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The forecasting of intense geomagnetic storms

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RESUMEN

Las investigaciones recientes han mostrado que las tormentas geomagnéticas intensas se producen cuando llega a la magnetopausa un viento solar que contiene un campo magnético con una componente sur intensa, el cual dura varias horas. La presencia de este tipo de campos se ha tratado de explicar mediante procesos tanto solares como interplanetarios, pero aún no está del todo claro cuál es su origen. En este artículo discutimos el problema general del pronóstico de tormentas geomagnéticas intensas con base en observaciones solares, se hace una revisión de los diferentes enfoques que se han dado a este problema y se extiende un estudio previo respecto a las fuentes solares de las tormentas geomagnéticas de mayor intensidad. La conclusión es que las evidencias apuntan hacia la ocurrencia de eventos solares explosivos (ráfagas o erupción de protuberancias) junto a un hoyo coronal y cerca del meridiano central del Sol como los eventos que potencialmente pueden producir perturbaciones geomagnéticas importantes. Se hacen también algunas sugerencias sobre como el pronóstico puede mejorarse utilizando imágenes en rayos X de los eventos solares, simulaciones MHD numéricas de la generación y propagación de los eventos transitorios en el medio interplanetario y el rastreo de las perturbaciones que viajan en el viento solar por medio de centelleo interplanetario de fuentes de radio celestes.

PALABRAS CLAVE: Tormentas geomagnéticas, perturbaciones interplanetarias, actividad solar.

ABSTRACT

Intense geomagnetic storms are produced by the arrival at the magnetopause of solar wind carrying a magnetic field with a large southward component lasting for several hours. Solar and interplanetary processes have been considered to explain the presence of this field, but many aspects of its origin are still unclear. The general problem of forecasting intense geomagnetic storms several days in advance from solar observations is discussed, reviewing the different approaches taken so far and extending a previous study of the solar sources of major geomagnetic storms. All evidence favours the occurrence of an explosive event (flare or prominence eruption) near a coronal hole and near the solar central meridian as a potentially geoeffective solar event. Comments are made on how our forecasting capability may improve with the use of soft X-ray images of coronal transients, numerical MHD simulations of the generation and propagation of solar transients in the interplanetary medium, and tracking of solar wind disturbances by means of interplanetary scintillation.

KEY WORDS: Geomagnetic storms, interplanetary disturbances, solar activity.

INTRODUCTION

In order to predict the occurrence of intense geomagnetic storms (IGSs), peak Dst < -100 nT, several days in advance, it is necessary to know the various cause-effect links of the chain starting with a solar event and ending in an IGS. Now it is clear that a magnetic coupling must exist between the solar wind and the Earth's magnetosphere, as first proposed by Dungey (1961) and later demonstrated by Rostoker and Falthammar (1967) and others. Gonzalez and Tsurutani (1987) showed that a necessary and sufficient condition for the occurrence of an IGS is the arrival at the magnetopause of a large and negative (< -10 nT) Bz component of the interplanetary magnetic field lasting more than 3 hours. However, there is not yet a general agreement on what solar event, or events, can generate this interplanetary magnetic field.

The relation between solar flares and strong magnetic perturbations has long been recognized. After the discovery of the solar wind and transient interplanetary (TIP) shocks, geomagnetic storms were associated with Earth passage of flare-produced shock disturbances (e.g. Hundhausen, 1972). However, many TIP shocks are not associated with flares and when they are, Tang *et al.* (1989) showed that there is no correlation between the flare parameters and the strength of the TIP shock at Earth. The sudden eruption of solar prominences has also been invoked as a source of geomagnetic perturbations (Joselyn and McIntosh, 1981; Wright and McNamara, 1983). Yet TIP shocks may be unrelated to prominence eruptions or flares.

Coronal mass ejections (CMEs) were first observed in the 1970's as changes in coronal structure that occur on a time scale between a few minutes and several hours. They appear as new, discrete, bright white light features moving outwards in the coronagraph field of view. Initially they were interpreted as resulting from flares or the eruption of prominences, but many CMEs turned out to be unrelated to these surface eruptive events and when they are, CMEs often start in the corona before the surface activity does. A statistical study made by Harrison (1994) of SMM CMEs in 1986-7 showed that only 21 (14%) of 151 CMEs were associated with an X-ray flare within ±2 hours of the initial observation of the CME and within 50° of the limb. The actual percentage may be somewhat higher because some associated flares may be occulted by the solar limb. When the CME occurs in association with a prominence eruption, the prominence material can also be seen in the coronagraph field of view. In the SMM CMEs in 1980 Webb and Hundhausen (1987) found bright cores of material, presumed to be remnants of H_α prominences, in about one third of the cases. At present CMEs are considered by many authors as the result of rearrangements of the large scale coronal magnetic fields (e.g. Kahler *et al.*, 1988; St. Cyr and Webb, 1991, Bravo, 1995), while some believe that they may be also produced by flares (e.g. Dryer, 1994).

Observations of CMEs on the Solwind coronagraph on board the P78-1 satellite have been compared with TIP shocks registered by Helios 1 spacecraft from 1979 to 1983 by Sheeley *et al.* (1985). Virtually every shock observed by Helios was preceded by a CME observed by Solwind. After that, it has been widely accepted that CMEs are the pistons driving TIP shocks and major geomagnetic disturbances. The new paradigm says that the fastest and largest CMEs typically contain shocks at their leading edges and strong magnetic fields in extended regions following the shocks, due to compression of the slower solar wind ahead of the CME. When these CME-driven solar wind disturbances arrive at the Earth's magnetosphere large geomagnetic storms often result, particularly when the magnetic field carried by the solar wind behind the shock or inside the body of the ejected plasma is directed southward (e.g. Gosling, 1993). Here we discuss the results of various studies relating interplanetary, geomagnetic, and solar observations to test this new paradigm and to assess our present capability to forecast intense geomagnetic storms.

RESULTS OF THE SOLWIND/HELIOS STUDY

Although the fastest and largest CMEs are widely accepted as the pistons driving TIP shocks, the velocity of the Solwind CMEs associated with Helios TIP shocks ranges from 100 km/s to 1750 km/s, and their final angular extension is from 20 to 200 degrees, with 2/3 of these smaller than 90° (see Figure 1). A scatter plot of both quantities is shown in Figure 2. It is clear that not only very fast and wide CMEs are associated with TIP shocks, but also slow and narrow CMEs. Moreover, the list from Sheeley *et al.* (1985) shows that there is no correlation between the CME speed in the coronagraph field and the speed or strength of the associated TIP shock. Then, the claim that CMEs are the pistons driving the shocks seems not to have a physical support. Some authors consider that magnetic clouds (that is, regions of plasma in the solar wind where the magnetic field intensity is high, its direction rotates smoothly by a large angle during an interval of the order of a day, and the proton temperature is low) are the interplanetary counterpart of CMEs. However, only 26 (46%) of the 56 TIP shock cases reported in Sheeley *et al.* (1985) had a clear magnetic cloud (or "piston") behind. It can be argued that the cloud was always behind the shock, but as it is smaller than the shock itself, it may be missed by the spacecraft. Then it would be expected that the widest CMEs should more likely correspond to the cloud cases. However, only 9 (47%) of the 19 CMEs with angular extension equal or greater than 90 degrees corresponded to cloud cases. Thus, the identification of the CME material with the interplanetary cloud is not clear either. As we shall see below, a more detailed analysis of the observations suggests another possibilities and casts additional doubts on the role of clouds as the pistons driving TIP shocks.

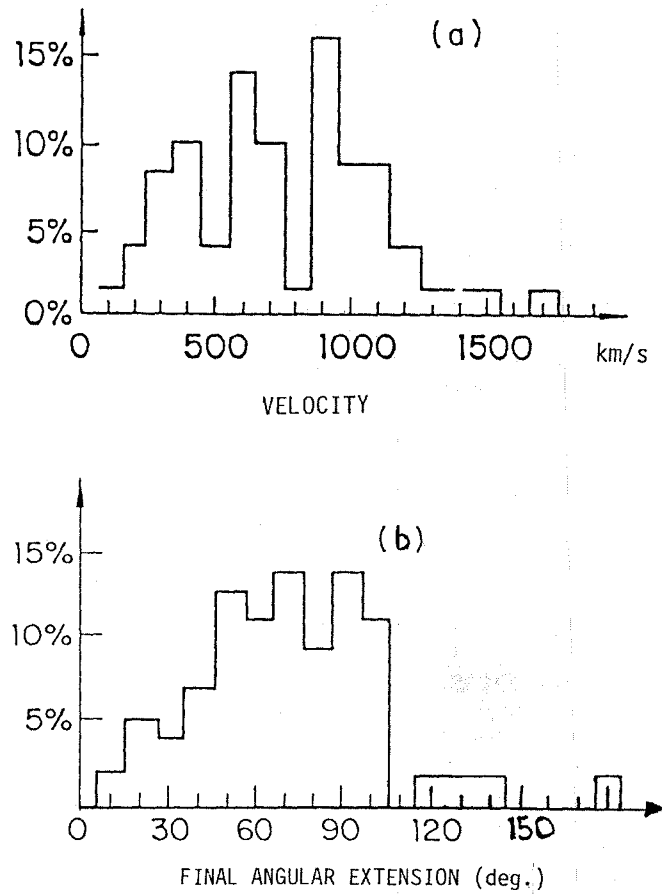

Fig. 1. (a) Velocity and (b) final angular width distribution of the Solwind CMEs associated with Helios TIP shocks. The event with a final angular extension of 200 degrees is not included in figure (b).

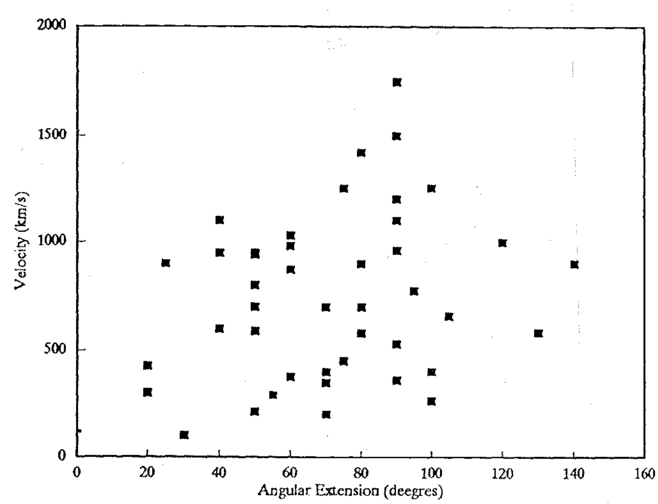

Fig. 2. Scatter plot of velocity and angular extension of Solwind CMEs associated with TIP shocks. No velocity could be determined for the two CMEs wider than 140 degrees.

In the Solwind/Helios study it was also found that about 34 (61%) of the CMEs associated with shocks were accompanied by an X-ray/flare event (F). Some of the fastest or widest CMEs do not belong to this category. Also the strength of the TIP shock is unrelated to whether or not an F event occurred. The associated flares include 4 unlocalized events, 7 events 50 degrees or more away from the limb over which the CME was observed, and 2 events behind the limb. If we disregard the 4 cases of unlocalized flares, it turns out that 23 in 52 (44%) CMEs had an association within the window considered by Harrison (1994), which means that CMEs associated with interplanetary shocks have a higher association with flares than does the general CME population. Interestingly, of 19 cases where the cloud was clearly seen and the flare observation was not in doubt, 16 (84%) corresponded to CMEs that occurred in association with an F event. This suggests that the interplanetary cloud was associated with the flare rather than with the CME itself. No information concerning prominence or filament eruptions (PE) was given in Sheeley *et al.* (1985), but a recent analysis of Helios data by Bothmer and Schwenn (1994) shows a good correlation between PEs and interplanetary magnetic clouds.

RESULTS OF THE IPS SURVEY

As mentioned above, the association of CMEs with surface explosive events (for the cases of TIP shocks with or without cloud) in the Solwind/Helios study could have been underestimated because some flares may be occulted by the solar limb. This problem is not present in the study of the solar origin of major interplanetary disturbances carried out by means of interplanetary scintillation (IPS) tracking. Using this method, Hewish and Bravo (1986) found that all TIP shocks were tracked back to a solar region containing a coronal hole. Thus we proposed that TIP shocks can be produced by a sudden and large increase in the speed of the solar wind from a hole (see also Bravo *et al.*, 1991a,b). An enlargement of the hole as a consequence of the emergence of new photospheric flux with different magnetic polarity was proposed by Bravo (1991) as the cause of the increase in the solar wind speed. Such an enlargement was actually shown for the case of a particular event in Bravo (1993). Enlargements of coronal holes in association with interplanetary and geomagnetic disturbances have been now frequently observed in Yohkoh SXT images (e.g. Watanabe *et al.*, 1994; Watari *et al.*, 1995).

In our IPS study we found that 42% (30 in 73) of transient interplanetary disturbances occurred when a major flare (usually with X-ray emission) and/or a prominence or filament eruption was near a coronal hole at the solar source region (Hewish and Bravo, 1986). These results were similar to the Solwind/Helios results. Bravo and Lanzagorta (1994) considered the 29 disturbances of the IPS period that produced a storm sudden commencement when arriving at 1 AU as evidence for a shock and looked for the presence of magnetic clouds behind them. We found that, when present, clouds appeared at very different distances behind the shock, with delay time ranging from 1 hour to more than 1 day after the shock passage at Earth. The delay was uncorrelated with the cloud velocity, which could be either lower or higher than that of the wind behind the shock. These findings add more doubts to the "piston" role of clouds.

The TIP shocks of the IPS period and their solar associations are listed in Table 1. Each event had only one associated X-ray flare or prominence eruption. The angular distance from the solar central meridian to the nearest coronal hole (CH) is shown as well as the angular distance (Δ) of the F or PE event to the nearest hole border. "CM" indicates that the structure was crossing central meridian at the time of the solar event. We see that clouds are associated with only 11 shocks (38%) and that all these cases corresponded to events when an F and/or a PE event took place near the coronal hole at the solar source of the disturbance. This is an even higher association than for the Solwind/ Helios study. Of 11 cases with clouds, 6 were associated with an F and 5 with a PE. The cloud cases were not the only shocks associated with F or PE events, but they were the ones where the coronal hole was no further than 10 degrees from central meridian and the F or PE occurred within 20 degrees from the hole's border. In the case of event 26, a magnetic cloud was not observed, but a "plasma cloud" (ejecta with high plasma density) was detected behind the shock.

Table 1

Transient interplanetary shocks of the IPS survey period

No.	Arrival at 1 AU	CLOUD	Ass. F or PE	CH	Δ
1	1978 08/18	NO	NO		
2	08/27	YES	PE(N18CM)	CM	15
3	09/05	NO	F(S15E52)	58	2
4	09/11	NO	NO		
5	09/20	NO	NO		
6	09/25	YES	F(N23E35)	CM	6
7	09/29	YES	F(N27W19)	CM	5
8	10/04	NO	NO		
9	10/09	YES	PE(N23E10)	CM	7
10	10/17	YES	PE(N21CM)	CM	5
11	10/29	YES	F(?)	10	
12	11/08	NO	NO		
13	11/12	YES	F(N17E01)	5	10
14	11/19	NO	NO		
15	12/18	NO	F(S15W54)	20	35
16	12/24	NO	NO		
17	1979 01/04	NO	F(S20E66)	CM	45
18	01/06	NO	NO		
19	01/09	NO	F(N17E52)	50	30
20	01/25	NO	NO		
21	02/21	YES	F(N17W14)	10	7
22	03/04	NO	NO		
23	03/06	NO	PE(S30W45)	30	45
24	03/09	YES	PE(N36W15)	CM	15
25	03/22	YES	F(S05W13)	10	20
26	04/05	NO	F(S25W14)	11	25
27	04/24	YES	PE(S10CM)	10	20
28	05/29	NO	NO		
29	07/12	NO	NO		

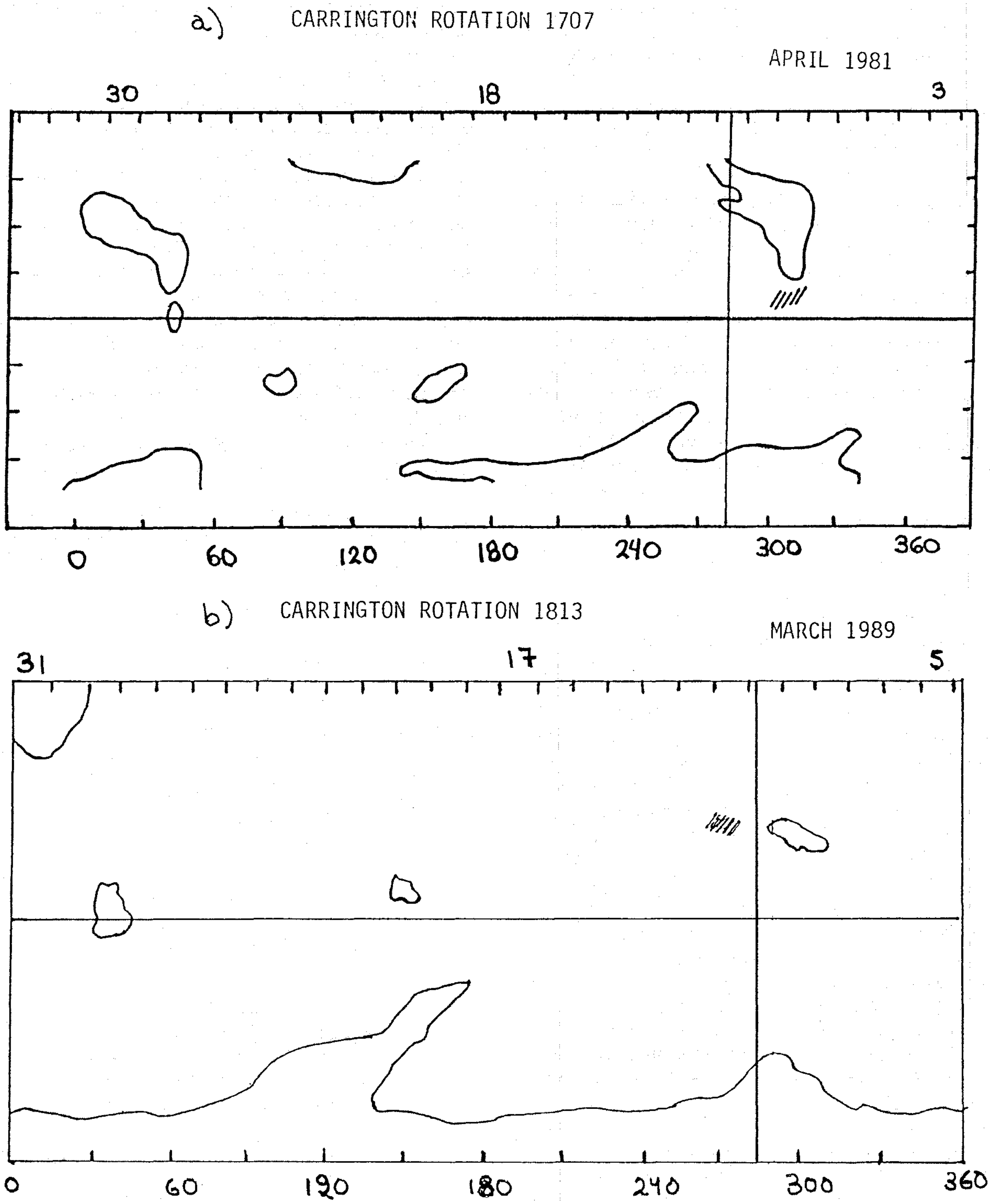

Fig. 3. (a) Carrington rotation 1701 showing coronal hole boundaries and the location of the flare associated by Cliver and Crooker (1993) with the great geomagnetic storm of 13 April 1981 (dashed region); the position of the solar central meridian at the time of the flare is indicated with a vertical line. (b) Carrington rotation 1813 showing the same for the greatest storm of 14 March 1989.

Combining the results of the Solwind/Helios and IPS studies we may conclude that major interplanetary disturbances seem to be associated with a CME and a coronal hole transient. Hence, a spatial association between CMEs and coronal holes must exist in the TIP shock cases. By taking the CMEs in the Solwind/Helios study, we have proved that this is the case (Bravo and Pérez-Enríquez, 1994). We have proposed a scenario where coronal hole enlargements and CMEs are associated phenomena, both being due to the emergence of new flux (Bravo, 1995). In this scenario the TIP shock is produced across the hole's flux tube by a sudden increase of solar wind velocity, and the CME material merges with the fast wind from the hole. Further, both the Solwind/Helios and the IPS studies suggest that the observation of a cloud behind the shock is associated with a surface explosive event (F and/or PE).

INTENSE AND LONG-LASTING Bz-SOUTH (Bz*) INTERPLANETARY FIELDS

As mentioned above, the important factor in the production of an intense geomagnetic storm (IGS) is the arrival at the magnetopause of a large negative (< -10 nT) Bz component of the interplanetary magnetic field lasting longer than 3 hours (or Bz* field for short). The TIP shock itself is not important as it has been shown that the geomagnetic storm intensity is not correlated with the strength of the shock and some IGS have occurred without any shock at all. Nor does it matter whether the "cloud" or the plasma body with the Bz* field is the piston driving the shock or if it is just carried by the wind. According to Gonzalez and Tsurutani (1987) there are two different possibilities for the appearance of Bz* in the solar wind with about the same frequency: (A) the Bz* is the result of compression of the ambient solar wind field produced by the ejection of a transient faster solar plasma; (B) the Bz* is within the transient ejected plasma body. The terms "CME", "piston", "cloud", "driver", etc, that have been used for the plasma body behind TIP shocks, have particular and different implications. So we prefer to use the term "ejecta" because: (1) it does not imply a particular shape or magnetic topology (it can be used for clouds, ropes, plasmoids, tongues, open field plasma, etc.); (2) it does not imply a particular solar region of origin (it may be ejected from an active region, a prominence, a coronal helmet, a coronal hole, etc.); (3) it does not imply any particular dynamic relation to TIP shocks (it may or not be a "piston"). The term "ejecta" applies to any parcel of solar wind with "unusual" characteristics that results from a transient solar event. Then, an ejecta is necessary, but not sufficient in order to obtain an interplanetary Bz*.

For type A cases, the ejecta must be very fast and its relative velocity to the ambient solar wind must be very high. Computer simulations show that the topology of the ambient interplanetary magnetic field around the Earth's magnetosphere (including the presence of the heliospheric current sheet) and the position on the Sun of the source of the interplanetary disturbance are other important factors (e.g Hakamada and Akasofu, 1982; Wu *et al.*, 1992; Dryer *et al.*, 1992). The simulations also show that the magnetic topology of the ejecta makes some differences, but Bz* components can even be created by a step increase in the velocity of the solar wind from already open field structures, that is with an ejecta from a coronal hole that suddenly increases the velocity of its wind. Another important factor favouring type A cases is the Earth's position in its orbit around the Sun (Russell and McPherron, 1973) as it has been proved that a seasonal variation in the occurrence of IGSs feature maxima at the equinoxes (e.g. Crooker *et al.*, 1992; Gonzalez *et al.*, 1992; Cliver and Crooker, 1993).

For type B cases, ejecta with the magnetic cloud structure are more suitable; however, it is sufficient for the ejecta to contain a strong magnetic field of only southward orientation. For such cases the local topology of the solar magnetic field at the site of the ejection seems to be important. However, attempts to relate local or source surface magnetic field orientations to the Bz* arriving at Earth have not been very successful (e.g. Joselyn, 1995; Hoeksema and Zhao, 1992). Perhaps the characteristics of the specific processes leading to the ejection may play an important role in determining the final magnetic structure of the ejecta. A part of the problem may be also that in some cases a solar source cannot be reliably associated with an interplanetary disturbance without some kind of tracking, such as that provided by IPS. Again, the characteristics of the ambient interplanetary field, and in particular the Russell-McPherron effect, may also contribute to increase the geomagnetic effects in type B cases.

THE SOLAR ASSOCIATION OF IGSS

When using IPS tracking to locate the solar sources of the 10 major geomagnetic storms in 1978-1979, as studied by Tsurutani *et al.* (1988), we obtained on several occasions a different source than that proposed by these authors (Bravo and Rivera, 1994). We found that 9 of the 10 events were associated with a disturbance generated in a region where an eruptive event (F or PE) took place near a coronal hole, near the solar central meridian. In 4 cases it was a PE alone, in 3 cases only an F, and in 2 cases, both. In the remaining case no F or PE event that could be related to the IGS took place anywhere on the solar disk in the time period. For this case no shock preceded the arrival of the plasma carrying the Bz*, which had a speed of about 400 km/s and the magnetic structure of a cloud. However several small coronal holes were present about solar central meridian even in this case. The presence of coronal holes near solar central meridian was common to all 10 cases. No systematic difference in the peak Dst value of the IGS was found between the F, PE, and null events.

We extended our study in Bravo and Rivera (1994) to the last nine events of the Cliver and Crooker (1993) list of all the great storms in the period 1957-1990 to see if the same pattern of a flare near a coronal hole and near solar central meridian appears. The analyzed events are listed in Table 2. They correspond to all the great geomagnetic storms in the period from 1981 to 1990; no data for solar coronal hole positions are available for earlier events. The flare associated by the authors with each storm is also indicated in the Table. We see that all the events are near the solar central meridian, except one of the two possible associations for the ninth event. We searched for the presence of a coronal hole near the solar flare reported by the authors using the HeI 10830 coronal hole maps in Solar Geophysical Data and in the Stewart *et al.* (1985) catalogue. In seven out of the nine cases (Nos. 1, 2, 3, 5, 6, 8, 9) the associated flare occurred in an active region within an angular distance of 20 degrees from a coronal hole border. Two examples are shown in Figure 3, corresponding

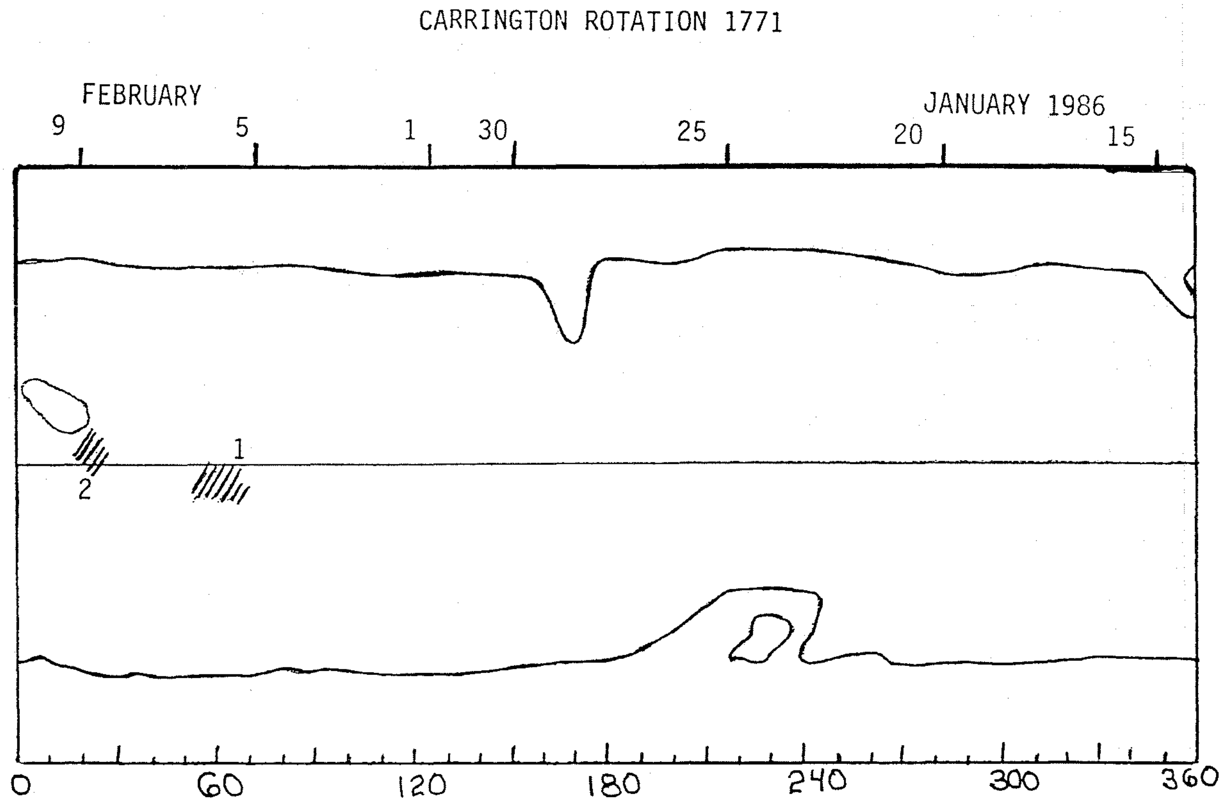

Fig. 4. Carrington rotation 1771 showing coronal hole boundaries and the position of the only two active regions of importance 3. Cliver and Crooker (1993) associated a major flare in region 1 on the 7th of February with the great geomagnetic storm of 9 February 1986. Another major flare occurred on the 8th in active region 2. The vertical line indicates the position of the solar central meridian at the time of the event on February 8th.

Table 2

Great storms and their solar association, 1981-1990

No.	STORM Date	-Dst(nT)	FLARE Date	UT	Lat/Lon
1	13 Apr., 1981	311	10	16:32	N07 W36
2	14 July, 1982	325	12	09:00	N11 E36
3	6 Sep., 1982	289	4	00:25	N12 E35
4	9 Feb., 1986	307	7	<09:35	S11 W21
5	14 Mar., 1989	599	10	18:37	N32 E22
6	19 Sep., 1989	257	15	22:30	N23 W24
7	21 Oct., 1989	270	19	12:29	S25 E09
8	17 Nov, 1989	266	15	06:38	N11 W28
9	10 Apr., 1990	278	7	15:11	N31 E62
			or 8	03:44	N24 E28

to the geomagnetic storm of 13 April 1981, which had a peak Dst value of -311 nT, and to the greatest storm of 14 March 1989, peak Dst value of -599. In case 4 (the great storm of 9 February 1986) the flare associated by the authors lies farther than 20 degrees from a coronal hole, but the hole (which was the only non-polar hole at that time) was very near central meridian. For this particular event another active region, where two flares of importance 1 had occurred on the 8th, was just beside the hole. The solar situation for this storm is shown in Figure 4. No IPS tracking of the corresponding interplanetary disturbance was made for the time of this event; thus the solar association may be incorrect as in the case of some of the events analyzed by Tsurutani *et al.* (1988). Actually, without a method for tracking interplanetary disturbances, it is not an easy task to decide which is the associated solar event, especially at times of high activity. Here MHD simulations of the propagation of interplanetary disturbances can also be very useful. For example, a 2D MHD simulation for the event in February 1986 (No.4) was carried out by Dryer *et al.* (1991) and their results indicate that the solar association as given in Table 2 is correct. In case 7, the associated flare occurred 9 degrees from central meridian, but no coronal hole was recorded on the HeI map in that region. Although there is not a 100% agreement, the results of this study reinforce the conclusion of our previous paper, namely that the great majority of IGSs is associated with the occurrence of an F or EP event near a coronal hole, close to the solar central meridian.

THE FORECASTING OF IGSs

From all the above considerations, we see that, even when we do not understand clearly all the steps of the processes starting at the Sun and ending in an IGS, and for both types (A and B) of geoeffective interplanetary transients, we can recognize some signs of alarm. In a sense this brings us back to the old paradigm, but with additional considerations. Although the new paradigm considers CMEs as the solar causes of IGSs, we have shown that almost all IGSs are related to solar events that include F and/or PE events. The flares and prominence or filament eruptions that can produce IGSs are those that occur near a coronal hole and near central meridian. Apparently, it is the position, more than the particular features of the explosive solar event, which make it a candidate for producing important geomagnetic effects. During the periods of analysis of the solar events related to IGSs no continuous monitoring of coronal holes was possible and so no short-term changes in them could be observed. However, such changes probably occurred in association with the interplanetary disturbances as has been shown recently by YOHKOH. In general, any sudden coronal hole enlargement, or the sudden creation of a new hole, must be accompanied by a CME, as such processes imply the opening of magnetic field lines previously closed where the coronal plasma was trapped. The characteristics (mainly the velocity) of the solar wind emitted from the hole may change when the hole changes. The sudden enlargement or creation of a coronal hole near central meridian will imply the ejection of material into the interplanetary medium directed towards the Earth and most probably the emission of faster solar wind. However, in most cases the ejections alone are not sufficient to produce an important geomagnetic perturbation: an associated F or PE event is also needed. The occurrence of these combined solar events near the equinoxes and when the Earth is crossing the heliospheric current sheet, increases their probability of producing an IGS.

CONCLUSIONS AND DISCUSSION

The main conclusion of this study is that in order to produce an intense geomagnetic storm the concurrence of several solar and interplanetary elements is required. Thus different observational tools must be used to forecast IGSs. Continuous monitoring of flares and filament or prominence eruptions, as well as the position and short-term changes of coronal holes, is required. At present, thanks to Yohkoh and SOHO instruments, we have the possibility to do this. It would also help to have systematic IPS monitoring of interplanetary disturbances from several observatories at different longitudes on Earth, using the Manoharan and Ananthakrishnan (1990) technique for measuring solar wind velocities from a single station in order to improve the location of the solar source of the disturbance. This will enable us to know when and from where an important disturbance was generated, and to estimate its time of arrival at Earth (see Bravo and Hewish, 1988). As one combines this information with a knowledge of the photospheric magnetic field and of the structure of the heliospheric neutral sheet, forecasts of IGSs at least one day in advance may become possible. But we still need to make many correlated solar and interplanetary observations to determine if every F or PE event associated with the enlargement of a coronal hole near solar central meridian leads to an IGS in the adequate interplanetary conditions. We also need to understand why an F or PE is present in type A events even though no obvious differences are observed in the CMEs or TIP shocks associated and non-associated with F or EP events. In type B events, it is not clear that the geoeffective ejecta is the active region or filament plasma itself, released at the moment of the surface explosion and finding its way out thanks to the nearness of the open field lines of the hole. It may be that the F or EP events are merely a result of a particular reordering of a much larger region that leads to a Bz* ejecta. Clearly, more theoretical models of the processes involved in the ejection of solar material are also necessary.

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