Geofísica Internacional (1992) Vol. 31, Num. 1, pp.11-18

Interplanetary-magnetosphere coupling during intense geomagnetic storms at solar maximum

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RESUMEN

Durante el intervalo del 16 de agosto de 1978 al 28 de diciembre de 1979, 90% de las tempestades geomagnéticas intensas ($Dst < -100nT$) fueron precedidas por la llegada a 1AU de ondas de choque interplanetarias rápidas, conforme fueron identificadas con datos de plasma y campos magnéticos colectados por la nave espacial ISEE-3. En relación con estos eventos, discutiremos las estructuras interplanetarias asociadas a campos magnéticos B_z negativos, de gran amplitud y larga duración, que se consideran como la causa principal de las tempestades intensas. Presentaremos también un resumen de las funciones de acoplamiento interplanetario-magnetosféricas, basadas en el proceso de reconexión en la magnetopausa terrestre. Terminaremos con una revisión sucinta de la evolución a largo plazo de las tempestades geomagnéticas intensas, tales como las mostradas en las distribuciones estacionales y del ciclo solar.

PALABRAS CLAVE: tormentas geomagnéticas; reconexión magnética.

ABSTRACT

During the interval of August 16, 1978 - December 28, 1979, 90% of the intense geomagnetic storms ($Dst < -100nT$) were preceded by the arrival of interplanetary fast forward shocks at 1AU, as identified with magnetic field and plasma data collected by the ISEE-3 spacecraft. For these events we discuss the interplanetary structures that are associated with the large-amplitude and long-duration negative B_z fields that are thought to be the main cause of the intense storms. We also present a summary of the interplanetary-magnetosphere coupling functions, based on the magnetopause reconnection process. We end by an overview of the long-term evolution of intense geomagnetic storms such as those associated to the seasonal and solar cycle distributions.

KEY WORDS: geomagnetic storms; magnetic reconnection.

1. INTRODUCTION

Because the emphasis of this review is to discuss the interplanetary origin of intense geomagnetic storms during solar maximum, we shall concentrate on the class of intense storms that are associated to fast forward shocks developed within 1AU.

Recent studies by González and Tsurutani (1987), Tsurutani *et al.* (1988, 1991) and Gosling *et al.* (1991) indicate that the category of storms that have the largest association with interplanetary shocks are the most intense ones. This level of storm intensity can be expressed by the storm index threshold $Dst < -100\ nT$. González and Tsurutani (1987), Tsurutani *et al.* (1988, 1991) and González *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), negative B_z component of the IMF. This review also concentrates on the origin of this type of B_z fields and on its quantitative interaction with the magnetosphere that leads to the development of the storms.

Figure 1 shows schematically the solar-interplanetary-magnetosphere coupling of interest. At the Sun the main ingredient is assumed to be a coronal mass ejection (CME), which can also be associated to the presence of a low-latitude short-lived coronal hole (González *et al.*, 1991), 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. 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 was situated in a halo orbit (about the L1 libration point), at approximately 240 Earth radii in front of the Earth (Figure 2), and measured 56 unambiguous fast forward shocks during the interval of August 16, 1978 to December 28, 1979. For this a full set of magnetic field (Frandsen *et al.*, 1978) and plasma (Bame *et al.*, 1978) data were used. From these 56 shocks González and Tsurutani (1987) reported that only nine preceded (within typical time lags) the occurrence of an intense geomagnetic storm ($Dst < -100\ nT$). Thus from the predictive point of

Solar-interplanetary-magnetosphere coupling

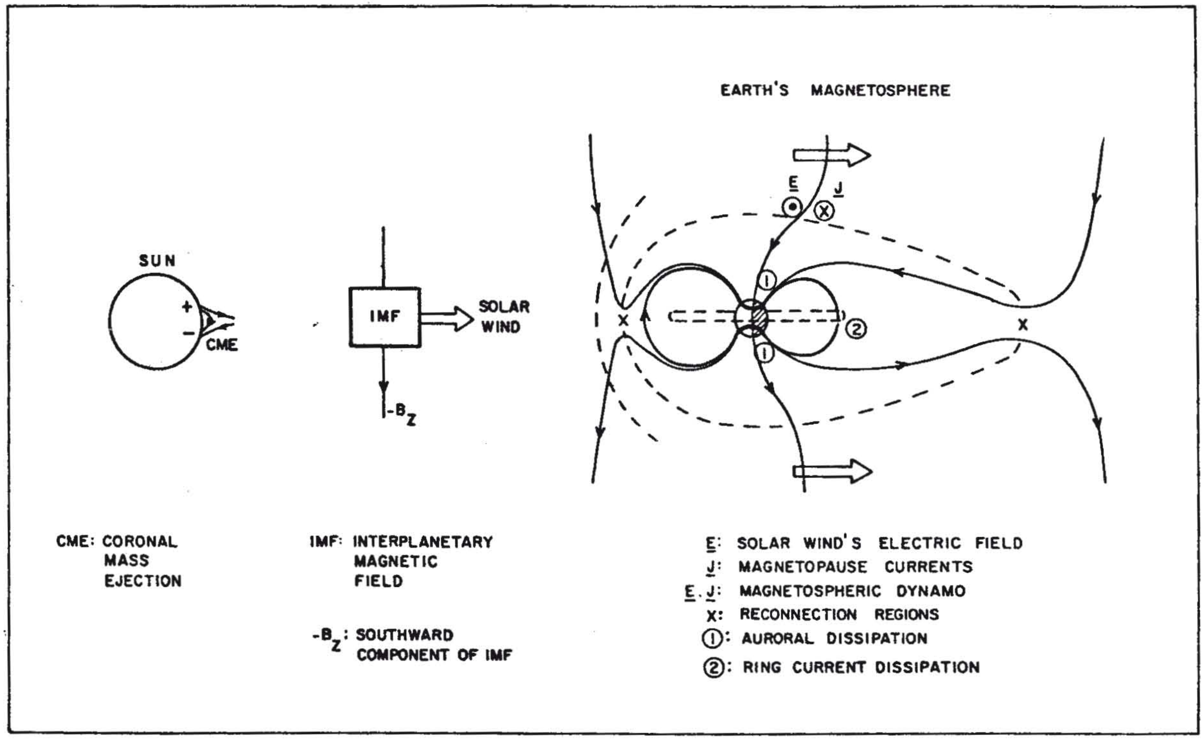

Fig. 1. Schematics of the solar-interplanetary-magnetosphere coupling during solar maximum years.

Halo-orbit around Sun-Earth libration point

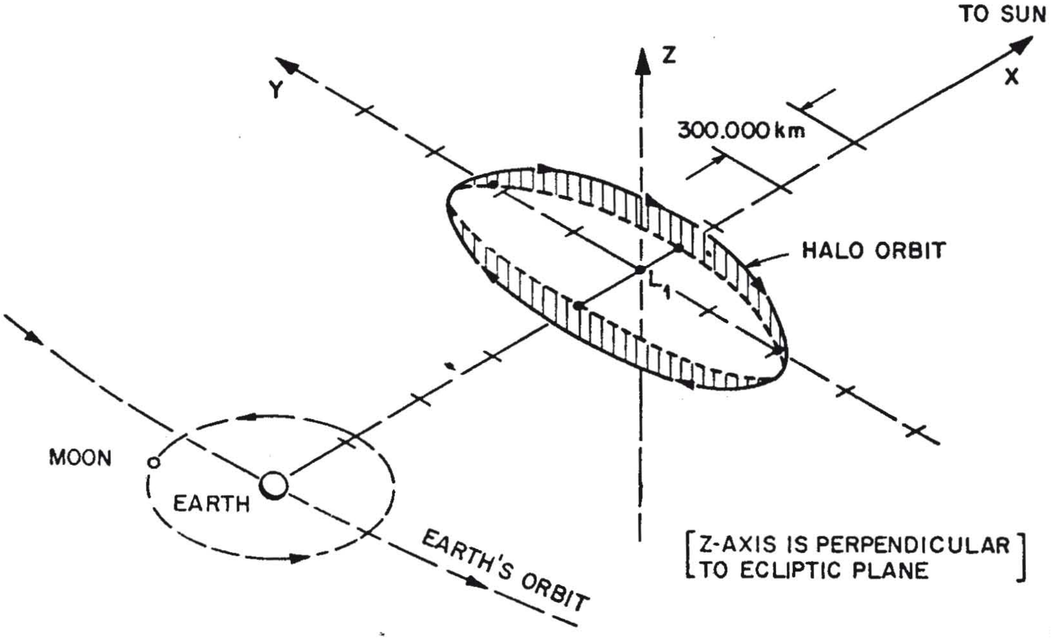

Fig. 2. The ISEE-3 orbit about the Sun-Earth Libration Point, L1. (XYZ) is the geomagnetic solar ecliptic coordinates.

view one can say that about 14% of the interplanetary shocks during solar maximum are expected to lead to the development of intense storms.

On the other hand, since nine of the intense storms that occurred within this interval were associated to 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 reached by Gosling *et al.* (1991).

With respect to any influence of the shock's strength on the intensity of the resulting storm it is known since long ago (e.g. Akasofu and Chapman, 1963) that there is no association at all. Figure 3 (taken from González 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.

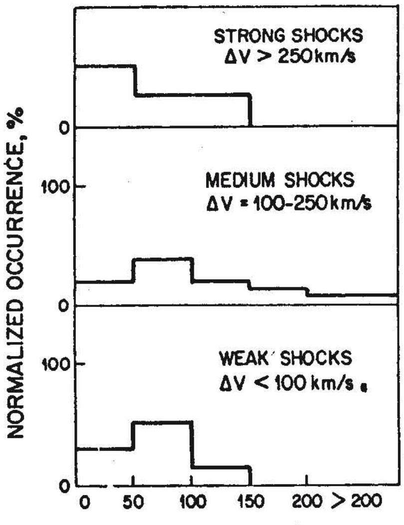

Fig. 3. Normalized occurrence of interplanetary shocks for the interval August 16, 1978 - December 28, 1979 observed by ISEE-3, as a function of the storm intensity (given by peak Dst). They are shown for three selected shock-strength intervals (strong, medium and weak). Taken from González and Tsurutani, 1987.

3. SOURCES OF SOUTHWARD IMF FIELDS FOR INTENSE STORMS

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

Figure 4 shows one example of such an association for 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 approximately til 18:25 hours UT of day 27 and also a driver gas region lasting approximately til 12:00 hours UT of day 28. The large $-B_z$ event is associated in this case with the driver gas for which a magnetic cloud (with rotation in the B_y component) was observed (González *et al.*, 1990a).

Figure 4 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. For the ISEE-3 studied interval Tsurutani and González (1987) reported the occurrence of 8 HILDCAA events, five of which followed an intense storm event as in the case of figure 4. Tsurutani and González (1987) and Tsurutani *et al.* (1990) associated these HILDCAA events to 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.

Tsurutani *et al.* (1988) studied the interplanetary structures that were associated to the negative B_z events responsible for the 10 intense storms of the González and Tsurutani (1987) study. Figure 5 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 that are 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 dwell on this matter any further.

For the ISEE-3 studied interval, González and Tsurutani (1987) also reported the occurrence of northward B_z event similar to the southward events but opposite in polarity ($B_z > +10$ *nT*, T > 3 hours). These northward IMF events were similar to the southward field events in several ways: the number is about the same (11 northward events vs 10 southward events); for both the northward and southward events, nine followed shocks within similar time lags. It is possible that these northward fields are also associated with structures similar to those shown in Figure 5 and, therefore, that the responsible physical processes for generating them do so with random orientations. However, during these northward B_z events the magnetosphere is in a quiet state, namely, the level of intensity of storms or substorms, if any, is very low.

4. SOLAR WIND-MAGNETOSPHERE COUPLING FUNCTIONS

Magnetic field reconnection between the southwardly 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, gives fairly high correlation values due to the fact that the B_z parameter is the main ingredient of the reconnection energy-transfer mechanism. More com-

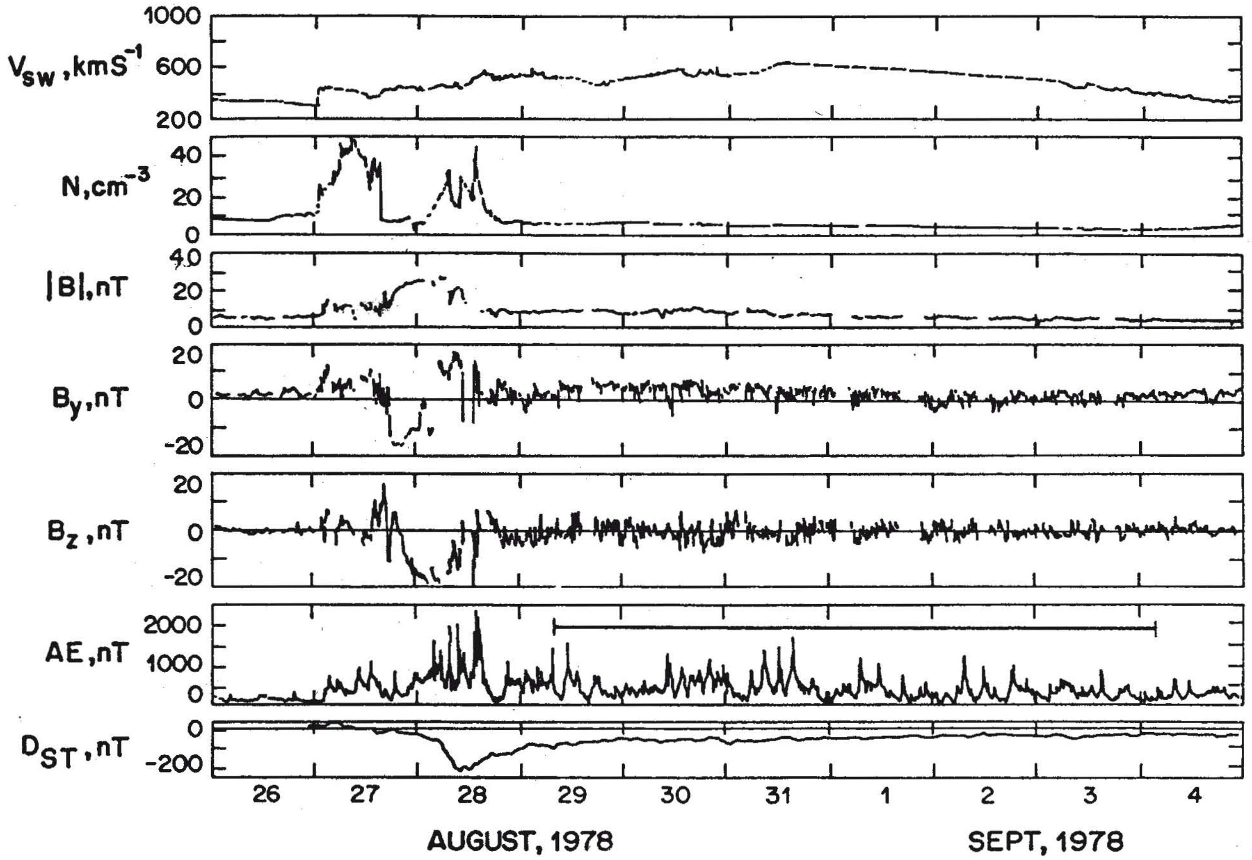

Fig. 4. Example of a shock (02:00 UT August 27), sheath and driver gas fields associated to the intense storm of August 28 (peak *Dst* = -220 *nT*). They were followed by a HILDCAA event (shown by a horizontal bar on the AE panel), which was accompanied by large alfvenic fluctuations in the magnetic field components B_y and B_z.

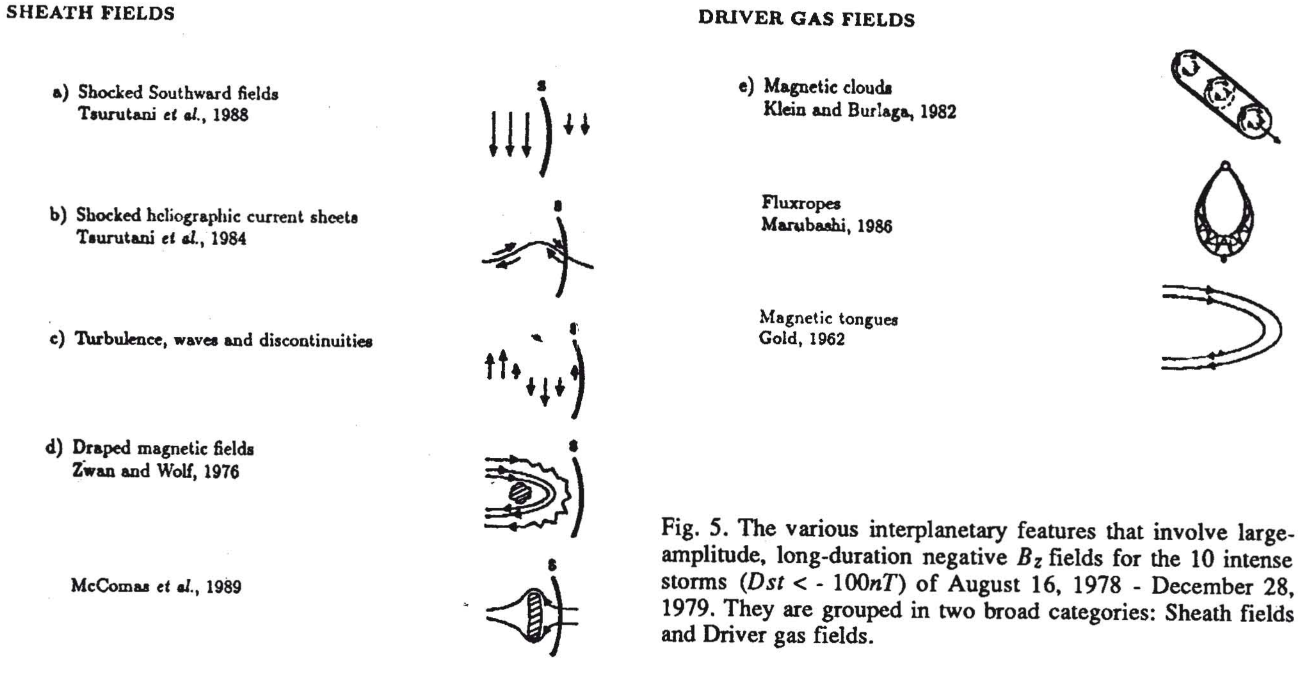

Fig. 5. The various interplanetary features that involve large-amplitude, long-duration negative B_z fields for the 10 intense storms ($Dst < -100nT$) of August 16, 1978 - December 28, 1979. They are grouped in two broad categories: Sheath fields and Driver gas fields.

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)	$\varepsilon = VL_0^2B^2\sin^4(\theta/2)$	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. (1983) 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)				

plex functions associated with the electric field transfer and with the energy transfer of magnetopause reconnection were later introduced (e.g. González and Mozer, 1974; Burton *et al.*, 1975; Murayama and Hakamada, 1975; Perreault and Akasofu, 1978; González *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 solar wind speed and density; B_T is the transverse (to the Sun-Earth line) component of the IMF vector, $B_T = (B_z + B_y)^{1/2}$ in solar magnetospheric coordinates; B is the IMF amplitude and θ is the angle between B_T and the geomagnetic field vector taken at the magnetopause; and L_0 is a constant scale-length factor (equal to 7 Earth radii). González (1990) 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 DISTRIBUTION OF INTENSE STORMS

It is known that geomagnetic activity has a seasonal variability with maxima at the two equinoxes (e.g. Russell and McPherron, 1973). However, it is not clear if such variability is distinguishable also for intense storms. This expectation is confirmed by the distribution shown in Figure 6. 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 of geomagnetic activity in general (e.g. Russell and McPherron, 1973; Murayama, 1974) are applicable or not to the category of intense storms (Clua de González *et al.*, 1991).

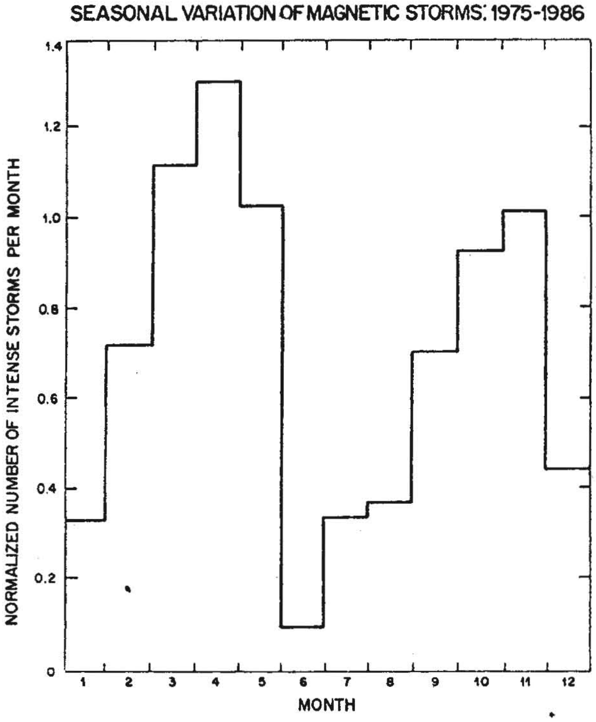

Fig. 6. Seasonal distribution at intense storms ($Dst < -100$ *nT*) for the interval 1975-1986. The normalized number of these storms per month is given.

González *et al.* (1990b) 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. Figure 7 (taken from González *et al.*, 1990b) shows this average dual peak distribution for solar cycles 13 to 21 (cycle 17 excluded) in which the average number of intense storms for the first peak, the valley and the second peak are given. The error bars represent the standard deviation of the mean. For comparison, the average number of storms during the preceding and following solar minimum years are also given. 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 $< -10nT$ 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.

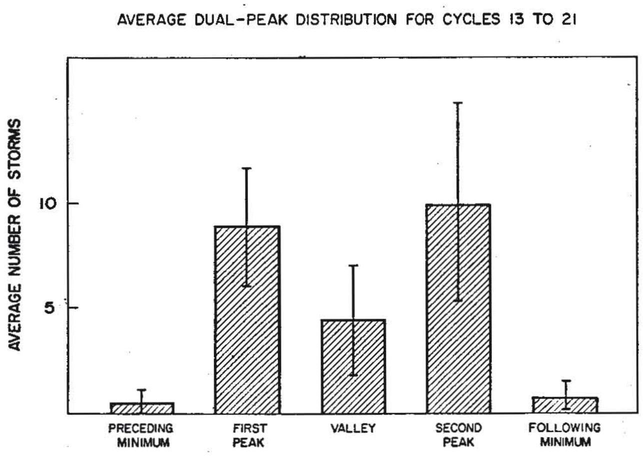

Fig. 7. Average number of intense storms for the dual-peak distribution feature of cycles 13 to 21 (except cycle 17). The average number of intense storms during the preceding and following solar minimum years are also given for comparison. The error bars are the standard deviation of the mean. Taken from González *et al.*, 1990b.

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 interplanetary-magnetosphere coupling during solar maximum years. Although this review does not deal with the solar origin of the interplanetary shocks, it is worth pointing out that the general "coronal mass ejection" process can involve at the solar surface not only active regions, as usually assumed, but also the simultaneous presence at low latitude of short lived coronal holes (González *et al.*, 1991). The importance of the role of such coronal holes as sources of interplanetary and geomagnetic disturbances has been mainly stressed in the work by Hewish and Bravo (1986).

ACKNOWLEDGMENTS

The authors benefited from discussions with O. Mendes, Jr. We thank the organizers of the Second Latin American Conference on Space Geophysics (held at Cuernavaca - Mexico in July 1991), and particularly the Convener Héctor Pérez de Tejada, for giving us the opportunity to present this review. This work was partially supported by the "Fundo Nacional de Desenvolvimento Científico e Tecnológico" of Brazil and partially by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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