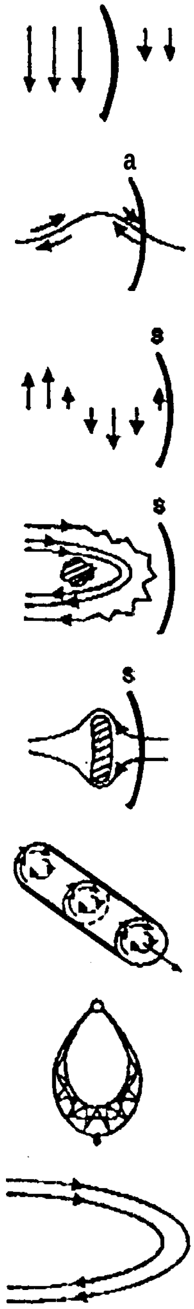


Figure 3. Example of a shock (02:00 UT August 27), sheath and driver gas fields associated with the intense storm of August 28 (peak $Dst = -220$ nT). They were followed by a HILDCAA event (shown by a horizontal bar on the AE panel)

Tsurutani *et* al. (1988) studied the interplanetary structures associated with the $-B_z$ events responsible for the 10 intense storms of the Gonzalez and Tsurutani (1987) study. Figure 4 is an updated version of those structures. They are divided in two groups: those that belong to the sheath region of the shock and those encountered within the driver gas region. About half of the 10 events belong to each of these two groups and can be associated with any of the suggested possibilities. Because the suggested structures are self explanatory, we shall not extend our discussion on this matter.



SHEATH FIELDS

a) Shocked Southward fields
Tsurutani *et* al., 1988

b) Shocked heliographic current sheets
Tsurutani *et* al., 1984

c) Turbulence, waves and discontinuities

d Draped magnetic fields
Zwan and Wolf, 1976

McComas *et al.*, *1989*

DRIVER GAS FIELDS

e) Magnetic clouds
Klein and Burlaga, 19S2

Fluxropes
Marubashi, 1986

Magnetic tongues
Gold, 1962

Figure 4. The various interplanetary features that involve large-amplitude, long-duration negative B_z fields for the 10 **intense storms** ($Dst < -100$ nT) of August 1978 – December 1979. They are grouped into two broad categories: Sheath fields and Driver gas fields.

4. Solar Wind-Magnetosphere Coupling Functions

Magnetic field reconnection between the southward directed IMF and the geomagnetic field (Dungey, 1961) is the most acceptable mechanism for the energy transfer responsible for the auroral and ring current energization processes. Since early work (Arnoldy, 1971; Tsurutani and Meng, 1972) it is known that a simple correlation between IMF $-B_z$ and magnetospheric dissipation parameters, such as the auroral index AE, give fairly high correlation values due to the fact that the B_z parameter is the main ingredient of the reconnection energy-transfer mechanism, More complex functions associated with the electric field transfer and with the energy transfer of magnetopause reconnection were later introduced (Gonzalez *et* al., 1989 and references therein). Table 1 is a summary of the most commonly used coupling functions. In this Table, v and ρ are the scalar wind speed and density, respectively; B_T is the transverse (to the Sun-Earth line) component of the IMF vector, $B_T = (B_z^2 + B_y^2)^{\frac{1}{2}}$ in solar magnetospheric coordinates; B *is* the IMF amplitude and θ is the angle between $\underline{B}_T$ and the geomagnetic field vector taken at the magnetopause; and L_o is a constant scale-length factor (equal to 7 earth radii). Gonzalez (1990a) showed that most of these functions can be derived as particular cases of more general expressions for the electric field and energy transfer at the magnetopause due to large-scale reconnection.

5. Seasonal and Solar Cycle Distributions of Intense Storms

It is known that geomagnetic activity has a seasonal variability with maxima at

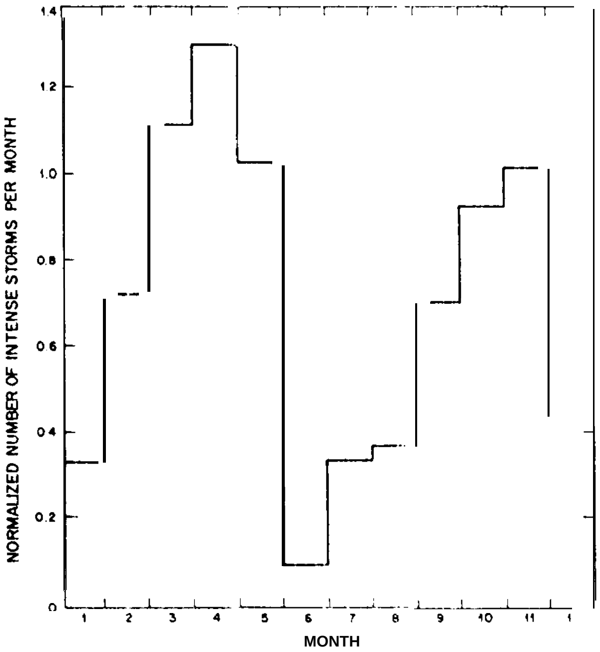


Figure 5. Seasonal distribution of intense storms (Dst < -100 nT) for the interval 1975-1986. The normalized number of these storms per month is given.

TABLE 1

MOST COMMONLY USED COUPLING FUNCTIONS FOR THE SOLAR WIND-MAGNETOSPHERE INTERACTION

(a) **Electric field related**		(b) **Power related**		(c) **Simple** expressions	
VB_z	Rostoker et al. (1972) Burton et al. (1975)	$\epsilon = VL_o^2B^2\sin^4(\theta/2)$	Perreault and Akasofu (1978)	B_z	Arnoldy (1971) Tsurutani and Meng (1972)
VB_T	Doyle and Burke (1983)	$(\rho v^2)^{1/2}VB_z$	Murayama (1986) Gonzalez et al. (1989)	B_zV^2, BV^2	Murayama and Hakamada (1975) Crooker et al. (1977) Baker et al. (1981) Holzer and Slavin (1982)
$VB_T\sin(\theta/2)$	Gonzalez and Mozer (1974) Doyle and Burke (1983)	$(\rho V^2)^{-1/3}VB_T^2\sin^4(\theta/2)$	Vasyliunas et al. (1982) Gonzalez et al. (1989)	B_z^2V, B^2V	Holzer and Slavin (1982) Baker et al. (1981)
$VB_T\sin^2(\theta/2)$	Kan and Lee (1979) Gonzalez and Gonzalez (1981) Reiff et al. (1981) Wygant et al. (1963) Doyle and Burke (1983)	$(\rho V^2)^{1/6}VB_T\sin^4(\theta/2)$	Vasyliunas et al. (1982) Bargatze et al. (1986) Gonzalez et al. (1989)		
$VB_T\sin^4(\theta/2)$	Wygant et al. (1983) Doyle and Burke (1983)				

the two equinoxes (e.g. Russell and McPherron, 1973). However it is not clear if such variability is also distinguishable for intense storms. This expectation is confirmed by the distribution shown in Figure 5. It refers to the intense storms (Dst <-100 nT) that occurred within the 1975–1986 interval. However it remains to be seen if the mechanisms suggested for the seasonal variability y of geomagnetic activity in general (e. *g.* Russell and McPherron, 1973; Murayama, 1 974) are or are not applicable to the category of intense storms (Clua de Gonzalez *et* al., 1991).

Gonzalez *et al.* (1990*b*) studied the solar-cycle distribution of intense storms for the interval 1880–1985 using the geomagnetic indices aa (1880–1964) and Dst (1965-1985). They showed that intense storms tend to occur within the solar cycle with a dual-peak distribution. On the average the first peak tends to occur close to solar maximum and the second peak about two years after solar maximum. These authors also showed that a similar dual-peak distribution occurred during the 1970–1981 interval for the yearly number of large negative B_z events with amplitudes < –10 nT and duration > 3 hours, supporting the association described in Section 3. However the exact nature of this dual-peak distribution still needs to be studied.

Conclusion

In this brief review some aspects of intense geomagnetic storms have been presented with the aim of suggesting further research within the framework of the solar-interplanetary -magnetosphere coupling. This review refers to solar maximum years within which the CMES and the eruptive solar flares are more abundant.

Acknowledgments

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