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Solar and interplanetary causes of very intense geomagnetic storms

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Abstract

The dominant interplanetary phenomena causing intense magnetic storms are the interplanetary manifestations of fast coronal mass ejections (CMEs). Two interplanetary structures are important for the development of such class of storms, involving an intense and long duration B_s component of the IMF: the sheath region just behind the forward shock, and the CME ejecta itself. Frequently, these structures lead to the development of intense storms with two-step growth in their main phases. These structures also lead sometimes to the development of very intense storms, especially when an additional interplanetary shock is found in the sheath plasma of the primary structure accompanying another stream. The second stream can also compress the primary cloud, intensifying the B_s field, and bringing with it an additional B_s structure. Thus, at times very intense storms are associated with three or more B_s structures. We also discuss evidence that magnetic clouds with very intense core magnetic fields tend to have large velocities, thus implying large amplitude interplanetary electric fields that can drive very intense storms. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Geomagnetic storms; Interplanetary-magnetosphere coupling; Disturbed solar wind

1. Introduction

The “average” solar wind has a speed (v) of $\approx$ 400 km/s and an embedded magnetic field (B) of $\approx$ 5 nT. For intense magnetic storms, the IMF intensity must be substantially higher than this value, and the solar wind speed also higher. The field must also be southwardly directed for a substantial length of time. Gonzalez and Tsurutani (1987) used ISEE-3 field and plasma data to determine an empirical relation for the interplanetary causes of intense magnetic storms, with $D_{st} \leqslant -100$ nT (Gonzalez and Tsurutani, 1987). They found that the interplanetary duskward electric fields ($-\mathbf{v}\times\mathbf{B}$) were greater than 5 mV/m over a period exceeding 3 h. This electric field condition is approximately equivalent to $B_z = -10$ nT. Although this empirical relationship was determined for a limited data interval during solar maxima, it appears to hold during solar minimum as well (Tsurutani and Gonzalez, 1995a).

The physical mechanism for solar wind energy transport into the magnetosphere is reasonably well understood. The coupling mechanism is magnetic reconnection between southwardly directed IMF and northward magnetopause fields (Dungey, 1961). Interconnection of interplanetary fields and magnetospheric dayside fields lead to the enhanced reconnection of fields on the nightside with the concomitant deep injection of plasma sheet plasma in the nightside. The latter leads to the formation of the storm-time ring current. Weiss et al. (1992) have indicated that the efficiency of this process during magnetospheric substorms is about 5%. Earlier estimates by Gonzalez et al. (1989) indicated that the efficiency during magnetic storms is 5–10%.

A clear understanding of the interplanetary structures that cause geomagnetic storms during solar maximum and near-minimum conditions should help to better define forecasting procedures, which are presently being considered as a fundamental ingredient for the so-called *space weather* research and forecasting.

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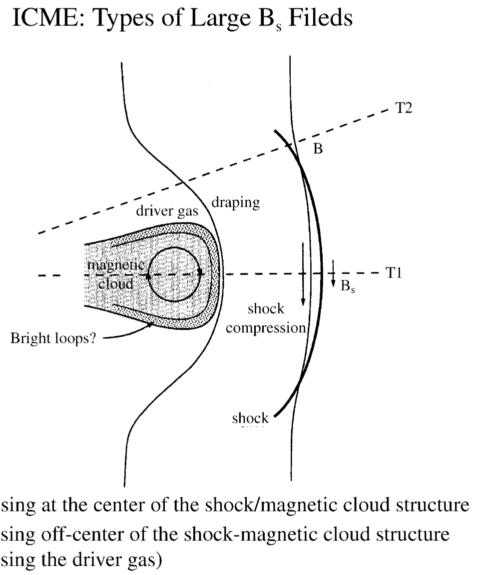

T1: Crossing at the center of the shock/magnetic cloud structure

T2: Crossing off-center of the shock-magnetic cloud structure (missing the driver gas)

Fig. 1. Regions of intense southward interplanetary magnetic fields during solar maximum, as remnants of a solar ejecta at 1 AU. T_1 and T_2 are two types of satellite crossings of the interplanetary structure.

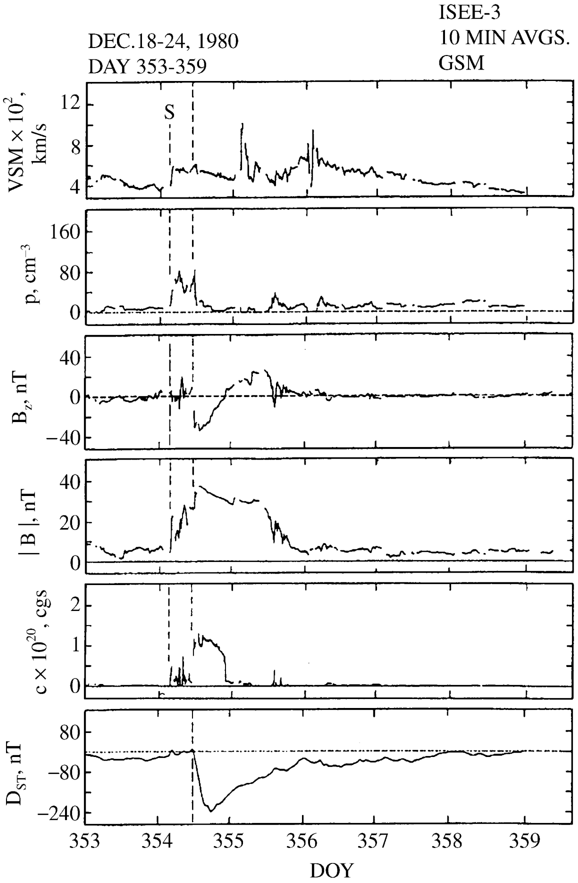

Fig. 2. A classical example of a magnetic storm driven by a magnetic cloud. The vertical dashed line labeled by a "S" indicates the presence of a fast forward shock. The vertical line to the right indicates the start of the magnetic cloud. The interplanetary parameters shown at the top four panels were measured by the ISEE-3 satellite. At the bottom panels the coupling parameter ε and the D_{st} index are shown.

2. Intense magnetic storms

During solar maximum (most active phase of the solar cycle), the sun's activity is dominated by flares and erupting filaments, and their associated coronal mass ejections (CMEs). Small-scale coronal holes are present at middle and low solar latitudes, and typically do not extend from the poles to the equator as often happens in the descending phase of the solar cycle. However, Gonzalez et al. (1996) and Bravo et al. (1998) have suggested possible roles of these small coronal holes in geoeffective solar activity.

The fast ($>$ 500 km/s) CMEs coming from the sun into interplanetary space (ICMEs) are the solar/coronal features that contain high magnetic fields. Fig. 1 is a schematic of the remnants of such a solar ejecta (driver gas) detected at 1 AU. There are two principal regions of intense fields. If the speed differential between the remnants of the coronal ejecta and the slow, upstream solar wind is greater than the magnetosonic wave speed (50–70 km/s), a forward shock is formed. The larger the differential speed, the stronger the Mach number of the shock.

The primary part of the driver gas might contain a so-called magnetic cloud structure (Burlaga et al., 1981; Klein and Burlaga, 1982). The magnetic cloud is a region of slowly varying and strong magnetic fields (10–25 nT or higher) with exceptionally low proton temperature and plasma beta, typically ≈0.1 (Tsurutani and Gonzalez, 1995a; Farrugia et al., 1993; Choe et al., 1992). The magnetic field often has a north-to-south (or vice versa) rotation and is elongated along its axis, forming a giant flux rope formed by field aligned currents (Burlaga, 1995). Whether these fields remain connected to the sun or not is currently being debated.

Other three-dimensional shapes, such as spherical, toroidal or cylindrical forms, have been explored as well (Ivanov et al., 1989; Dryer, 1994; Vandas et al., 1993; Farrugia et al., 1995). Simple configurations such as the so-called *magnetic tongues* proposed by Gold (1962) have not been shown to exist yet.

A classic example of a magnetic storm driven by a magnetic cloud is shown in Fig. 2. The forward shock is denoted by an "S" and a vertical dashed line in the figure, and the start of the magnetic cloud by a second dashed vertical line.

The storm main phase (storm onset, or SO) occurs in near-coincidence with the sharp southward turning of the IMF at the magnetic cloud boundary. The delay is ≈1 h (Gonzalez et al., 1989). The storm main phase (decrease

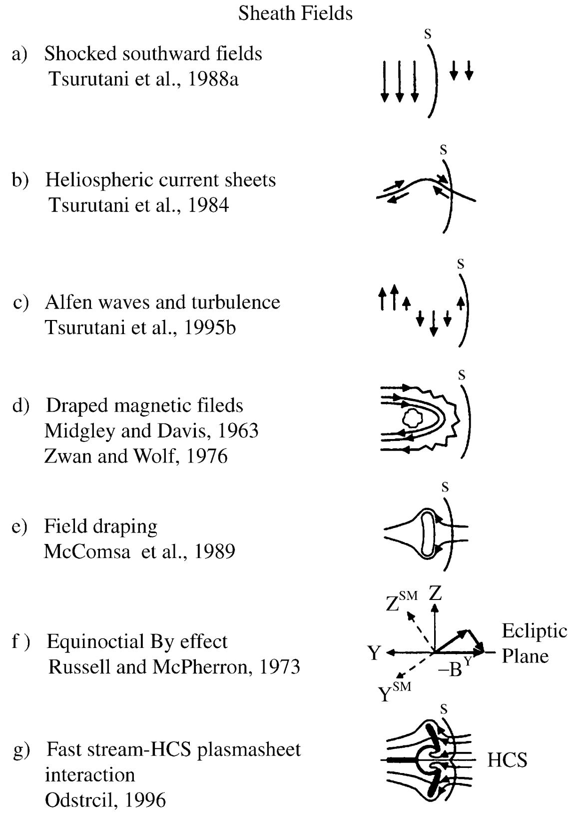

Fig. 3. Schematics of types of “sheath” magnetic field structures, as proposed by the referenced authors.

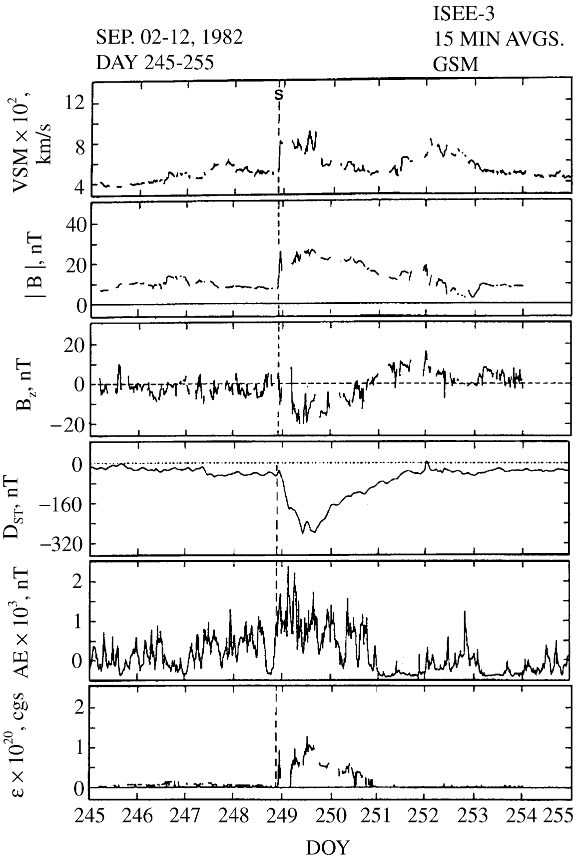

Fig. 4. Example of a magnetic storm caused by shock compression of interplanetary B_S fields. The vertical dashed line labeled by a “S” indicates the presence of a fast forward shock. The interplanetary parameters shown at the top three panels were measured by the ISEE-3 satellite. At the bottom three panels the D_{st} index, the *AE* index and the ε coupling parameters are shown.

in D_{st}) development is rapid and the decrease monotonic. In the example of Fig. 2, the peak D_{st} value of −239 nT is reached ≈2 h after the peak B_S value of ≈30 nT.

There are numerous mechanisms that lead to southward component fields in the sheath (Tsurutani et al., 1988a; Tsurutani et al., 1992; Zwan and Wolf, 1976; McComas et al., 1989; Russell and McPherron, 1973; Odstrcil et al., 1996). A number of these are indicated schematically in Fig. 3.

Fig. 4 illustrates the generation of magnetic storms by sheath fields due to the shock compression mechanism. The peak B_S value of ≈20 nT is reached at ≈1200 UT of day 249 and the peak D_{st} of −280 nT several hours later. The mechanism for the southward component magnetic fields causing this storm are shock compression plus possible effects of draping.

Whether intense interplanetary fields are those of the sheath or the ejecta, the energy injection mechanism into the magnetosphere is the same. In general, the IMF structures leading to intense magnetic storms have features similar to the examples shown. The IMF B_S is intense and has a long duration (Gonzalez and Tsurutani, 1987).

In contrast to solar maximum, where polar coronal holes are not very important, during the descending phase of the solar cycle such coronal holes have major, even dominant, effects on the interplanetary medium. Polar coronal holes extend from the polar regions down to the equator and sometimes even far past the equator (Jackson, 1997). They are areas of open magnetic field lines. Ulysses has shown that holes are regions of fast streams with velocities of 750–800 km/s (Phillips et al., 1994) and are dominated by large amplitude Alfvén waves (Tsurutani et al., 1995a; Smith et al., 1995). The Alfvén waves are continuously present in the high velocity streams.

During the descending phase of the solar cycle, when the holes migrate down to lower latitude as “fingers”, the streams emanating from the holes “corotate” at ≈27 day intervals (as seen at the Earth), and are known as corotating streams. Plasma from these streams impinge on the Earth’s magnetosphere at periodic intervals and cause recurrent geomagnetic storms (Sheeley et al., 1976; Burlaga and Lepping, 1977). However these storms are mostly of moderate intensity (Tsurutani et al., 1995b).

Corotating streams can create intense magnetic fields if the streams interact with streams of lower speeds (Belcher and Davis, 1971; Tsurutani et al., 1995a,b). The magnetic fields of the slower speed stream are more curved due to the lower speeds (following the classical Archimedean spiral structure), and the fields of the higher speed stream are more radial because of the higher speeds. The stream–stream interface is the boundary between the slow stream and fast stream plasmas and fields.

This overall structure was first found in the Pioneer 10 and 11 data and were named Corotating Interaction Regions (CIRs) by Smith and Wolf (1976). See also Burlaga et al. (1985).

3. Complex interplanetary structures leading to intense storms

In several instances more than one interplanetary structure can be associated with the origin of intense storms. Such complex structures have started to receive more attention in the literature (Burlaga et al., 1987; Behannon et al., 1991; Lepping et al., 1997; Cane and Richardson, 1997; Crooker et al., 1998; Knipp et al., 1998). However, due to the lack of several spacecraft simultaneously observing such structures, we do not have as yet a clear picture about their overall configuration.

Most of the reported complex structures involve a fast forward shock, followed by a magnetic cloud, and usually another high speed stream is found to follow the magnetic cloud (Dal Lago et al., 2000). This second stream seems to be of different types. Perhaps the most commonly found is a corotating one (e.g. Bothmer and Schwenn, 1995; Cane and Richardson, 1997; Knipp et al., 1998), preceded by a corotating interaction region (CIR). As it is commonly known though, CIRs are not expected to form a shock at distances of 1 AU or less (Smith and Wolf, 1976) and, therefore, there are no clear reported events with a stream, preceded by a shock, following magnetic clouds. Nevertheless, Lepping et al. (1997) reported the event of October 18–20, 1995, also discussed by Tsurutani et al. (1999), in which a shock/compressional wave has been noted within and close to the rear end of the cloud. This event is shown in Fig. 5. A strong magnetic compression exists at point C of this figure (region "D" is interpreted to be a CIR). The field compression is ≈36%. There are coincident increases in plasma density and velocity. We note however, that the density at this time is ≈20/cm, a value which rapidly decreases towards the front (antisolar) portion of the magnetic cloud. Thus, the wave compression will decrease drastically as the wave propagates forward. It is unclear what will happen to this wave when it reaches the other side of the cloud. It may be sufficiently dispersed or it may reform as a shock. An argument was presented by Tsurutani and Gonzalez (1997) that the presence of shock/strong compressions may not be possible within magnetic clouds because of the low beta conditions present there. The low beta values (≈ 0.1) in clouds imply large Alfvén/magnetosonic speeds which would ordinarily preclude the formation of shocks within magnetic clouds.

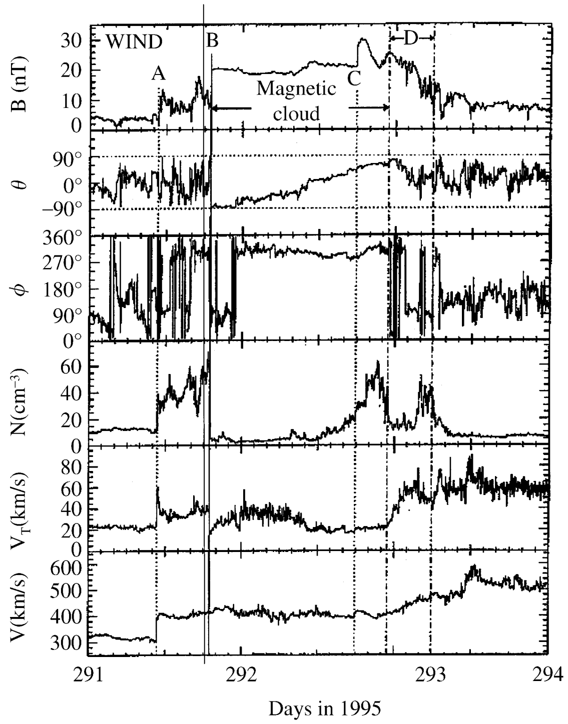

Fig. 5. Example of a complex interplanetary structure (October 18–20, 1995), involving a transient high speed stream (shock at A), with a magnetic cloud, and a following probable corotating stream (with a CIR at D). There is a shock like/compression structure at C (at the rear end of the cloud and ahead of the secondary stream).

The shock-like structure in the event reported by Farrugia et al. (1997) may also be interpreted as leading some type of a transient stream, instead of a corotating one, although there is no sufficient information to help us identify such a transient event. The presence of large-amplitude Alfvenic fluctuations in the stream is not necessarily a signature of a corotating stream, since Tsurutani and Gonzalez (1987) have reported trains of Alfvenic fluctuations following transient streams for intervals near solar maximum. This fact led Gonzalez et al. (1996) to suggest a CHARCS (coronal hole-active region-current sheet) model in order to incorporate the Alfvenic fluctuations originated in transient low latitude coronal holes, located near the streamer belt at the sun, with a region from where the CME could have emerged.

Other type of complex structures involve a possible association of the magnetic cloud with the interplanetary current sheet (Akasofu, 1981; Tsurutani et al., 1984; Knipp et al., 1998; Crooker et al., 1998). In this case the field

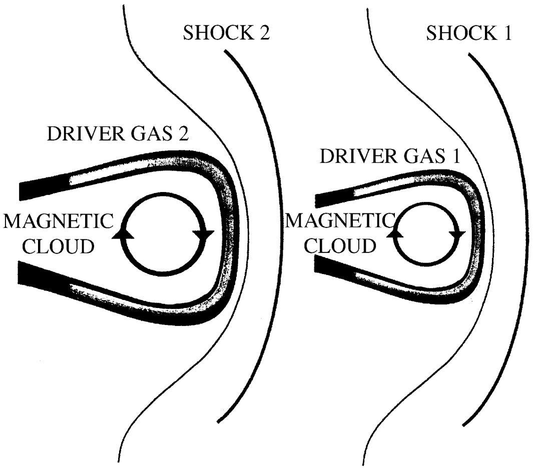

Fig. 6. Schematic showing two consecutive high speed streams, both involving fast forward shocks and driver gas/magnetic cloud structures.

rotations within the clouds appear to form part of larger-scale rotations beyond the cloud boundaries. It is interesting to investigate the diverse B_s structures which could come out from the different types of high speed stream/magnetic cloud interactions with the current sheet (e.g. Odstrcil et al., 1996).

Events with a transient fast stream, involving a magnetic cloud, and being closely followed by another similar structure has not been clearly observed yet. This interesting scenario is illustrated in Fig. 6. Certainly, this type of structure would involve a sequence of several B_s structures, contributing to the formation of a very intense magnetic storm. Bothmer and Schwenn (1995) have claimed that the storm of July 3–6, 1974, could have involved a series of fast CMEs. However in the available data for this event, it is difficult to identify the driver gas/magnetic cloud signatures accompanying the series of consecutive three shocks that seem to have been observed (Borrini et al., 1982). It is important to point out that in the scenario illustrated in Fig. 6, the subsequent high-speed structure could bring a higher kinematic pressure ($\frac{1}{2}\rho v^2$) than the previous structure. In such a case one could expect that the leading magnetic cloud would be compressed, thus resulting in an intensification of the B_s part of the cloud, especially if the loading cloud has a north–south polarity. This effect would contribute to a further increase in the associated storm intensity.

Finally, the difficulty to identify two or more structures in a complex interplanetary event, leading to intense storms, becomes even more evident when the driver gas does not correspond to the classical flux rope model (Marubashi, 1986), or when the observing satellite crosses the cloud very far from its center (Tsurutani and Gonzalez, 1997). Other structures perhaps may exist, such as a “magnetic tongue” (Gold, 1962), and deserve special investigation.

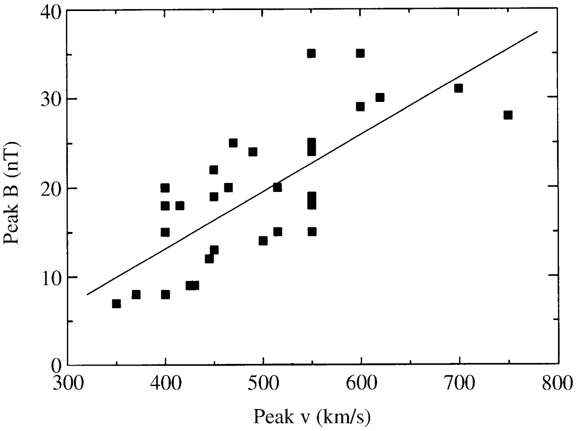

Fig. 7. Peak values of the magnetic field intensity and the solar wind speed for the magnetic cloud events studied by Gonzalez et al. (1998). This figure shows that the faster the cloud moves the higher the core magnetic field is.

4. Causes of very intense storms

4.1. *Fast ICME magnetic fields*

Gonzalez et al. (1998) have found a general relationship between the speed of the ICME and the magnetic field intensity in the magnetic cloud. To examine this relationship quantitatively, Gonzalez et al. (1998) combined published examples of clouds with those observed by the ISEE-3 satellite in 1979 and identified following the criteria given by Burlaga (1995). Fig. 7 displays the cloud field intensity versus the cloud velocity for all these events. This figure shows that there is a clear tendency for the cloud to have higher magnetic fields associated with higher velocities, relative to inertial space. At this time, the physical causes of the relationship between the cloud’s $|B|$ and v are uncertain. Compression of the cloud is certainly occurring, but it is uncertain whether all of the field increase can be accounted for by such an effect. Another possibility is that this relationship may be related to the CME release and acceleration mechanisms at the Sun. The $|B|$–v relationship may give important clues as to these mechanisms.

Similar results were later obtained by Marubashi (2000), although the criteria to sample the peak B and peak v values differ slightly among these papers.

An ISEE-3 subset of driver gas-non cloud events were also studied by Gonzalez et al. (1998). For those events they showed that there is no clear trend in the $|B|$–v relationship. An explanation for this different behavior is also presently unknown.

4.2. *Interplanetary shock effects*

One mechanism to create higher field strengths would be for a second interplanetary shock to (further) compress

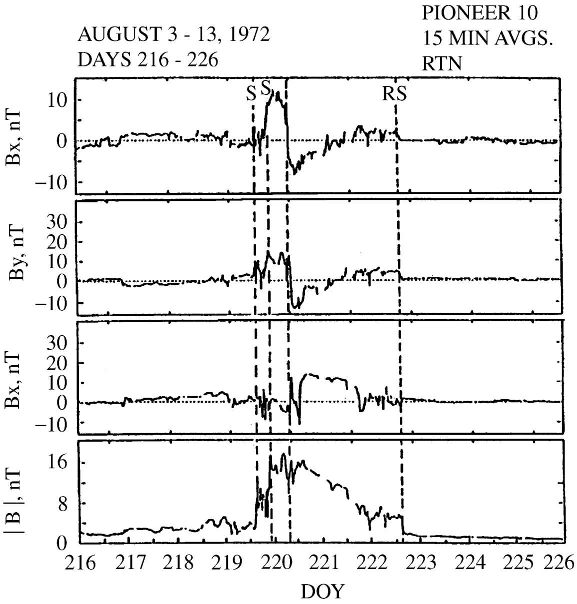

Fig. 8. Pioneer 10 IMF data at 2.2 AU from the Sun (Smith and Sonett, 1976), showing a shock compression of the sheath field. The first shock compresses the ambient field by about 4 times and the second shock compresses the sheath field by about 2 times.

the high fields existing in the ICME/sheath regions (of Fig. 1). One mechanism to have shocks occurring within sheaths is to have the shocks propagate from the downstream ICME/sheath structures up into the front side region of the sheath. To determine what the possibility of each of these mechanisms might be, simulation efforts are recommended.

Shock compression of sheath fields has been previously observed. Fig. 8 shows the magnetic field for the August 1972 event at Pioneer 10 (2.2 AU), as reported by Smith and Sonett (1976). At this distance, the highest measured magnetic field strengths ($\approx$18 nT) are associated with this process. The first shock compresses the ambient magnetic field by $\approx$4 times and the second shock by $\approx$2 times. Exactly how this second shock was present in the sheath is not known.

The August 1972 interplanetary event had a velocity greater than 1500 km/s at 1 AU (the plasma instruments were saturated). The magnetic cloud field strength reached 16 nT at 2.2 AU, corresponding to 51 nT at 1 AU (assuming a $r^{-1.7}$ radial dependence). The field at 1 AU would be higher if a steeper dependence is assumed. Note that this $|B|$–v relation is in general agreement with the trend of Fig. 7. The magnetic field was plotted in solar heliospheric, or RTN, coordinates.

4.3. Double and triple-step storms

Another way to get large $D_{\rm st}$ events is to have two-step storm main phases, with the second enhancement of the $D_{\rm st}$ index closely following the first one (Tsurutani and Gonzalez, 1997). Kamide et al. (1998) in an analysis of more than 1200 magnetic storms have shown that such events are quite common and are caused by two IMF southward field events of approximately equal strength. Kamide et al. argue that this could also be viewed as two "moderate" magnetic storms with the $D_{\rm st}$ base of the second well below that of the first. Grande et al. (1996) and Daglis (1997) have studied the March 23, 1991 double magnetic storm using CRRES ion composition data. Grande et al. point out that the first event is dominated by Fe^{+9}, whereas the second by Fe^{+16}. A likely explanation is that the first event was caused by sheath southward IMFs (shocked, slow solar wind plasma and fields) and the second was from the remnants of the ICME itself (magnetic cloud). The peak $D_{\rm st}$ for the first event was ≈ -100 and ≈ -300 nT for the second event. We note, however, that these values were not pressure-corrected. The field at the storm initial phase was $\approx +60$ nT indicating that the correction would be substantial.

We reexamined the interplanetary causes of great magnetic storms ($D_{\rm st} < -250$ nT) which have corresponding interplanetary data (reported in Tsurutani et al., 1992). Three of the four largest events have complex main phases. The April 12–13, 1981 and the July 13–14, 1982 events are double main phase storms. The September 4–6, 1982, and the February 7–9, 1986 storms had a main phase that took days to develop, and can be viewed perhaps as triple-step storms, namely in which the main phase of the storm develops in three consecutive steps (with a criteria similar to that defined for the two-step storms by Kamide et al., 1998). The latter could be due to a complex ICME/sheath region and to a precursor $B_{\rm s}$ field ahead of the shock.

Some of the largest magnetic storms registered since the $D_{\rm st}$ index became available (1957) occurred in the 1957–1959 era. These events occurred prior to the advent of in situ space plasma measurements. However, with our recent knowledge of the interplanetary causes of magnetic storms, we can make an educated guess as to their interplanetary causes. Some of these events seem to have involved double and triple storms.

Fig. 9 shows the March 13–14, 1989 event, the largest recorded during recent times ($D_{\rm st} = -600$ nT, uncorrected for pressure). There is a slowly developing main phase prior to a sharp $D_{\rm st}$ decrease at 20 UT day 13. The whole main phase takes over 24 h. This most certainly indicates the presence of a complex sheath region existing ahead of a magnetic cloud. The storm profile indicates that this may be viewed as a triple storm event.

Unfortunately, there are no solar wind data for the March 1989 very intense storm, from which we could learn about the interplanetary B_z structures responsible for this triple-step storm. Vieira et al. (2000) have shown that about 15% of intense storms caused by magnetic clouds can be of the triple-step type, especially when large amplitude density waves/discontinuities exist within the cloud, thus causing an additional $B_{\rm s}$ structure.

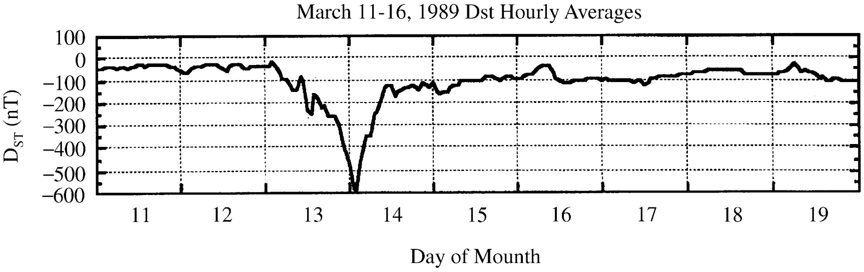

Fig. 9. D_{st} profiles for the largest magnetic storm recorded during recent times ($D_{st} \approx -600$ nT). The event occurred on March 13–14, 1989. The whole main phase took over 24 h, showing the presence of a complex sheath region ahead of a magnetic cloud.

5. Discussion

We have only discussed obvious cases where double main phase storms have led to very intense storm events. Clearly, if a southward-oriented sheath field region is followed by a magnetic cloud with a south–north orientation, the two main phases of the storm might be hard to identify using only the D_{st} data.

For the triple-step storms, in addition to the sheath and magnetic cloud fields, there is a need of an additional B_s structure. This would show up as a second stage sheath field (for example, due to a second shock) or to a substantial B_s field already existing ahead of the shock. Another possibility could be if the ICME/sheath system is closely followed by another interplanetary structure with a substantial B_s field, such as another stream or a kinky heliospheric current sheath (Tsurutani et al., 1984).

What can be the magnetospheric processes associated with such double and triple storm effects? One speculation is that stochastic electric fields drive plasma sheet old ring current particles deep into the magnetosphere where the second and third storm fields do not sweep them out. Thus there would be residual ring current particles left over and the new ring current is simply added, giving a much larger D_{st}. Chen et al. (1992, 1997) have shown that previous ring current particles can get energized to higher energies by new large-scale electric fields and can diffuse radially to lower L values, thus leading to a more energetic ring current. Another possibility is that the first storm may have "primed" the plasma sheet for the second and the third event. Borovsky et al. (1997) have shown that the plasmasheet can be "superdense" at times and Kozyra et al. (1998) have shown that this can lead to a larger ring current. The above ideas are interesting but clearly more work is needed to determine the exact mechanism(s).

Since for magnetic clouds the total field typically has a substantial southward component (Gonzalez et al., 1994), the results shown on Fig. 7 could imply that the interplanetary dawn-dusk electric field, given by $\mathbf{v} \times \mathbf{B}_s$ is enhanced by *both* factors ($\mathbf{v}$ and $\mathbf{B}_s$). Therefore, the consequent magnetospheric energization (that is governed by this electric field) becomes more efficient for the occurrence of magnetic storms, which at extreme conditions can drive very intense storms.

6. Concluding remarks

There has been a great deal of focus on magnetic clouds because of their strong interaction with the earth's magnetosphere, leading to magnetic storms during the B_s portion of the cloud; and also due to the complementary weak interaction during the B_n portion of the cloud, leading to geomagnetic quiet intervals. A point that is often missed is that magnetic clouds are only present in one out of six fast ICMEs/driver gases (Tsurutani et al., 1988b). The reasons for the complex field configuration for the more abundant cases should be investigated and explained. It is particularly important to investigate the nature of fast interplanetary driver gas events that are not magnetic clouds, and that in some instances also lead to the development of intense storms. The large intensity and long duration B_s fields present in these events may, among other possibilities, perhaps be related to "magnetic tongue" structures (Gold, 1962), or to the result of intense interactions of the driver gas with the interplanetary current sheet (Tsurutani et al., 1984; Odstrcil et al., 1996). Furthermore, when a driver gas is not observed and an intense magnetic storm follows a geoeffective solar wind interval preceded by an interplanetary shock, it is possible that the satellite has missed the driver gas, or that the B_s structure, responsible for the storm, is the result of large-amplitude (nonlinear) Alfvén waves amplified by their interaction with the shock (Gonzalez et al., 1995; Gonzalez et al., 1996).

Concerning B_s intensifications by interplanetary processes associated with complex structures, it is important to emphasize the need to investigate the nature of the processes involved. In particular, computer simulational work about subsequent CMEs, which could lead through an appropriate combination of interactions (subsequent B_s compressions for example) to the development of very intense storms, is encouraged.

To predict the occurrence of a magnetic storm one needs to be able to predict three interplanetary parameters: v, B_s

and the duration of B_s. The first parameter can be obtained with several days advanced warning by placing a coronograph in space with a spacecraft/sun/earth angle of $\approx 90^\circ$, such as that planned in the NASA/STEREO mission for CMEs research. From the work of Gonzalez et al. (1998) we could make an educated guess about peak B values for intense storms, by knowing the peak values of the CME speed when the CMEs are magnetic clouds. For this class of CMEs one could eventually get some statistical knowledge about the B_s field when the rotation of the cloud is in the appropriate direction. Such study could be complemented by the results of estimates about the occurrence of B_s fields from the helicity, orientation and polarity of erupting filament observations at the Sun (e.g. Bothmer and Schwenn, 1994; Rust, 1994). However, in general, we are currently not able to predict the last two parameters: B_s and the duration of B_s. Unfortunately, these are the most important parameters in determining the storm intensity.

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