INTERPLANETARY ORIGIN OF GEOMAGNETIC STORMS

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Abstract. Around solar maximum, the dominant interplanetary phenomena causing intense magnetic storms ($Dst < -100$ nT) are the interplanetary manifestations of fast coronal mass ejections (CMEs). Two interplanetary structures are important for the development of storms, involving intense southward IMFs: the sheath region just behind the forward shock, and the CME ejecta itself. Whereas the initial phase of a storm is caused by the increase in plasma ram pressure associated with the increase in density and speed at and behind the shock (accompanied by a sudden impulse [SI] at Earth), the storm main phase is due to southward IMFs. If the fields are southward in both of the sheath and solar ejecta, two-step main phase storms can result and the storm intensity can be higher. The storm recovery phase begins when the IMF turns less southward, with delays of $\approx$ 1–2 hours, and has typically a decay time of 10 hours. For CMEs involving clouds the intensity of the core magnetic field and the amplitude of the speed of the cloud seems to be related, with a tendency that clouds which move at higher speeds also posses higher core magnetic field strengths, thus both contributing to the development of intense storms since those two parameters are important factors in genering the solar wind-magnetosphere coupling via the reconnection process.

During solar minimum, high speed streams from coronal holes dominate the interplanetary medium activity. The high-density, low-speed streams associated with the heliospheric current sheet (HCS) plasma impinging upon the Earth's magnetosphere cause positive Dst values (storm initial phases if followed by main phases). In the absence of shocks, SIs are infrequent during this phase of the solar cycle. High-field regions called Corotating Interaction Regions (CIRs) are mainly created by the fast stream (emanating from a coronal hole) interaction with the HCS plasma sheet. However, because the B_z component is typically highly fluctuating within the CIRs, the main phases of the resultant magnetic storms typically have highly irregular profiles and are weaker. Storm recovery phases during this phase of the solar cycle are also quite different in that they can last from many days to weeks. The southward magnetic field (B_s) component of Alfvén waves in the high speed stream proper cause intermittent reconnection, intermittent substorm activity, and sporadic injections of plasma sheet energy into the outer portion of the ring current, prolonging its final decay to quiet day values. This continuous auroral activity is called High Intensity Long Duration Continuous AE Activity (HILDCAAs).

Possible interplanetary mechanisms for the creation of very intense magnetic storms are discussed. We examine the effects of a combination of a long-duration southward sheath magnetic field, followed by a magnetic cloud B_s event. We also consider the effects of interplanetary shock events on the sheath plasma. Examination of profiles of very intense storms from 1957 to the present indicate that double, and sometimes triple, IMF B_s events are important causes of such events. 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. Finally, we argue that a combination of complex interplanetary structures, involving in rare occasions the interplanetary manifestations of subsequent CMEs, can lead to extremely intense storms.

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1. Introduction

The primary cause of magnetic storms is associated with interplanetary structures with intense, long-duration and southward magnetic fields (B_s) which interconnect with the earth's magnetic field and allow solar wind energy transport into the earth's magnetosphere (Gonzalez et al., 1994). It is the purpose of this paper to review the sources of such interplanetary magnetic fields distinguishing between solar maximum and the declining phases of the solar cycle.

The 'average' solar wind has a speed of $\approx$ 400 km s^{-1} and an embedded magnetic field of $\approx$ 5 nT. For major magnetic storms, the IMF intensity must be substantially higher than this value, and the solar wind speed (v) 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 magnetic storms with $Dst \leq -100$ nT. For the ten events studied, they found that the interplanetary duskward electric fields ($-\mathbf{v} \times \mathbf{B}$) were greater than 5 mV m^{-1} over a a period exceeding 3 hours. The 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). This is schematically shown in Figure 1. 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 to 10%.

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

2. Solar Maximum

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

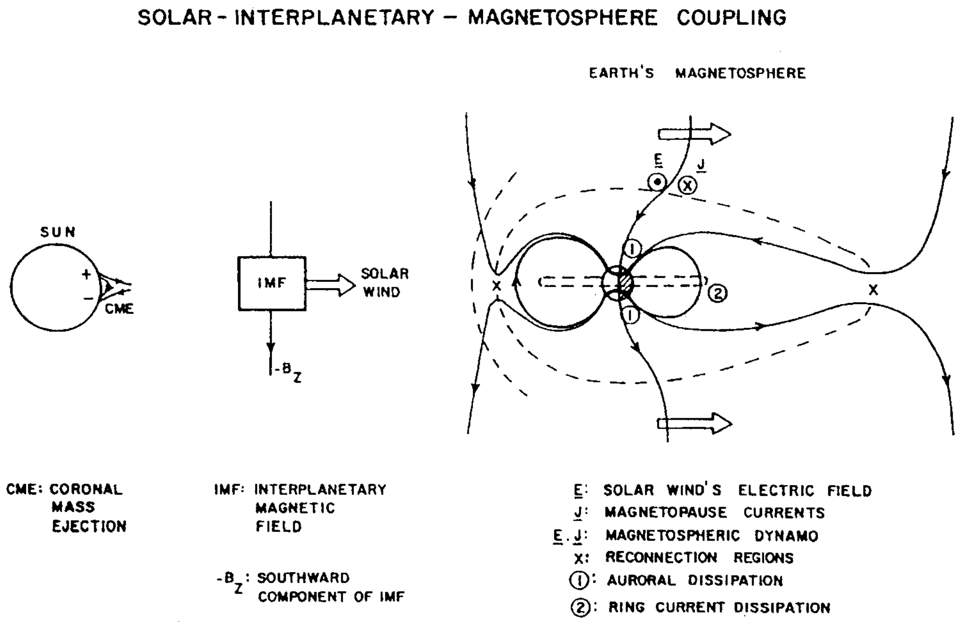

Figure 1. Schematic of interplanetary-magnetosphere coupling, showing the reconnection process and energy injection into the nightside magnetosphere, which lead to the formation of the storm-time ring current (Gonzalez and Tsurutani, 1992).

Bravo et al. (1998) have indicated possible roles of these small coronal holes in geoeffective solar activity.

The fast (> 500 km s^{-1}) CMEs coming from the Sun into interplanetary space are the solar/coronal features that contain high magnetic fields. Figure 2 is a schematic of the remnants of such a solar ejecta (driver gas) detected at 1 AU (each of the three main identifying features of CMEs observed close to the Sun have not been identified at 1 AU; see Tsurutani and Gonzalez, 1995a, for details). 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^{-1}), a forward shock is formed. The larger the differential speed, the stronger the Mach number of the shock. The average interplanetary quiet field is 3–8 nT and shock compression (magnetic field jump) across the shock of this field is roughly proportional to the Mach number. Interplanetary shocks typically have Mach numbers of 2–3, so the interplanetary 'sheath' fields downstream of the shock are typically up to 9–24 nT. In exceptional events, the speed differential is larger than Mach 4, (e.g., Kennel et al., 1985) and a maximum compression in the field of $\approx$4 is attained.

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

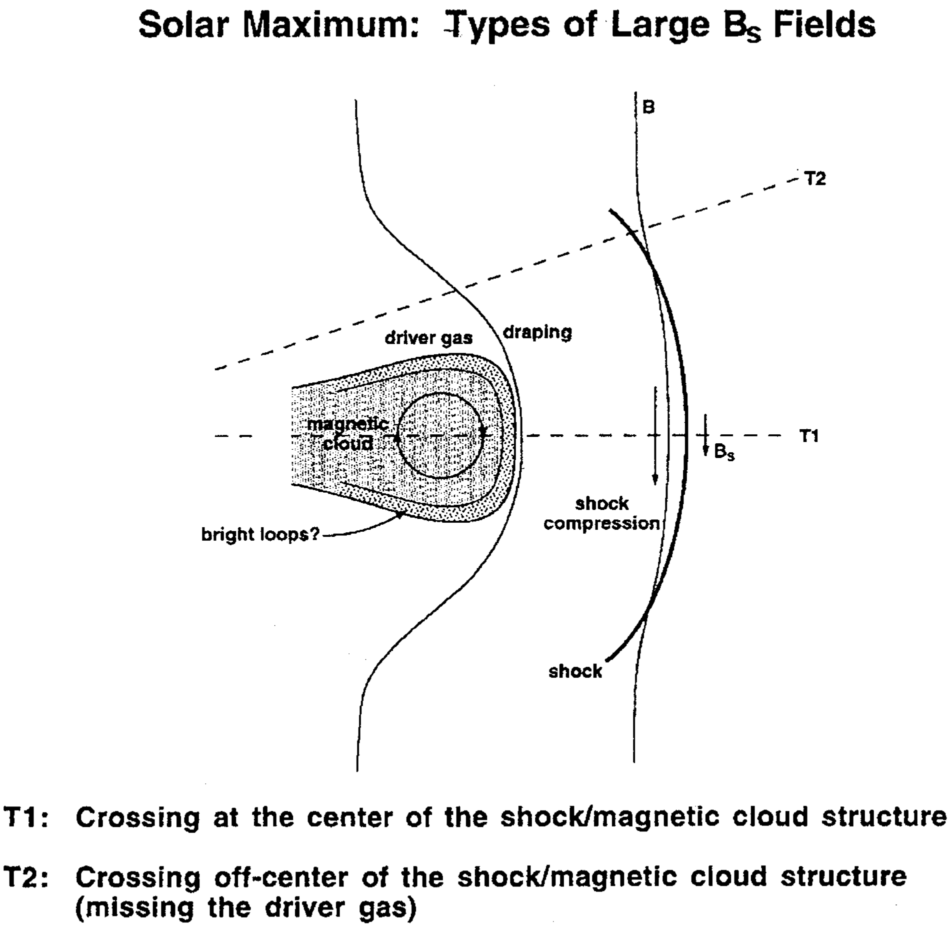

Figure 2. Regions of intense southward interplanetary magnetic fields during solar maximum, as remnants of a solar ejecta at 1 AU. T_1 and T_2 are two types of satellite crossings of the interplanetary structure.

and Gonzalez, 1995a; Farrugia et al. 1993, Choe et al., 1992). The magnetic field often has a north-to-south (or *vice versa*) rotation to it 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 so-called *magnetic tongues* proposed by Gold (1962) have been sought but were not found in the ISEE-3 1978–1979 data set.

At the present time we have not identified all of the component pieces of a CME at 1 AU. A ‘classic’ CME has three parts. Furthest from the Sun are bright outer loops. Next is a dark region, and closest to the Sun are bright twisted filaments. It has been speculated by Tsurutani and Gonzalez (1995a) that the magnetic cloud most probably corresponds to the central, dark region of the CME. This is because magnetic clouds are characterized by low ion temperatures (Farrugia et al., 1997). If the above argument is correct, then where are the loops and filaments? An intriguing possibility can be found in the work by Galvin et al. (1987), who have emphasized the existence of an anomalous region just upstream of a magnetic cloud (Tsurutani et al., 1988a, 1994; Gosling et al., 1987). This interval is characterized by higher density and temperature plasma, and enhanced He^{++}/H^{+} values, as well as by enhanced Fe. This region is also bounded by magnetic field discontinuities. It is speculated that this plasma is the remnant of the bright loops of a CME. Such structures upstream of magnetic clouds are present 20–40% of the time at 1 AU. Recently, Burlaga et al. (1998) have associated a very cold region of exceptionally high density, observed at the rear of a magnetic cloud, with the interplanetary extension of a prominence material.

2.1. STORMS CAUSED BY MAGNETIC CLOUDS

A classic example of a magnetic storm driven by a magnetic cloud is shown in Figure 3. 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 preshocked solar wind speed is $\approx$ 400 km s^{-1} and the post shock speed $\approx$ 550 km s^{-1}. The magnetic field increased from -6 nT to -22 nT across the shock. Because $B_z \approx 0$ in the sheath, there is no increased ring current activity associated with the sheath fields.

The plasma density increases from 5 cm^{-3} to $>$ 40 cm^{-3} across the shock. Because of this density (and velocity) increase across the shock, the increased *ram* pressure exerted on the earth's magnetosphere, ρv^2, causes a sudden compression of the magnetosphere and a positive jump in the horizontal component of the equatorial-region field. A positive jump in Dst is noted at the time of the shock. This is a sudden impulse (SI) event. Since the SI is eventually followed by a storm main phase, it is called a storm sudden commencement or SSC (however, it has been argued by Gonzalez et al., 1992, that this latter term is an artificial label because the physics of a SI – ram pressure increase – is independent of whether it is followed by a storm main phase or not).

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 $\approx$ 1 hour (Gonzalez et al., 1989). The storm main phase (decrease in Dst) development is rapid and the decrease monotonic. In the example of Figure 3, the peak Dst value of -239 nT is reached $\approx$ 2 hours after the peak B_s value of ≈ -30 nT. It should be noted that the southward turning of the IMF was abrupt, and after the maximum B_s was reached, B_s was constant for several hours and the field then slowly and smoothly rotated to a northward direction.

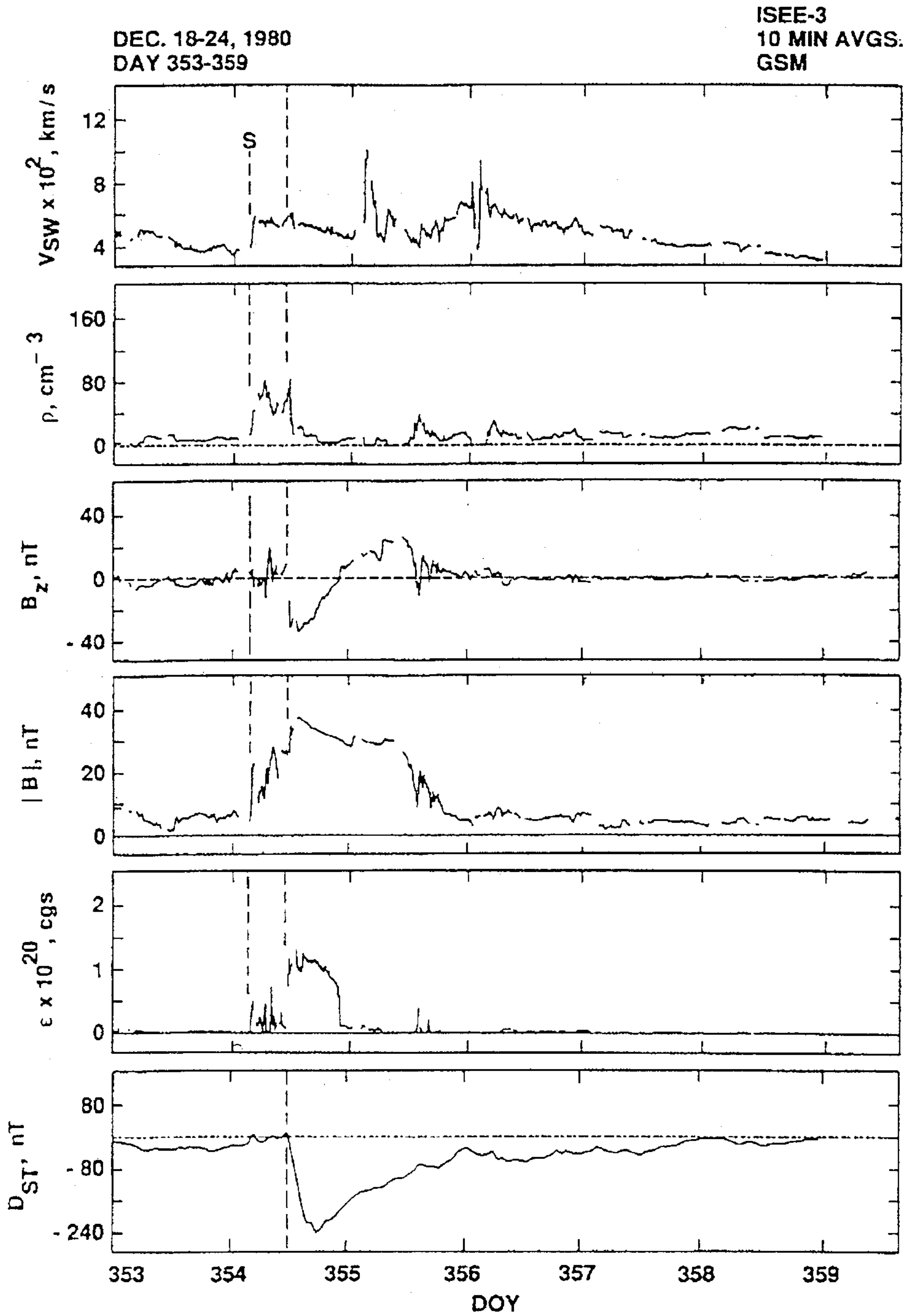

Figure 3. A classical example of a magnetic storm driven by a magnetic cloud. The vertical dashed line labeled by a 'S' indicates the presence of a fast forward shock. The vertical line to the right indicates the start of the magnetic cloud. The interplanetary parameters shown at the top four panels were measured by the ISEE-3 satellite. At the bottom panels the coupling parameters ϵ (Perreault and Akasofu, 1978) and the Dst index are shown.

The storm recovery phase is initiated by a gradual turning of the IMF to a northward direction from 16:00 UT day 354 to 14:00 UT day 355. The recovery starts as the field becomes less southward, is smooth and the e^{-1} time scale is a fraction of a day. Further discussions on the configuration and evolution of magnetic clouds and their geoeffectiveness can be found in the review paper by Farrugia et al. (1997).

2.2. MAGNETIC STORMS CAUSED BY SHEATH FIELDS

There are numerous mechanisms that lead to southward component fields in the sheath (Tsurutani et al., 1988a, 1992; Zwan and Wolf, 1976; McComas, 1989; Russell and McPherron, 1973; Odstrcil, 1998). A number of these are indicated schematically in Figure 4. Two of the mechanisms lead to the intensification of magnetic fields, independent of whether they are oriented in a northward or a southward direction. They are shock compression (b), discussed previously, and (d) draping. In the former mechanism, the shock compresses both the magnetic field and plasma. In the latter mechanism (Tsurutani et al., 1992), draping of magnetic fields around a large object (in this case, the solar ejecta) leads to a squeezing of plasma out the ends of magnetic flux tubes. Although the dynamic pressure ($B^2/8\pi + \Sigma_i N_i k T_i$) is maintained across the whole sheath, draping leads to lower beta plasmas and thus higher field strengths. The so-called ‘plasma depletion layer’ adjacent to the earth’s magnetopause is a simple consequence of this effect, and should be present to some degree near the sheath stagnation points at all large objects where magnetic draping occurs.

Figure 5 illustrates the generation of magnetic storms by sheath fields due to the shock compression mechanism. From day 245 until the shock on day 248, the B_z value was fluctuating, but generally had a southward component. There is corresponding auroral electrojet (AE) activity as well as ring current (Dst) activity present. Dst was ≈ -30 nT from day 245 until the middle of day 247, and ≈ -50 nT thereon until the shock. These Dst values are relatively constant with little or no sign of the classic main phase/recovery phase signatures.

There is a short duration increase (small spike) in Dst at and just after the shock due to solar wind ram pressure effects. This Sudden Impulse is the totality of the storm initial phase. The B_z values in the sheath region behind the shock are fluctuating, but primarily directed southward from the shock until 16:00 UT day 250. The peak B_s value of ≈ -20 nT is reached at $\approx 12:00$ UT day 249 and the peak Dst 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.

2.3. STATISTICAL ASPECTS OF STORM ORIGINS

Whether intense interplanetary fields are those of the sheath or the ejecta, the energy injection mechanism into the magnetosphere is the same. This has been schematically shown in Figure 1. In general, the IMF structures leading to great

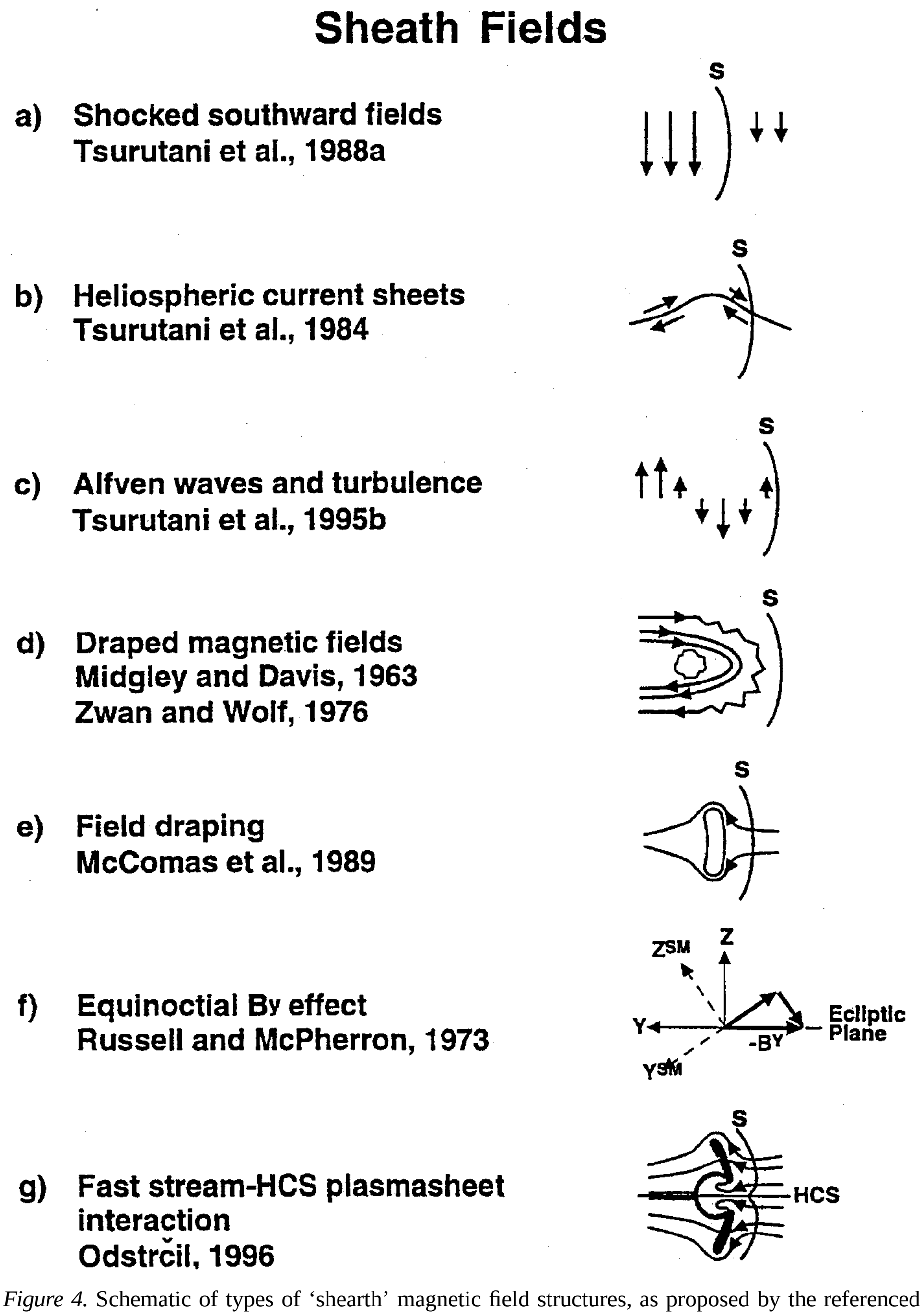

Figure 4. Schematic of types of 'shearth' magnetic field structures, as proposed by the referenced authors.

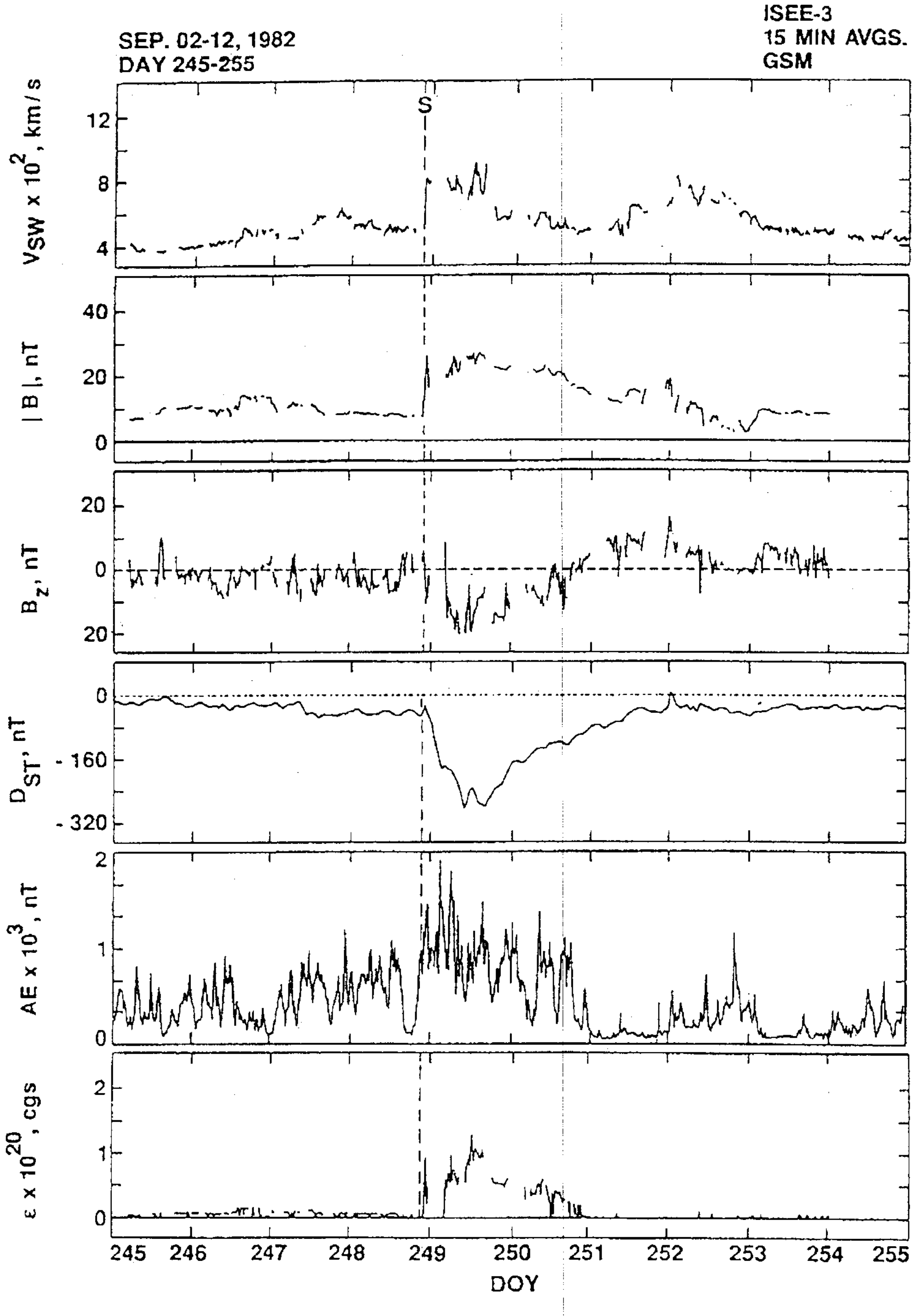

Figure 5. Example of a magnetic storm caused by shock compression of interplanetary B_s fields. The vertical dashed line labeled by a 'S' indicates the presence of a fast forward shock. The interplanetary parameters shown at the top three panels were measured by the ISEE-3 satellite. At the bottom three panels the Dst index, the AE index, and the ϵ coupling parameter are shown.

TABLE I
ISEE-3 statistics (August 1978–December 1979)

Storm intensity	No. of events	Definition	Association with shocks (56) (fast speed ICMEs)
Intense	10	$Dst < -100$ nT	80%
Moderate	40	-100 nT $\leq Dst \leq -50$ nT	45%
Small	62	-50 nT $\leq Dst \leq -30$ nT	25%
		Shocks and magnetic storms	
		15% followed by intense storms	
		35% followed by moderate storms	
		30% followed by small storms	
		15% followed by no storms*	

*$Dst \geq -30$ nT.

TABLE II
Statistics for August 1978–October 1982

Storm intensity	Kp definition	Dst definition	Shock associaton	ICME association
Big	$8 \leq Kp \leq 9$	$Dst \leq 200$ nT	100%	90%
Intense	$Kp = 7$	-200 nT $\leq Dst \leq -100$ nT	80%	80%
Moderate	$5 \leq Kp \leq 6$	-50 nT $\leq Dst \leq -30$ nT	40%	40%

($Dst < -250$ nT) and intense ($Dst < -100$ nT) 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 Tables I and II we give the causal connection between shocks/solar ejecta and storms of various levels of strength where we have defined the latter as follows. Big: $Dst < -200$ nT, intense: -200 nT $\leq Dst < -100$ nT, moderate: -100 nT $\leq Dst < -50$ nT, small: -50 nT $\leq Dst < -30$ nT magnetic storms. These come from prior work of the authors and from Gosling et al. (1991). Gosling et al. used Kp indices, and we have indicated the approximate Dst values corresponding to these values. The tables show that big storms have a 90% correspondence with fast solar eject events (with shocks), while small storms have only a 24% correspondence with fast solar ejecta.

Table I indicates that solar ejecta led by shocks do not always cause intense ($Dst < -100$ nT) magnetic storms. Studies using the ISEE-3 1978–1979 data indicate that only one out of every six solar ejecta (17%) are geoeffective in causing

TABLE III

Interplanetary association of moderate storms*

ISEE-3 (August 1978–December 1979)
40% shock
23% high-speed stream without shocks
17% high-low speed stream interaction
10% noncompressive density enhancements (NCDEs)
10% other (including Alfvénic fluctuations)

*-100 nT $\leq Dst \leq -50$ nT.

intense storms (Tsurutani et al., 1988b). From 57 fast solar ejecta events, it was found that some of the events did not have substantial B_s, others had large B_s values, but were highly fluctuating (about $B_z = 0$ nT) in time. The important point is that they did not have $B_s > 10$ nT for $T > 3$ hours. Table III gives the statistics for moderate magnetic storms. At these lower levels of storm intensity, one notes that the interplanetary causes are much more diverse. There are many mechanisms responsible for the causative B_s values. One such case (Alfvén fluctuations) were indicated in Figure 5 for the geomagnetic activity in the preshock interval. The general southward component, possibly intensified by the Russell–McPherron (1973) mechanism, and fluctuating B_z led to $Dst \approx -50$ nT.

2.4. VISCOUS INTERACTION

The Earth's magnetopause can absorb solar wind energy through the fluid analogy of a viscous interaction (Axford and Hines, 1961). More specifically, mechanisms such as the Kelvin–Helmholtz instability (Parker, 1958; Chen and Hasewaga, 1974; Southwood, 1974) or magnetosheath cross-field diffusion due to magnetopause boundary layer waves (Tsurutani and Thorne, 1982; Thorne and Tsurutani, 1991), are possible ways to inject solar wind energy into the magnetosphere.

An upper limit of the efficiency of solar wind energy access to the magnetosphere has been explored by examining intervals where the northern IMF component has characteristics: $B_n > 10$ nT and $T > 3$ hours. These interplanetary conditions allow reconnection between the IMF and terrestrial field tailward of the cusp (Dungey, 1961; Russell, 1972) hence justifying the statement that this is an upper limit calculation. The actual efficiency value might be lower. Without going through the (reasonably simple) details of the calculations, the conclusion is that ≈ 1 to 4×10^3 of the solar wind ram energy is converted to magnetospheric energy in the form of auroral particles energy, Joule heating, or ring current particle energy (Tsurutani and Gonzalez, 1995b).

The efficiency of solar wind energy injection during magnetic reconnection events such as substorms and intense storms is 5–10% (Weiss et al., 1992; Gonzalez et al., 1989). The intercomparison of these numbers indicates that viscous interaction appears to be not more than 1%. The highest solar wind speed event ever detected ($v > 1500$ km s^{-1}, August, 1972) has also been studied for this effect. The efficiency of viscous interaction was found to have approximately the same value for this event as well (Tsurutani et al., 1992). It should be noted that northward B_z intervals satisfying the $B_z > +10$ nT and $T > 3$ hours criteria are often found to be a portion of a magnetic cloud. Thus, since magnetic clouds often have south and then northward magnetic field orientations (or *vice versa*), clouds often cause magnetic storms followed by geomagnetic quiet (or *vice versa*).

3. Descending Phase of the Solar Cycle

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). Coronal holes are low temperature regions above the Sun, observed in soft X-rays (Timothy et al., 1975). 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^{-1} (Phillips et al., 1994) and are dominated by large amplitude Alfvén waves (Tsurutani et al., 1994, 1996; 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 $\approx$ 27-day intervals (as seen at the Earth), and thus plasma from these streams impinge on the Earth’s magnetosphere at periodic intervals and cause recurrent geomagnetic storms (Sheeley et al., 1976; Burlaga and Leping, 1977).

High speed streams emanating from coronal holes can create intense magnetic fields if the streams interact with streams of lower speeds (Belcher and Davis, 1971; Tsurutani et al., 1995a, b). A schematic of such an interaction is given in Figure 6. The magnetic fields of the slower speed stream are more curved due to the lower speeds, and the fields of the higher speed stream are more radial because of the higher speeds. The stream-stream interface (IF) is the boundary between the slow stream and fast stream plasmas and fields.

Anti-sunward of the IF are the compressed and accelerated slower speed plasma and fields. Behind the IF are the compressed and decelerated high speed stream plasma and fields. At large heliospheric distances (> 1.5 AU), where these corotating structures are well developed, they are bounded by fast forward (FS) and fast reverse (RS) shocks. This overall structure was first found in the Pioneer 10 and 11 data and were named Corotating Interaction Regions (CIRs) by Smith and Wolf (1996). See also Burlaga et al. (1985). As far as geomagnetic storms are

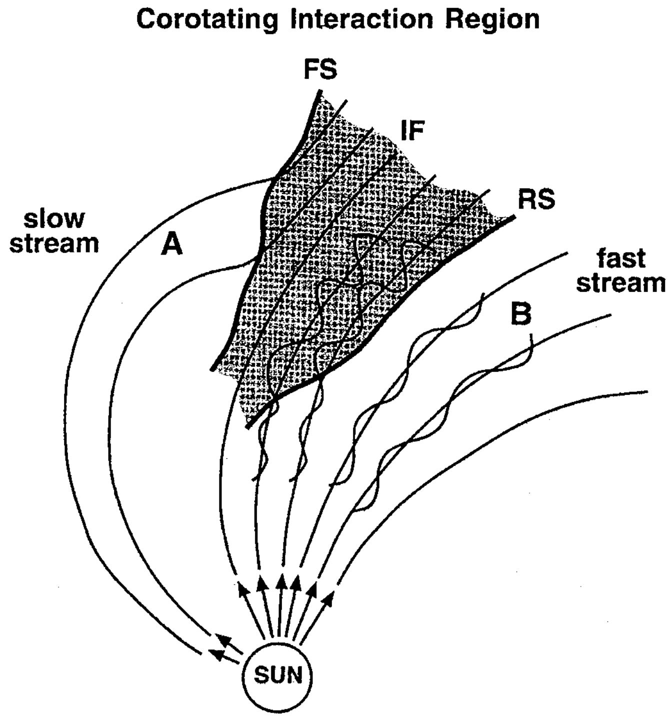

Figure 6. Schematic of the formation of corotating interaction regions (CIRs) during the descending phase of the solar cycle. The composition of the plasma and magnetic field fluctuations are also shown. The magnetic fields of the slower speed stream are more curved, whereas those of the higher speed stream are more radial.

concerned, the important feature of CIRs is that they are characterized by intense magnetic fields. The intensifies can reach $\approx$ 30 nT.

At 1 AU, CIRs are not fully developed. They almost never have forward shocks (this can and has been used as a reasonably reliable identifying feature) and usually do not have reverse shocks ($\approx$ 80% of the time). We therefore call these proto-CIRs (PCIRs) in this paper.

An example of a PCIR and its consequential magnetic storm activity is shown in Figure 7. This event is typical of the events studied for the 1973–1975 epoch (Tsurutani et al., 1995b), where two corotating streams (from two coronal holes) per solar cycle dominated interplanetary activity.

An unusually high plasma density can be typically found near the heliospheric current sheet (HCS), the region separating the north and south hemisphere heliospheric magnetic fields. This high density plasma has been called the HCS plasma sheet by Winterhalter et al. (1995). However, R. P. Lepping (personal communication) notes that this plasma sheet may not always be present. The HCS is identified by a reversal in the Parker spiral direction by $\approx$ 180 or a simultaneous reversal in the signs of both B_x and B_y.

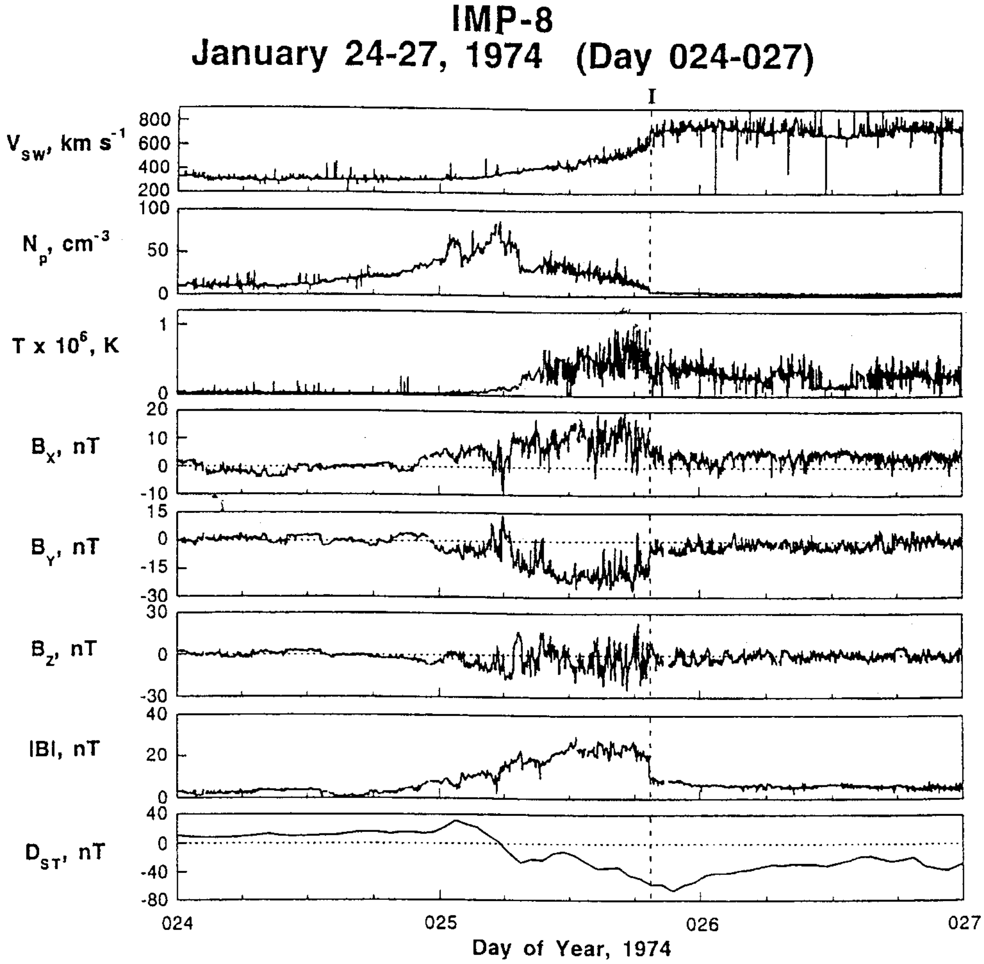

Figure 7. Example of a PICR and associated geomagnetic activity, typical of 1973–1975. The high speed-lower speed interface is marked by the dashed vertical line, ahead of which one can see the compressed plasma and magnetic field associated with the PCIR. The interplanetary parameters for this event were measured by the IMP-8 satellite.

The high density plasma of the HCS plasma sheet can cause the ‘initial phase’ of a magnetic storm. Note that this ‘phase’ of the storm is caused by interplanetary conditions totally unlike those during solar maximum. Here the high densities are associated with a low velocity stream ($v < 400$ km s^{-1}). Since the PCIRs typically do not have forward shocks at 1 AU, there will typically be a lack of a sudden impulse associated with this type of a storm.

The PCIR can be responsible for the main phase of the magnetic storm. However for PCIRs, B_z is typically highly fluctuating throughout the interval. There may be a net southward component within the PCIR, but this can be accompanied by a much larger fluctuation amplitude, causing typically only a moderate storm.

TABLE IV

Geoeffectiveness of proto-CIRs, IMP-8 days 1–241, 1974, well-developed streams*

Storm intensity	Definition	Geoeffectiveness
Intense	$Dst < -100$ nT	0%
Moderate	-100 nT $\leq Dst \leq -50$ nT	29%
Small	-50 nT $\leq Dst \leq -30$ nT	29%
Negligible storm activity	-50 nT $\leq Dst$	41%

*$v = 600$–850 km s^{-1}.

Why are such fluctuations present? One possible answer is schematically shown in Figure 6. If B_z fluctuations (Alfvén waves) are present in the high speed stream proper, then the deceleration and compression due to passage through the reverse shock could lead to amplification of such oscillations. *Ulysses* results are consistent with such a scenario. However, corotating streams seem to be far less geoeffective in creating intense or moderate magnetic storms (Tsurutani et al., 1995b).

A summary of the geoeffectiveness of PCIRs is given in Table IV. This was derived from a subset of the 1974 data set. Similar results have been obtained for the 1973 and 1975 data sets.

3.1. Maximimum geomagnetic activity and HILDCAAs

Although it is clear that there are far more large Dst events during solar maximum than during solar minimum, the same cannot be said for auroral zone (AE) activity. For the period 1973–1975, the annual AE average (of the 2.5 min values) were: 247, 283, and 224 nT, respectively. For 1979–1981, the annual AE values were 221, 180, and 237 nT. The 283 nT value for 1974 was larger than any of the solar maximum year (Tsurutani et al., 1995a).

The interplanetary phenomena, responsible for this substorm activity, are prolonged intervals of Alfvénic fluctuations throughout the slow recovery of Dst, causing continuous substorms.

The cause of such continuous substorms are the large amplitude B_z fluctuations in the IMF. Although the average B_z value is near zero, the large amplitude fluctuations provide very large B_s intervals and concomitant substorms through the reconnection process. The IMF fluctuations have been examined and have been shown to be Alfvén waves propagating outward from the Sun in these coronal hole streams. The fluctuations are more or less continuous and the southward components of the larger period waves cause High Intensity Long Duration Continuous AE Activity (HILDCAAs) (Tsurutani and Gonzalez, 1987; Tsurutani et al., 1990; Gonzalez et al., 1995).

4. Complex Interplanetary Structures Leading to Storms

In several instances more than one interplanetary structure can be associated with the origin of intense storms. Such complex structures have recently started to receive more attention in the literature (Burlaga et al, 1987; Behannon et al., 1991; Schwenn, 1995; 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 yet a clear idea about them.

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. 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 Richardsen, 1997; Knipp et al., 1998), preceded by a corotating interaction region (CIR). As it is known though, CIRs do not form a shock at distances of 1 AU or less (Smith and Wolf, 1976) and, therefore, there are no 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. (1999a), in which a shock/compressional wave has been noted within and close to the rear end of the cloud. This event is shown in Figure 8. A strong magnetic compression exists at point C of this figure (region 'D' is interpreted to be a CIR). The field compression is $\approx$ 36%. There are coincident increases in plasma density and velocity. We note however, that the density at this time is ≈ 20 cm^{-3}, 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 Alfvénic fluctuations in the stream (as seen in Figure 8) is not necessarily a signature of a corotating stream, since Tsurutani and Gonzalez (1987) have reported trains of Alfvénic 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 Alfvénic 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.

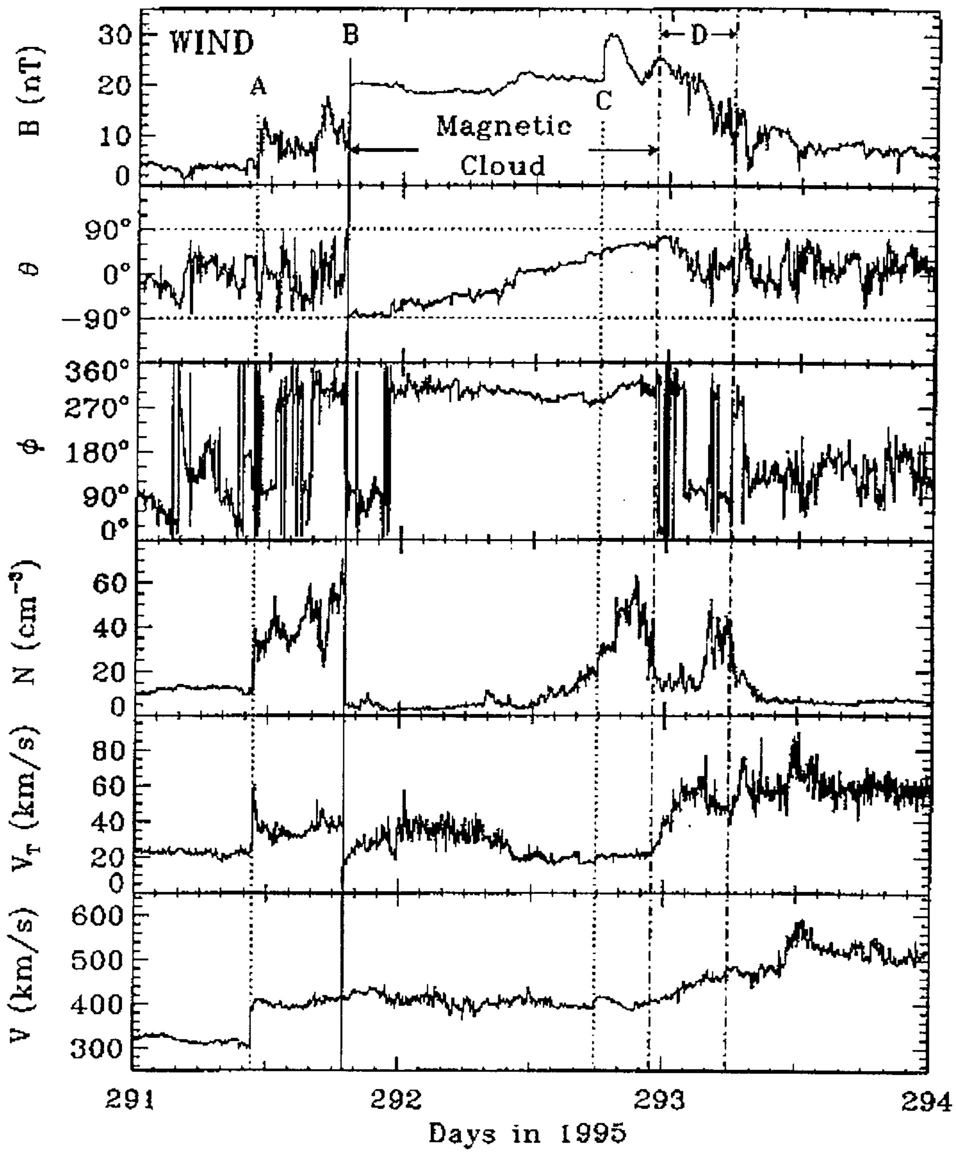

Figure 8. Example of a complex interplanetary structure (October 18–20, 1995), involving a transient high speed stream (shock at A), with a magnetic cloud, and a following probable corotating stream (with a CIR at D). There is a shock like/compression structure at C (at the rear end of the cloud and ahead of the secondary stream).

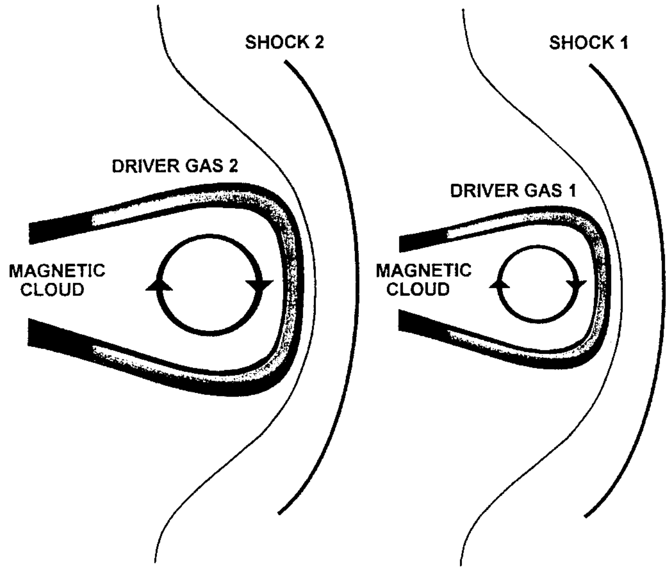

Figure 9. Schematic showing two consecutive high speed streams, both involving fast forward shocks and driver gas/magnetic cloud structures.

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, 1998).

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 Figure 9. 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 Figure 9, 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 leading to an intensification of the B_s part of tho cloud. 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 especial investigation.

5. Causes of Very Intense Storms

5.1. 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. combined published examples of clouds with those observed by the ISEE-3 satellite in 1979 and identified following the criteria given by Burlaga (1995). Figure 10 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 the faster it propagates 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.

Figure 11 displays the ISEE-3 subset of driver gas-non cloud events also studied by Gonzalez et al. (1998). One can see that this plot is largely scattered without any clear trend for a $|B|$–v relationship, as that shown in Figure 2 for the cloud events. An explanation for this different behavior is also presently unknown.

5.2. 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 Figure 2). One mechanism to have shocks occurring within sheaths is to have the shocks propagate from the downstream magnetosheath up into the front side sheath regions. 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. Figure 12 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 ≈ 4 times and the second shock by ≈ 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^{-1} at 1 AU (the plasma instruments were saturated). The magnetic cloud field strength

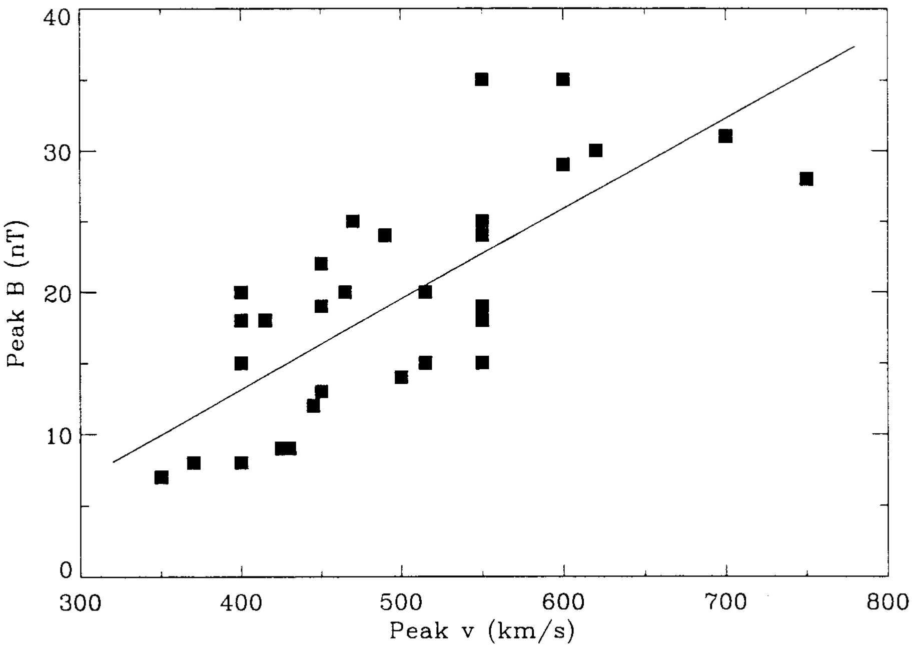

Figure 10. Peak values of the magnetic field intensity and the solar wind speed for the magnetic cloud events studied by Gonzalez et al. (1998). This figure shows that the faster the cloud moves the higher the core magnetic field is.

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 Figure 10. The magnetic field was plotted in solar heliospheric, or RTN, coordinates.

5.3. Double and Triple-Step Storms

Another way to get large Dst events is to have two storm main phases with the second closely following the first (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 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. 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 Dst for the first event was ≈ -100 nT and ≈ -300 nT for the second event. We note however that these values were not

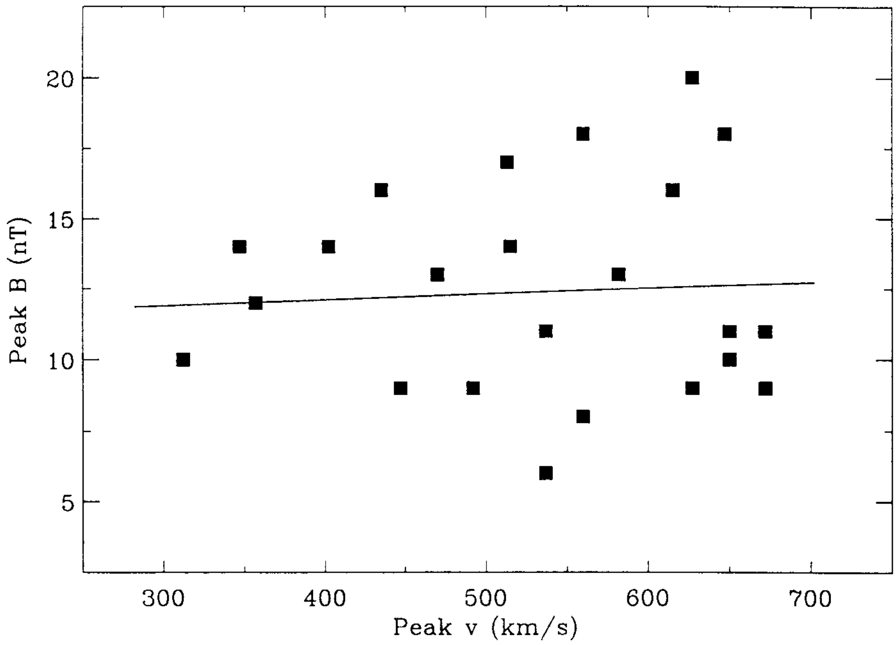

Figure 11. Peak values of the magnetic field intensity and of the solar wind speed for the driver gas–non-cloud events of 1979, measured by the ISEE-3 satellite. This figure doe snot shown any association between those parameters, contrasting with what is shown in Figure 8.

pressure-corrected. The field at the storm initial phase was $\approx +60$ nT indicating that the correction will be substantial.

We re-examined the interplanetary causes of great magnetic storms ($Dst < -250$ nT) which have corresponding interplanetary data (reported in Tsurutani et al., 1992). The Dst profiles are shown in Figure 13. 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. The latter could be due to a complex ICME/sheath region and to a precursor B_s field ahead of the shock.

5.4. Superintense Magnetic Storms

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. Figure 14 shows the profile of the three storms that had (uncorrected) peak Dst values < -400 nT. There is one event for each of the years 1957 through 1959. The main phases of each of the three storms are

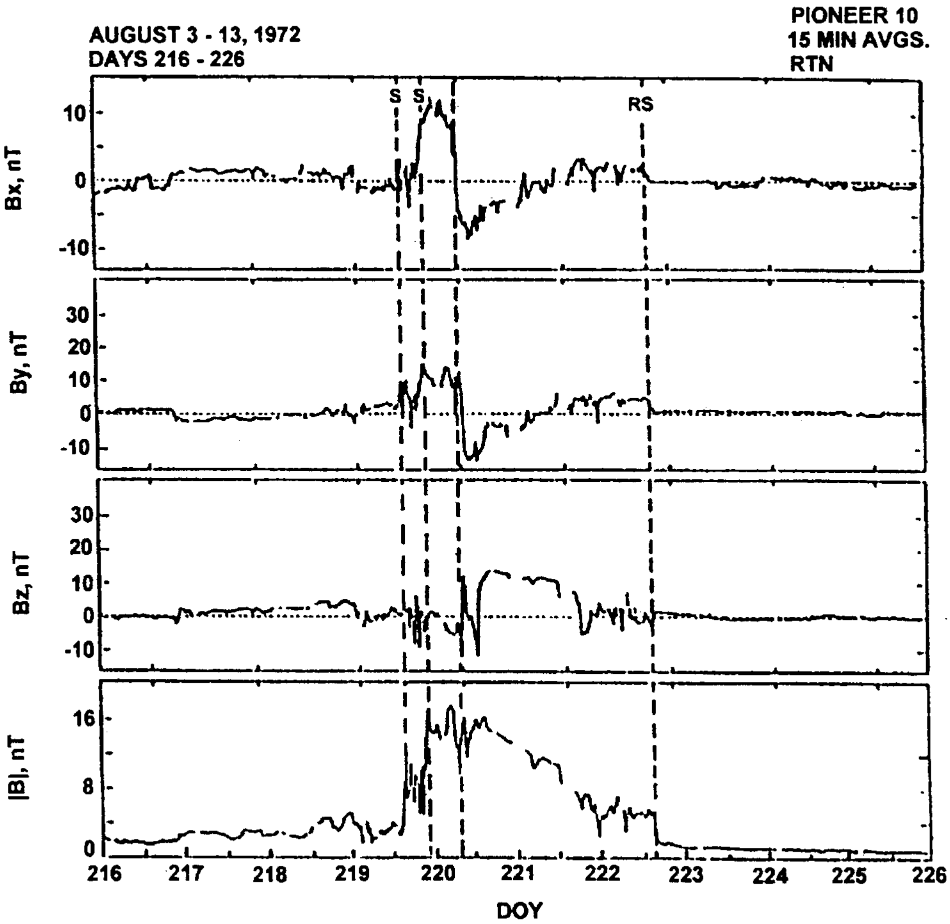

Figure 12. Pioneer 10 IMF data at 2.2 AU from the Sun (Smith and Somett, 1976), showing a shock compression of the sheath field. The first shock compressed the ambient field by about 4 times and the second shock compresses the sheath field by about 2 times.

relatively short, all less than 12 hours. The July 15, 1959 event was clearly a double storm event, whereas the September 13, 1957 event appears as a triple storm event.

We also display the March 13–14, 1989 event, the largest recorded during recent times ($Dst = -600$ nT, uncorrected for pressure). This is shown in Figure 15. There is a slowly developing main phase prior to a sharp Dst decrease at -20 UT day 13. This profile is similar to the February 7–9, 1986 event discussed previously. The whole main phase takes over 24 hours. 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.

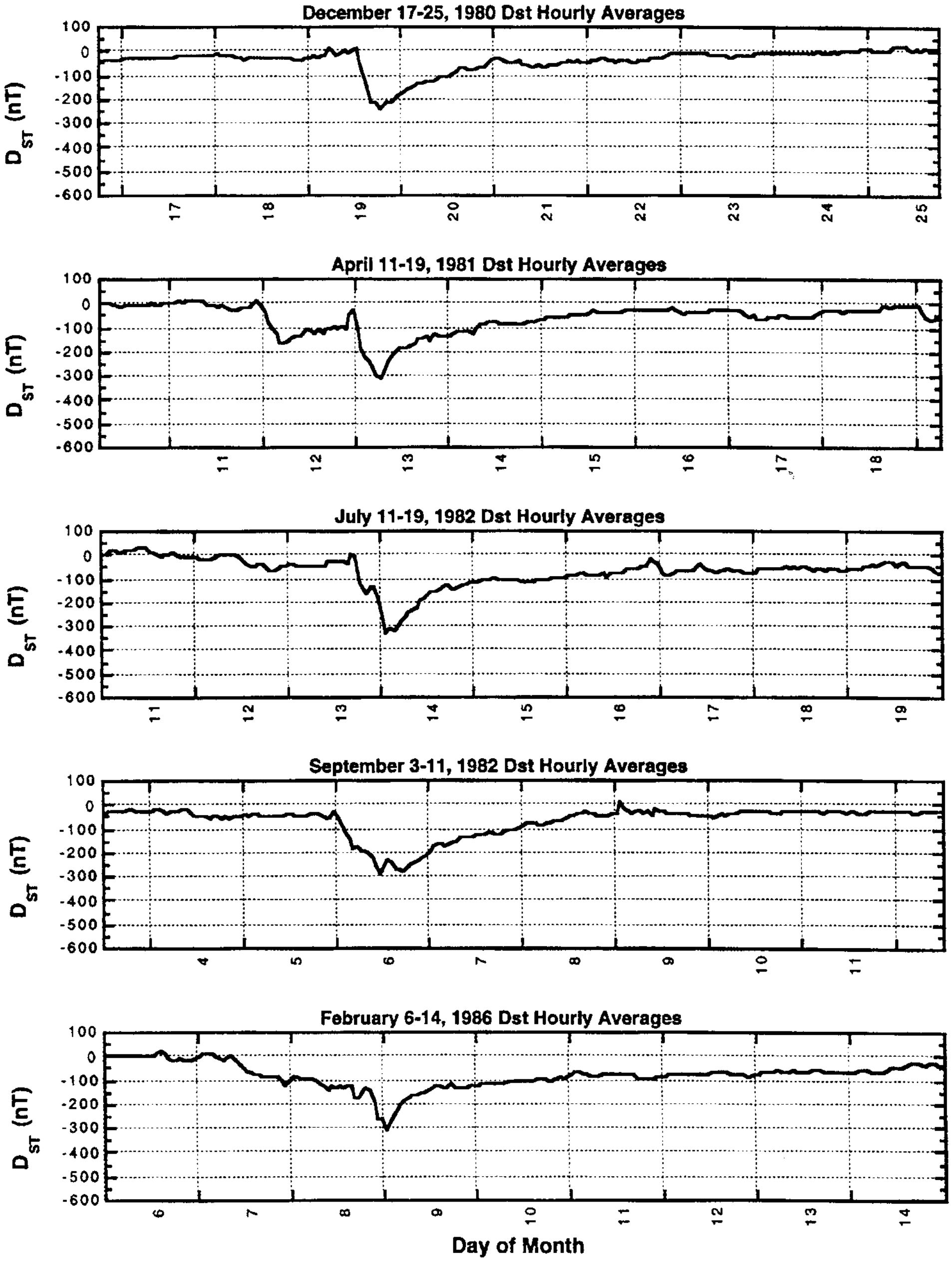

Figure 13. Dst profiles for the five largest magnetic storms during the period of 1980 and 1986 $Dst < -250$ nT) that have corresponding interplanetary data.

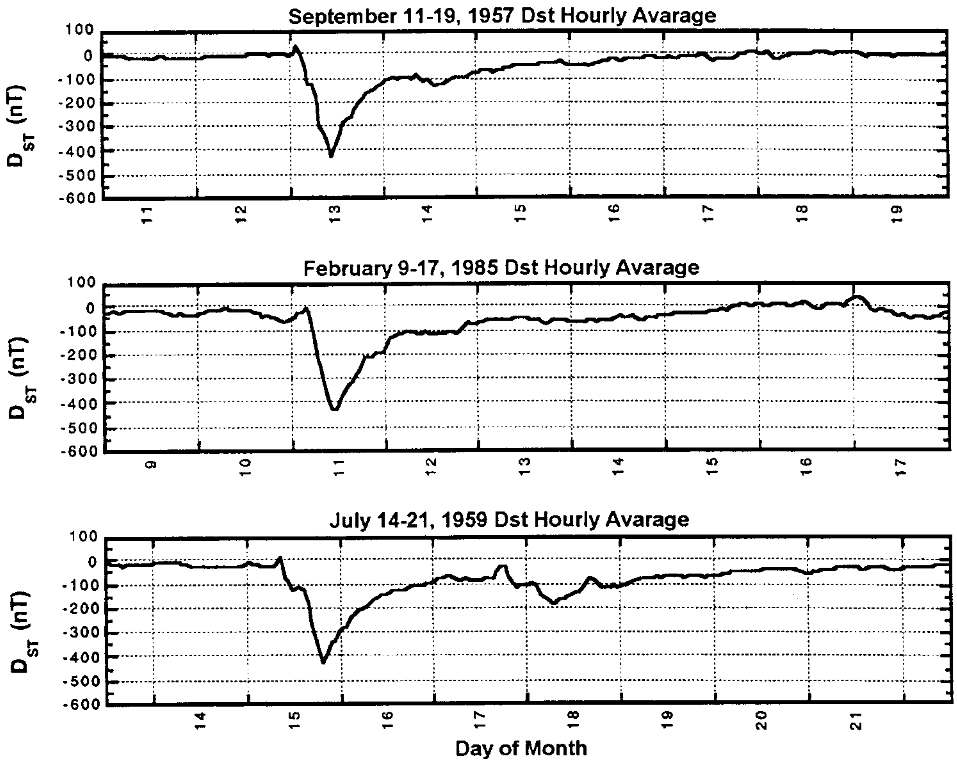

Figure 14. Dst profiles for the largest magnetic storms in 1957–1959 era ($Dst < -400$ nT). The events occurred prior to the advent of *in situ* space plasma measurements.

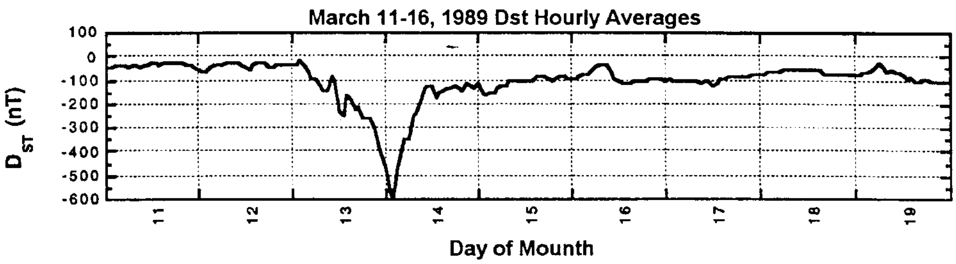

Figure 15. Dst profiles for the largest magnetic storm recorded during recent times ($Dst \approx -600$ nT). The event occurred on March 13–14, 1989. The whole main phase took over 24 hours, showing the presence of a complex sheath region ahead of a magnetic cloud.

5.5. Discussion

Since for magnetic clouds the total field typically has a substantial southward component (Gonzalez et al., 1994), the results shown on Figure 10 imply that the interplanetary dawn-dusk electric field, given by $-\mathbf{v} \times \mathbf{B}_s$ is enhanced by *both* factors. 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.

Although the 1957–1996 interval did not have sufficient interplanetary data available to examine the causes of all of the very intense storms, use of existing Dst profiles can allow one to make reasonable hypotheses of the interplanetary causes of such events. It is found that double and triple storms caused by two and three IMF B_s events may contribute significantly to the occurrence of very intense storms. We found no evidence of double shock events causing $Dst < -400$ nT magnetic storms. However, it should be noted that the storm sample used was quite limited.

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 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 causes of such double and triple storm effects? One speculation is that stochastic electric fields drive plasmasheet 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 Dst. 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. Tsurutani et al. (1998) have discussed one mechanism to provide an energetic oxygen enriched population to the plasmasheet. The above ideas are interesting but clearly more work is needed to determine the exact mechanism(s).

6. Solar Cycle and Seasonal Distribution of 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; 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. A more detailed study of this different (non-classical) distribution has been carried out by

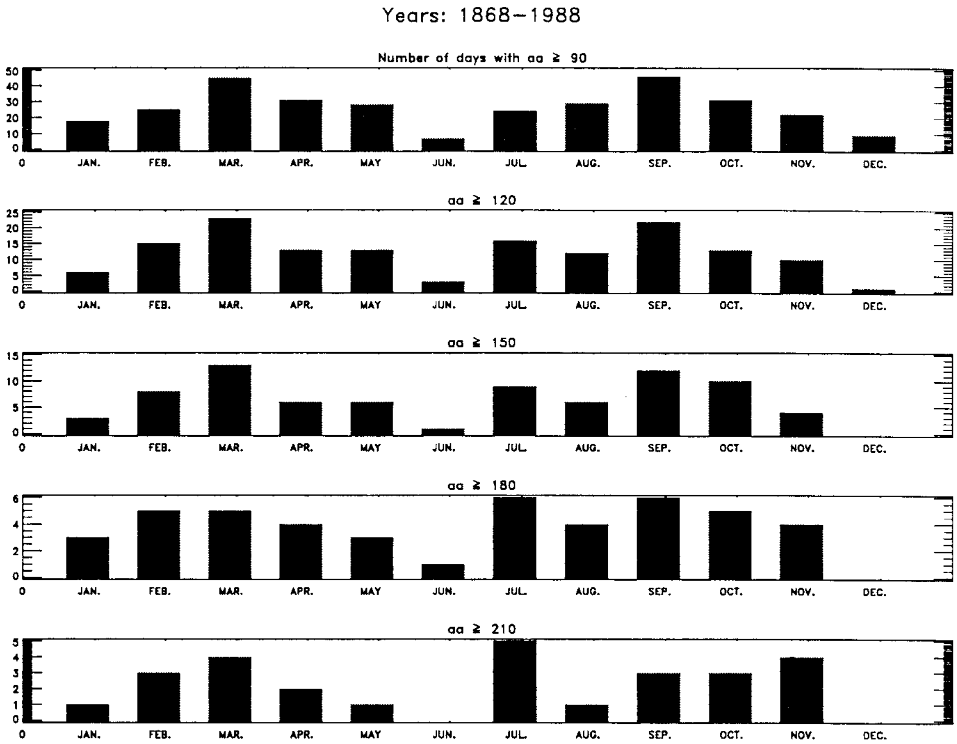

Figure 16. Seasonal distribution of magnetic storms for the 1868–1988 interval, as represented by the *aa* index. The levels of geomagnetic activity increase from fairly intense (*top*) to very intense (*bottom*). See text for details about the change in the classical pattern of the seasonal distribution of geomagnetic activity.

Clúa de Gonzalez et al. (1998), using several geomagnetic indices. Figure 16 shows the seasonal distribution for the interval 1868–1988, using the aa index, for several levels of geomagnetic activity. One can see from this figure that, for the range of activity involving moderate to fairly intense activity ($aa \leq 90$) the classical type of distribution is still found. However, for the higher levels of activity the July peak becomes pronounced and for the most intense level of activity (bottom panel) the shape of the distribution greatly departs from the classical one. Similar results were found for seasonal geomagnetic activity distributions using other indices (Dst and AE). At the moment there is not yet a clear consensus about the physical processes that are involved in the (non-classical) seasonal distribution of intense storms (e.g., Gonzalez et al., 1994). However, in addition to the known mechanisms that contribute to the classical distribution (e.g., Clúa de Gonzalez et al., 1993), it appears that the role of ionospheric conductivity in the development of storms and substorms needs to be considered.

It is also known that geomagnetic activity as a whole tends to become enhanced during the descending phase of the solar cycle (e.g., Sugiura, 1980; Legrand and

Simon, 1991). However, Gonzalez et al. (1990) showed that intense storms (peak $Dst \leq -100$ 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 hours 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 $\pm 30°$ around the solar equator (Gonzalez et al., 1996).

Figure 17 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. (1995b) 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).

Recently, Newell et al. (1998) have claimed that the solar cycle distribution of intense aurorae is uncorrelated with solar activity. These authors looked to the cause of such an effect in the role that ionospheric conductivity seems to play in auroral phenomeana. However, Tsurutani et al. (1999b) have argued that the Newell et al. results are in agreement with the expected uncorrelation of solar and auroral activities described above and illustrated in Figure 17.

7. Current Outstanding Problems

(1) 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 typical 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

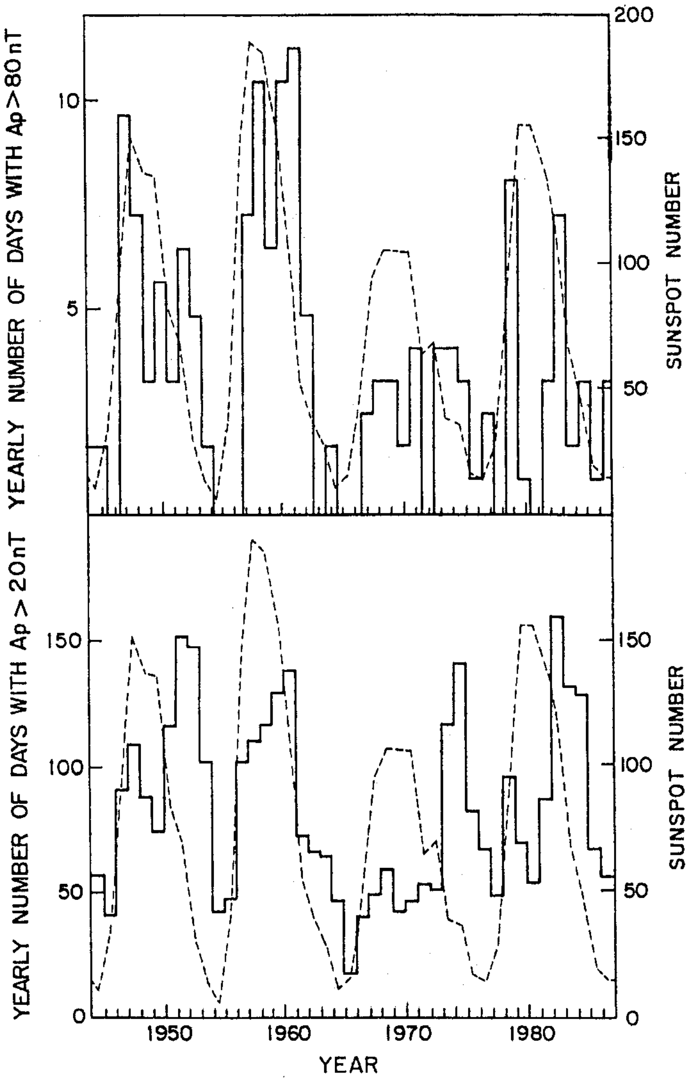

Figure 17. Solar cycle distribution of geomagnetic activity as measured by the *Ap* index. *Top:* Dual-peak type distribution of intense storms. *Bottom:* Single-peak type distribution of storms including low to moderate levels of intensity.

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, 1996)). Furthermore, when a driver gas is not observed and an intense magnetic storms follows an interval preceded by an interplanetary shock, it is possible that the satellite missed the driver gas, or that the B_s structure, responsible for the storm, be the result of further amplification by the shock of large amplitude (nonlinear) Alfvén waves emanating from coronal holes (Gonzalez et al., 1995, 1996).

(2) Because of the geoeffectiveness of fast ICMEs/driver gases and their sheaths, these solar/interplanetary phenomena have received the most attention. However, little is known about ‘slow’ CMEs, those ejecta events that do not produced upstream shock waves. Questions we need to understand are: why aren’t these geoeffective? Is the lack of sheath fields the cause of the lack of storms? Do these ICMEs/driver gases never/seldom have magnetic cloud field configurations? Or are the ICME/driver gas fields less intense, implying an intrinsic relationship between CME field strength and velocity? The results reported by Gonzalez et al. (1998) have started to answer to some of these questions. Further development of these studies and understanding of the associated physical processes are necessary.

(3) About B_s intensifications by interplanetary processes associated with complex structures (summarized in Section 4), 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.

(4) An important task that needs especial and extensive study is that dealing with the search of interplanetary manifestations of each of the structures commonly associated with the CME: the bright loop, the dark region and the filament. Some initial efforts have been recently started (Tsurutani and Gonzalez, 1997; Burlaga et al., 1998).

(5) 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 coronagraph in space with a spacecraft/Sun/Earth angle of $\approx 90°$. A CME event occurrence plus its velocity can be obtained by the coronagraph measurements. From the work of Gonzalez et al. (1998) we could make an educated guess about peak B_s values for intense storms, by knowing the peak values of the CME speed. 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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