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Interplanetary phenomena associated with very intense geomagnetic storms

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Abstract

The dominant interplanetary phenomena that are frequently associated with intense magnetic storms are the interplanetary manifestations of fast coronal mass ejections (CMEs). Two such interplanetary structures, involving an intense and long duration B_s component of the IMF are: the sheath region behind a fast forward interplanetary 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, when combined, 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.

Another aspect that can contribute to the development of very intense storms refers to the recent finding 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 magnetospheric energization.

Keywords: Solar activity; Interplanetary magnetic fields; Geomagnetic storms

1. Introduction

For intense magnetic storms ($-250\text{ nT} \leqslant Dst < -100\text{ nT}$) the solar wind speed and the IMF intensity must be substantially higher than their "average" values, of $v \approx 400$ km/s and $B \approx 5$ nT, respectively. 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 $Dst \leqslant -100$ nT. 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, 1995).

The most commonly accepted coupling mechanism is magnetic reconnection between southwardly directed IMF and northward magnetopause fields (Dungey, 1961; Gonzalez and Mozer, 1974). Interconnection of interplanetary fields and magnetospheric dayside fields leads 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 should help to better define

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forecasting procedures, which are presently being considered as a fundamental ingredient for the so called *space weather* research and forecasting.

The interplanetary structures responsible for intense storms are fairly well documented (e.g. Tsurutani and Gonzalez, 1997). However super intense storm events, appear to be associated with more complex interplanetary structures. It is the main purpose of this paper to present some progress in the understanding about the interplanetary origin of very intense storms.

2. Intense magnetic storms

During solar maximum, 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), Srivastava et al. (1998) and Bravo et al. (1998) have suggested possible roles of these small coronal holes in geoeffective solar activity.

The fast ($\gtrsim$ 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 solar ejecta (driver gas) detected at 1 AU. There are two principal regions of intense fields: the ejecta (driver gas) itself and the sheath region behind the shock. If the speed differential between 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 $\approx$ 0.1 (Tsurutani and Gonzalez, 1995; Farrugia et al., 1993; Choe et al., 1992). The magnetic field often has a north-to-south (or vice versa) rotation and is more aligned along its axis near the center, 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 so-called *magnetic tongues* proposed by Gold (1962) have not been shown to exist yet.

As illustrated in Fig. 1, the other important region where intense B_s fields can be found is the sheath region where the shock compressed plasma is located. There are numerous mechanisms that lead to southward component fields in the sheath (e.g. Gonzalez et al., 1999).

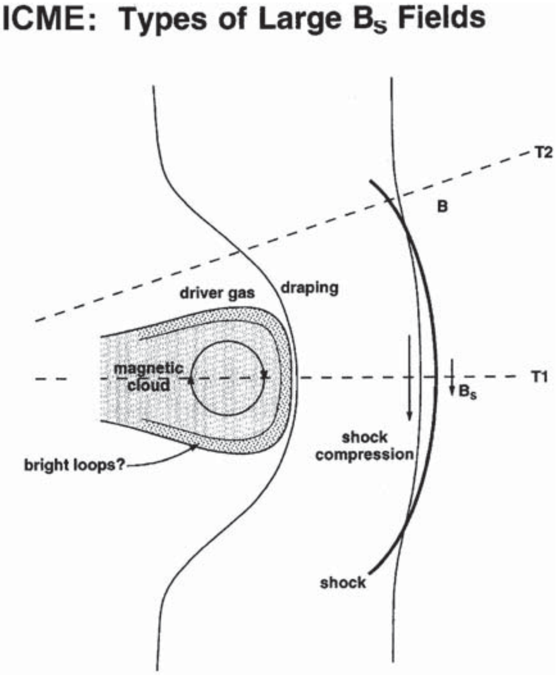

Fig. 1. Regions of intense southward interplanetary magnetic fields during solar maximum, as remnants of a solar ejecta at 1 AU. T_1 and T_2 are two types of satellite crossings of the interplanetary structure. (T_1): Crossing at the center of the shock/magnetic cloud structure; and (T_2): crossing off center of the shock/magnetic cloud structure (missing the driver gas).

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 an intense and long duration B_s component (Gonzalez and Tsurutani, 1987).

2.1. Complex interplanetary structures

In several instances more than one interplanetary structure can be associated with the origin of intense storms. (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 multi-spacecraft observations of 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., 2001). 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

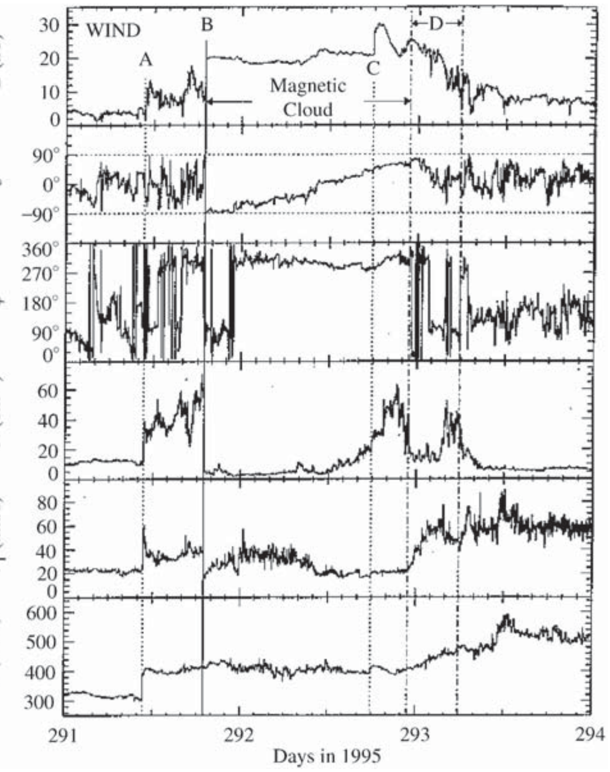

Fig. 2. Example of a complex interplanetary structure (October 18–20, 1995), involving a transient high speed stream (shock at *A*), with a magnetic cloud, and a following probable corotating stream (with a compression region at *D*). There is a shock like/compression structure at *C* (at the rear end of the cloud and ahead of the secondary stream).

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. 2. A strong magnetic compression exists at region *D*, starting at line *C*, of this figure. There are coincident increases in plasma density and velocity. We note however, that the density at this time has 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.

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 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. Certainly, this scenario 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 this scenario, the subsequent high speed structure could bring a higher dynamic 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 leading cloud has a north–south polarity. This effect would contribute to a further increase in the associated storm intensity.

Dal Lago et al. (2001) have studied the interaction of a high speed stream following a magnetic cloud during the event of April 1–2, 1973. Fig. 3 shows some interplanetary parameters and the *Dst* index for this event. These authors have shown that the high speed stream compresses the cloud's magnetic structure from behind, leading to a bigger southward magnetic field in the rear region of the cloud since it had a North–South polarity. If it had not been for the arrival of the high speed stream, the cloud's B_s field would have had a smaller amplitude, thus causing a magnetic storm of lesser intensity than that observed. Therefore, compression of the cloud's magnetic field with a North–South polarity by a high speed stream, appears to be an important interplanetary mechanism to enhance the geoeffectiveness of the magnetic cloud interaction wiht the earth's magnetosphere.

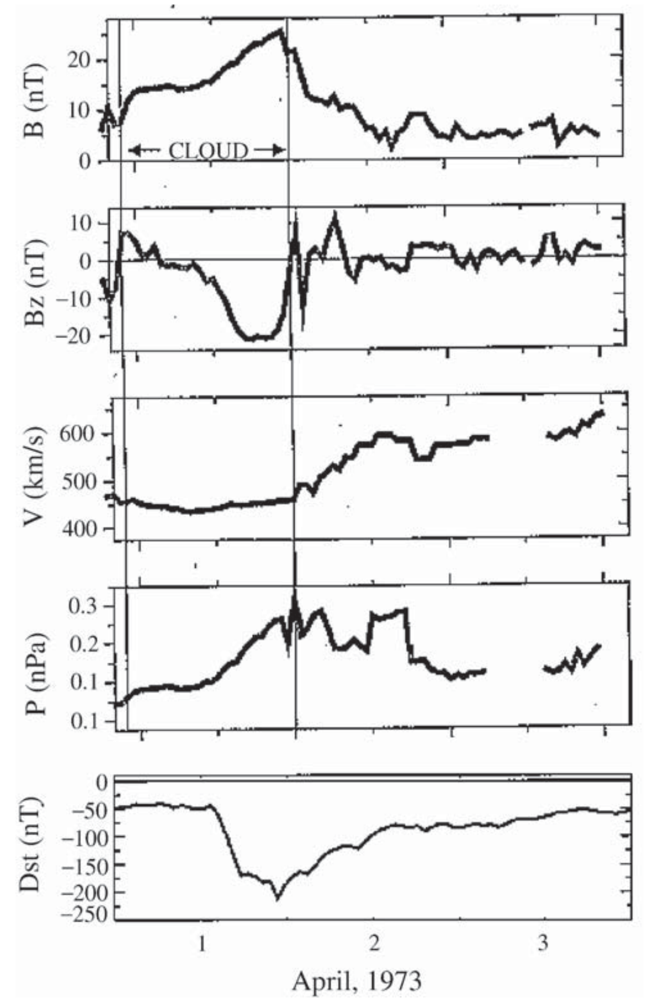

Fig. 3. Example of compression by a high speed stream of a magnetic cloud of NS polarity leading to a more intense magnetic storm event.

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.

2.2. *Solar cycle and seasonal distribution of intense storms*

It is known that geomagnetic activity as a whole has a seasonal variability with maxima at the equinoxes (e.g. Russell and McPherron, 1973). However it has been claimed (Clúa de Gonzalez et al., 1993; 2001; Bell et al., 1997) that the distribution of very intense storms does not follow the profile of the classical seasonal distribution showing, for example, an additional peak around the month of July.

It is also known that geomagnetic activity as a whole tends to become enhanced during the descending phase of the solar cycle (e.g. Legrand and Simon, 1991). However, Gonzalez et al. (1990) showed that intense storms (peak $Dst \leqslant -100$ nT) tend to show two peaks within the solar cycle, one somewhat ahead or at the solar maximum and the other, 2 or 3 years after solar maximum. It was also shown by Gonzalez et al. (1990) that the solar cycle distribution of B_s fields with intensities > 10 nT and duration > 3 h have a similar dual-peak distribution as that for the intense storms. This is in agreement with the association of intense storms with such class of B_s fields initially suggested by Gonzalez and Tsurutani (1987). It is interesting to point out that a similar dual peak was found in the solar cycle distribution of low latitude coronal holes, within ±30° around the solar equator (Gonzalez et. al., 1996).

Fig. 4 shows a comparison of the dual-peak type of distribution for intense geomagnetic activity ($Ap > 80$ nT) with the single peak type of distribution of general geomagnetic activity, including the much more numerous small to moderate events ($Ap < 20$ nT). The cause of the latter type of distribution for geomagnetic activity as a whole can be related to the works by Tsurutani et al. (1995) and by Tsurutani and Gonzalez (1997), in which the authors found that corotating streams, at the descending phase of the solar cycle are more geoeffective in leading to enhanced moderate geomagnetic activity during prolonged intervals of time, as compared to the transient character of the dual-peak type distribution of intense storms. The probable agent in causing the prolonged moderate activity are large amplitude Alfvén wave trains emanating from coronal holes, which due to the fluctuating character of the IMF-B_z field can cause continuous AE activity (Tsurutani and Gonzalez, 1987).

3. Very intense storms

3.1. *Interplanetary shock effects*

One mechanism to create higher field strengths would be for a second interplanetary shock to (further) compress 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. 4 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 (≈17 nT) are associated with this process. The first shock compresses the ambient magnetic field by ≈4 times and the second shock by ≈2 times. Exactly how this second shock was present in the sheath is not known.

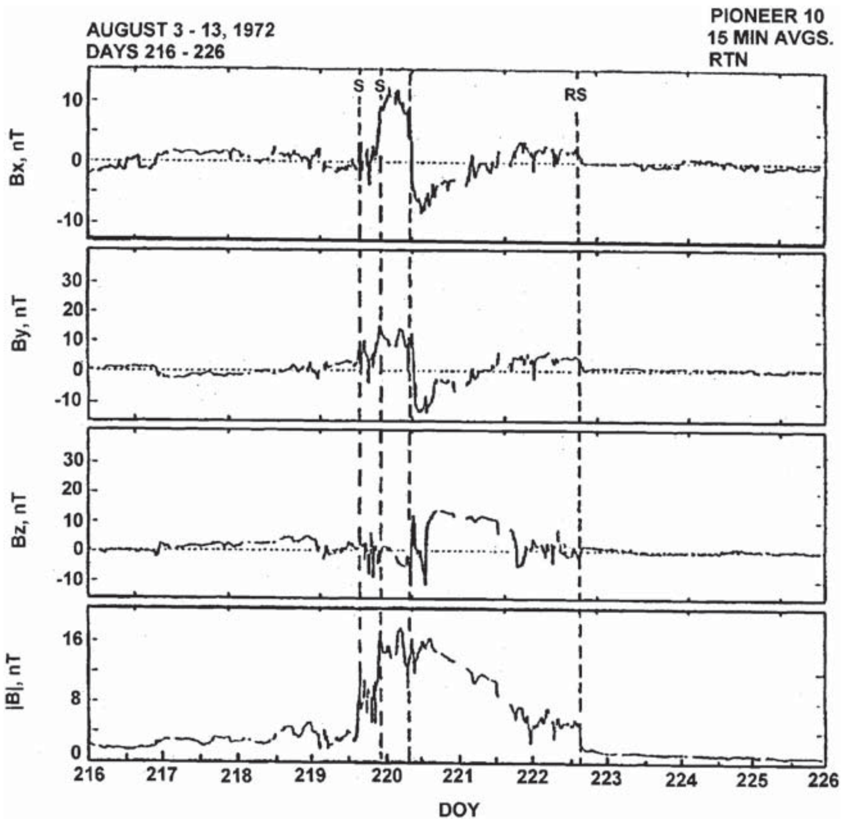

Fig. 4. Pioneer 10 IMF data at 2.2 AU from the Sun, for the August 1972 event (Smith and Sonett, 1976), showing a shock compression of the sheath field.

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.

3.2. Double and triple-step storms

Another way to get large *Dst* events is to have two-step storm main phases, with the second enhancement of the *Dst* 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. (1998) argue that this could also be viewed as two "moderate" magnetic storms with the *Dst* 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. (1996) 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).

We reexamined the interplanetary causes of great magnetic storms ($Dst < -250$ 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_s field ahead of the shock.

Some of the largest magnetic storms registered since the *Dst* 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. 5 shows the March 13–14, 1989 event, the largest recorded during recent times ($Dst = -600$ nT, uncorrected for pressure). There is a slowly developing main phase prior to a sharp *Dst* decrease at 20 UT day 13. The whole main phase takes over 24 h. This most certainly indicates the

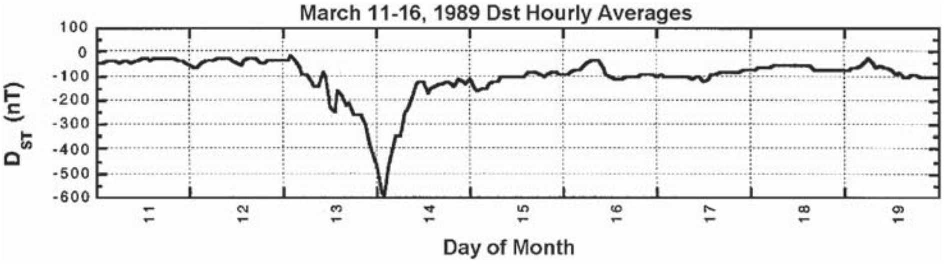

Fig. 5. *Dst* profiles for the largest magnetic storm recorded during recent times ($Dst \approx -600$ nT). The event occurred on March 13–14, 1989. The whole main phase took over 24 h, showing the presence of a complex sheath region ahead of a magnetic cloud.

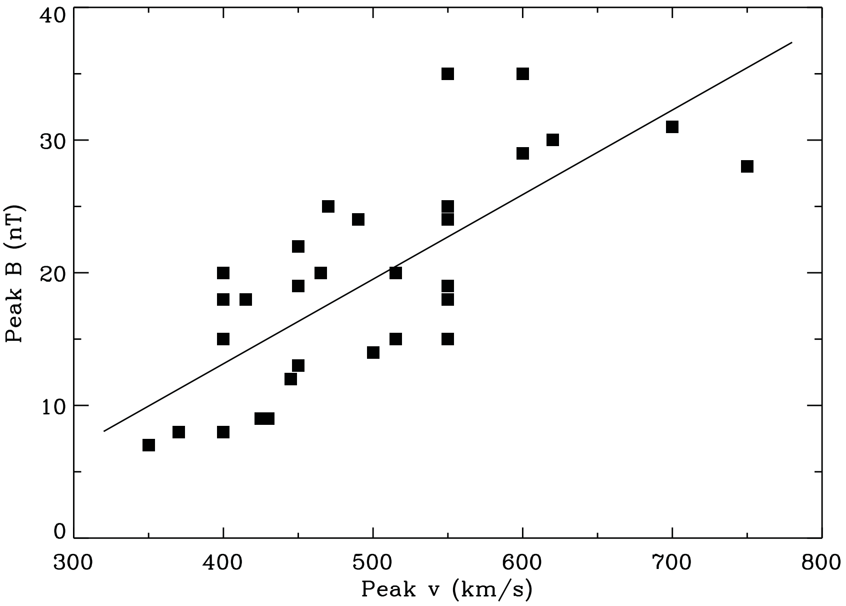

Fig. 6. Peak values of the magnetic field intensity and the solar wind speed for the magnetic cloud events studied by Gonzalez et al. (1998). This figure shows that the faster the cloud moves the higher the core magnetic field is.

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. (2001) 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_s structure.

3.3. *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. 6 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.

Not shown on this graph are the particularly high fields and velocities of the extreme August 1972 event. This general $|B| - v$ relationship holds for this extreme event as well.

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. Discussion

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 less than a half of fast ICMEs/driver gases (Tsurutani et al., 1988). The reasons for the complex field configuration for the more abundant cases should be investigated and explained. 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 (non linear) Alfvén waves amplified by their interaction with the shock (Gonzalez et al., 1995, 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 consecutive 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.

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 *Dst* 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 sheath field (accompaning 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).

Since for magnetic clouds the total field typically has a substantial southward component (Gonzalez et al., 1994), the results shown in Fig. 6 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.

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