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GREAT MAGNETIC STORMS

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Abstract. The five largest magnetic storms that occurred between 1971 to 1986 are studied to determine their solar and interplanetary causes. All of the events are found to be associated with high speed solar wind streams led by collisionless shocks. The high speed streams are clearly related to identifiable solar flares. It is found that: 1) it is the extreme values of the southward interplanetary magnetic fields rather than solar wind speeds that are the primary causes of great magnetic storms, 2) shocked and draped sheath fields preceding the driver gas (magnetic cloud) are at least as effective in causing the onset of great magnetic storms (3 of 5 events) as the strong fields within the driver gas itself, and 3) precursor southward fields ahead of the high speed streams allow the shock compression mechanism (item 2) to be particularly geoeffective.

Introduction

It has been demonstrated that there are a variety of interplanetary phenomena associated with southward magnetic fields which cause magnetic storms (Burlaga et al., 1987; Tsurutani et al., 1988; McComas et al., 1989, Gosling et al., 1990; 1991). Some of these features/mechanisms are: the shock compression of quiet upstream B_S, sheath field draping, waves and turbulence, compressed heliospheric current sheets, driver gases/magnetic clouds (coronal mass ejections), and compound streams. Recently, Gosling et al. (1991), from a statistical analysis, have indicated that the subset of interplanetary causes are different for different levels of storm intensities.

In this paper we wish to briefly address the interplanetary and solar causes of the very largest (great) magnetic storms. We have selected the five largest magnetic storms that have occurred in the interval of 1971 to 1986, using the D_{ST} index. Prior to 1971, there is little interplanetary data to use for an analysis of this type.

The D_{ST} index is constructed from near-equatorial magnetic data and is a superior storm index in comparison to midlatitude indices such as Kp and Ap which are sensitive to substorms as well (Tsurutani and Gonzalez, 1990; Joselyn and Tsurutani, 1990). The great storm onsets occurred on: July 13, 1982 (peak D_{ST} = - 325 nT), April 13, 1981 (D_{ST} = - 311 nT), February 7, 1986 (D_{ST} = - 312 nT), September 5, 1982 (D_{ST} = - 289 nT) and December 19, 1980 (D_{ST} = - 249 nT). It should be noted that four of the storms occurred in the latter portion of (or slightly after) the 1979-1981 solar maximum, and one event (February, 1986) near solar minimum. The biggest event of our study, July 13, 1982, was the 8th largest within the D_{ST} tape interval of 1957 to 1986. The largest event was the July 15, 1959 storm (peak D_{ST} = - 429 nT). Six of the seven most intense events since 1942 occurred during the 1957-1960 epoch when, unfortunately, interplanetary data were not available.

We have chosen to study the very largest magnetic storms, not only to determine if there are different interplanetary and solar causes (or if there are even finer subsets of causes), but also to understand the physics of such events to be able to eventually predict their occurrence. Predictions will help prevent magnetospheric satellite damage, urban power outages and will give warnings of impending radiation hazards to humans flying at high altitudes (Allen et al., 1989).

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Approach

We have used the Boulder World Data Center A D_{ST} tape (courtesy of H. Kroehl) to identify the five largest magnetic storms which have occurred from 1971 until 1986. High and midlatitude geomagnetic indices such as AL, AE, and Kp were also obtained from the WDC A. The spacecraft plasma and field data (ISEE-3, IMP-8, and ISEE-1) were obtained from the Space Science Data Center, GSFC, courtesy of J. King.

The severe (peak) D_{ST} values used in this study are higher than the thresholds of any other prior study. Burton et al. (1975) studied storms with D_{ST} between - 40 nT and - 130 nT. Tsurutani et al. (1988) examined storms with - 220 nT $\leq$ D_{ST} $\leq$ - 100 nT, intensities almost totally complementary with the Burton et al. study and the present one. Burlaga et al. (1987) studied "major" storms with Ap > 90, a threshold somewhat comparable to the Tsurutani et al. study, but with overlap of only 4 out of 17 events. The Gosling et al. (1990; 1991) studies used a criteria of Kp > 8- or Kp > 6- for at least three 3-hour periods within a 24-hour interval, the highest storm criteria other than this present study.

Although the criteria of the above storm studies were lower than the present study, several publications (Burlaga et al., 1987; Gosling et al., 1990, 1991) have included information on the events. However, none of the studies address the specific physical causes of the intense interplanetary sheath B_S which led to the onsets of the great magnetic storms. This will be one the important focuses of this note.

Results

Figure 1 illustrates the September 5, (Day 248), 1982 event. From top to bottom, the panels are: the solar wind velocity, the plasma density, electron temperature, magnetic field magnitude, the GSM B_z component, D_{ST}, AE, and the epsilon parameter. This figure indicates that the onset of the storm main phase (indicated by the abrupt decrease in D_{ST}) is coincident with the passage of the shock. The shock is emphasized by the dashed vertical line at ~ 2100 UT day 248 (September 5), 1982. The fast forward shock is identified by the abrupt increase in velocity from ~ 500 km s^{-1} to ~ 800 km s^{-1} and in the magnetic field magnitude, from ~ 8 nT to ~ 26 nT. The propagation time delay of the field and plasma at ISEE-3 to the magnetosphere have not been taken into account in the Figure. This delay should be much less than 1 hour for these high solar wind speeds and is negligible for data plots shown on these scales. The cause of the D_{ST} decrease and AE increase is the southward IMF component at and immediately behind the shock.

"Precursor" geomagnetic activity exist prior to the storm onset. From the middle of day 247 until the storm onset, D_{ST} was $\approx$ – 50 nT. From the beginning of day 246 until midday 247, D_{ST} was $\approx$ - 30 nT. To demonstrate that this is not simply an artifact of determining the "zero level" of the D_{ST} index, the AE electrojet index is also shown. The latter indicates that substantial auroral activity was ongoing throughout day 246 to day 248, with AE typically having values of ~ 500 nT. This is consistent with the nonzero D_{ST} values.

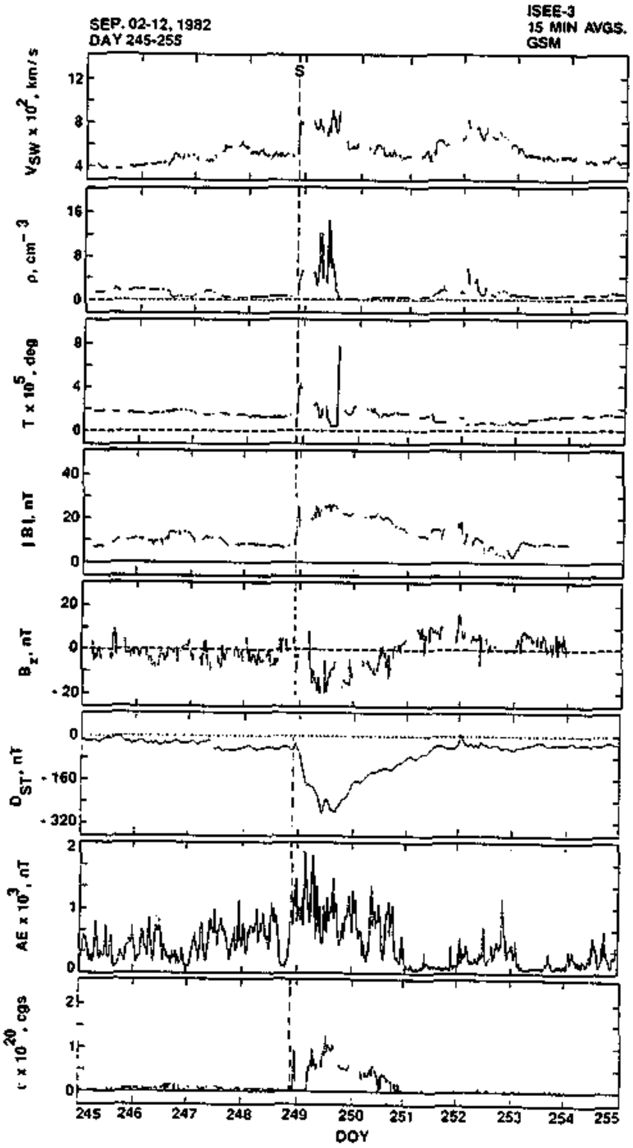

Figure 1. The September 5, 1982 great magnetic storm. The magnetic storm onset occurs at ~ 2100 UT day 248, 1982 coincident with an interplanetary shock at the leading edge of a high speed stream. There is precursor geomagnetic activity prior to the storm onset. Shock compression and field draping of preexisting upstream B_S is the apparent cause of the intense B_S causing the great magnetic storm.

The cause of this long duration (days) precursor activity is apparent from examining the interplanetary B_Z component. Although B_Z varies widely from + 10 nT to - 10 nT from day 246 until the time of the shock, it can be noted that the average component is approximately - 3 to - 4 nT. This general southward tilt of the IMF led to magnetic reconnection, the auroral substorms and the "low level" D_{ST} activity. If the reader makes a careful examination, it can be noted that individual "small' southward dips in B_Z are correlated with subsequent increases in AE.

The onset of the storm main phase (D_{ST} decrease) is correlated with the abrupt B_S and epsilon increases at the shock. There is therefore no long (hrs) initial phase for this storm. Shock compression of the upstream southward directed IMF is an obvious mechanism for the generation of the intense southward magnetic fields (Tsurutani et al., 1988) which in turn causes the onset of the main phase of the storm. The increase in B_S with distance from the shock may be explained by the Zwan-Wolf (1976) field draping effect, leading to the further intensification of B_S and thus the storm. This type of draping occurs in the Earth's magnetosheath as the shocked solar wind flows around the magnetosphere, (Midgley and Davis, 1963; Crooker and Siscoe, 1977; Tsurutani et al., 1982). Several interplanetary coupling parameters were examined. One of the parameters, epsilon, is shown in the Figure. This parameter had the best cross correlation coefficient with D_{ST} for this event, (not shown) but for other events studied, some other interplanetary parameters were often slightly better. Epsilon is shown only as an illustrative example.

To put the solar wind stream and magnetic field into context, we briefly review some previous statistical results on the properties of both solar wind velocities and B_Z. Feldman et al. (1977) found that the mean solar wind speed at 1 AU is 468 km s^{-1} (for all phases of the solar cycle) with a standard deviation of 116 km s^{-1}. Thus, 90 % of the time ($\pm 2\sigma$), the solar wind is roughly in the range of 320 to 710 km s^{-1}. Siscoe et al. (1978) and Tsurutani et al. (1990) have provided statistics for the interplanetary B_Z. They determined that the B_Z yearly average and the most probable value are ~ 0 nT. Both studies showed that there were high $|B_Z|$ values which were outside normal distribution functions. They speculated that these high field values were due to magnetic fields associated with high speed streams. Siscoe et al., from a fit to the high $|B_Z|$-end tail, determined that the probability of $B_Z \leq$ - 20 nT and - 30 nT were 4.3 x 10^{-4} and 7 x 10^{-5}, respectively. Tsurutani et al. found no $|B_Z|$ values > 20 nT in their study of 1979 data (note no great storms occurred in 1979).

The solar wind profile for the event given in Figure 1 is simple. The peak velocity of the high speed stream is only ~ 750 - 800 km s^{-1}, just outside of the 90% probability range and not unusually high for CME - related streams which occur during or near solar maximum. The peak B_S values reached and perhaps exceeded 20 nT (in the data gap at ~ 0900 UT day 249).

The location of a possibly driver gas with the high speed stream is not certain, as different methods give somewhat different answers (see Zwickl et al., 1983 for a discussion). However, since a possible driver gas is relevant towards understanding the stream features, this will be discussed briefly. Gosling et al. (1990) found counter-streaming electrons occurring from 0450 UT September 6 lasting for 57.2 hours. However, at the start of the interval, the plasma density is high (3 - 12 cm^{-3}), the temperature typical of the quiet solar wind (1 - 2 x 10^5K) and the magnetic fields are relatively turbulent. Thus, according to the Zwickl et al. (1983) driver gas criteria, the other plasma and field parameters are not consistent with the existence of a driver at the beginning of this event. There is a later interval, from 1430 to ~ 2400 UT day 249, which is a more likely candidate. The plasma density is < 1 cm^{-3} and the magnetic field is very quiet, satisfying two of the Zwickl et al. (1983) driver gas indicators. The bidirectional electrons exist at this time as well. This later time, however, is after the peak B_S and corresponds to the recovery phase of the storm.

Table 1 gives a summary of the interplanetary causes of the five great storms. Most events were associated with magnetic field intensities in the range of 25 to 35 nT. The southward component was often a large portion of the total field. In two cases, April 13, 1981 and December 19, 1980, the maximum B_S component was essentially equal to the maximum field magnitude, e.g., the field pointed almost totally southward. It is interesting to note that these two events were driver gas events, where the field was in the form of a magnetic cloud (Klein and Burlaga, 1982). The latter event, December 19, 1980, was previously discussed by Zhang and Burlaga (1988).

Three of the storm onsets were caused by shock compression of preexisting southward fields and two by fields within the driver gas. The former is quite a surprise because this mechanism accounted for only one in five sheath B_S events in the study of lesser intensity storm (-220 nT $\leq D_{ST}$ - $\leq$ 100 nT) events (Tsurutani et al. 1988).

Table 1. A summary of the interplanetary magnetic field properties causing great magnetic storms. The columns are, from left to right: the peak solar wind velocity, the peak interplanetary magnetic field magnitude, peak B_S, peak D_{ST}, the cause of the large southward fields, and the associated solar event. The intensity of the solar event and the date and time are given.

DATE	V_{SW}, km s^{-1}	PEAK |B|, nT	Bz, nT	PEAK D_{ST}, nT	INTERPLANETARY CAUSES	Solar Event
February 7, 1986	> 800	25-30	-10 to -20	-312	Shock Compression/ field draping	3/X1.7 (0630 UT 2/6/86
September 5, 1982	750	25	-15 to -20	-289	Shock Compression/ field draping	3/M4 (0200 UT 9/4/82)
July 13, 1982	1360	60	-50	-325	Shock Compression/ field draping	2/X7.1(0955 UT 7/12/8
April 13, 1981	600	30	-30	-311	Driver Gas/ Magnetic Cloud	1/X1.1 or 3/X2.5 (1117 UT or 1655 UT, 4/10/81)
December 19, 1980	550	35	-35	-249	Driver Gas/ Magnetic Cloud	2/M5.1 or 1/M4.7 (1200 UT or 1500 UT, 12/16/80)

The intensities and times of the solar events are listed in the right-hand column of Table 1. All five magnetic storms were associated with solar flares (and presumably coronal mass ejections). In the intensity designation, X1.7 indicates that the peak 1-8A soft x-ray flux was 1.7 x 10^{-4} watts m^{-2} (M = 10^{-5} watts m^{-2}). The number designation at the far left is the Hα optical area of the flare. 1, 2, 3 and 4 correspond to 2.1-5.1$^{\circ 2}$, 5.2-12.4$^{\circ 2}$, 12.5-24.7$^{\circ 2}$ and > 24.7$^{\circ 2}$, respectively. Note that none of the flares are "importance" 4 and two of the five are only M class flares.

Our model of the shock compression and field draping is shown in Figure 2. In the Figure the sun is on the left and the solar wind is propagating to the right. The upstream southward fields are compressed at the shock leading to intense B_S which cause the onset of the great magnetic storms. The stronger the shock, the greater the compression ratio of the downstream to upstream field values (up to a limit of 4.0). The southward field component intensifies further as the sheath magnetic fields drape around the CME. This is accomplished by the Zwan-Wolf effect where the magnetosheath plasma is squeezed out along the lines of force into the downstream (sunward) region, leaving a low beta, high field region near the nose of the CME.

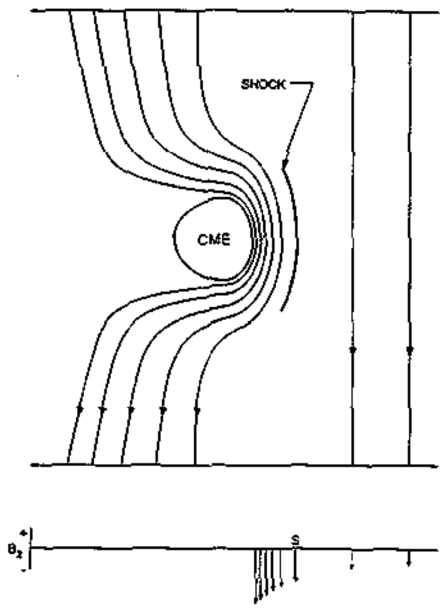

Figure 2. A schematic of the shock compression/field draping model.The high speed stream and shock are propagating from left-to-right. The bottom insert gives the magnitude of the B_S fields. From right-to-left are the: quiet interplanetary fields, the shock (denoted by an "s"), the shocked draped fields and the driver gas (CME). The quiet B_S is substantially intensified by the shock compression. Simple field draping around the driver gas and expulsion of the plasma lead to further B_S intensification.

Discussion

We have examined the interplanetary and solar causes of five great storms. It is determined that all five storms are associated with solar flares (Table 1). We argue that each interplanetary event (except for one) is a relatively simple isolated stream and the intense B_S causing the storm is not associated intense high speed stream - high speed stream interactions related to multiple solar mass ejections (flarings) from the same (or different) solar sites. For the one exception (April 13, 1981), the southward magnetic field was associated with a magnetic cloud and it is not obvious that the complexity of the solar wind stream had any effect on the field magnitude or its orientation.

The above results are considerably different than those for the lesser intensity (major) storms (-220 nT $\leq D_{ST} \leq -100$ nT) studied by Tsurutani et al. (1988). In that study, prominence eruptions were relatively more important (3 of 10 events, compared 0 of 5 here). One event (of ten) was not even related to a high speed stream, but was caused by a Noncompressive Density Enhancement (NCDE). A general conclusion that can be made from these comparisons is that as the level of intensity of the resultant magnetic storm increases, the general magnitude of the related causative interplanetary and solar activity also increases. However, this is obviously somewhat of a loose relationship. Great magnetic storms do not occur solely as a consequence of extremely large (X-class) solar flares, nor do all X-class solar flares cause great magnetic storms.

The solar wind velocities during the storms were not all exceptional, as illustrated by Figure 1 and Table 1. Two of the events had peak velocities equal to or less than 600 km s^{-1} (April 13, 1981 and December 19, 1980), quite unimpressive for high speed streams occurring during solar maximum. The unexceptional velocities were surprising in light of general expectations and previous statistical studies (Svalgaard, 1977; Legrand and Simon, 1989). It should be noted that in both of these events, the interplanetary cause of the IMF B_S is a magnetic cloud in the driver gas. These are intrinsic fields associated with the coronal ejecta. It is obvious that both V_{SW} and B_S are important parameters in the interplanetary - magnetospheric coupling function. High values for either one or both values can lead to high interplanetary electric fields. The point that we make in this paper is that the values of B_s are exceptionally high in all five cases whereas this is not true for the solar wind velocities.

The solar wind velocities associated with shock compression/field draping B_s events were considerably higher. Two of the events were possibly associated with speeds greater than 1000 km s^{-1} (the February 7, 1986 event peak velocity occurred within a data gap). This is to be expected as the higher the velocity, the greater the compression of the upstream magnetic fields.

The solar wind just upstream of the event shown in this paper had a velocity of ~ 500 km s^{-1} and an ambient magnetic field strength of ~ 8 nT. From the Feldman et al. (1977) statistics quoted earlier, these velocities are within one sigma of the average and can be considered "typical" values, if such a quantity exists. On the other hand, Burlaga et al. (1987) have defined a "fast flow" as any type with speed greater than 450 km s^{-1}, and a "compound stream" as "two peaks in the magnetic field strength (and velocity)". Thus, by the Burlaga et al. definition, this small (upstream) velocity would qualify as a fast stream, and the interaction as a compound stream. The physical mechanism that has been proposed that could make compound streams geoeffective is that "the speed of a fast flow or shock that follows and rides on another fast flow will be higher than that of an isolated shock or fast flow". Although a higher resultant speed undoubtedly occurs, the emphasis in this paper is that velocity is not the most important solar wind parameter causing great magnetic storms. The strength of B_s is clearly the dominant cause.

We do not wish to leave the reader with the feeling that multiple coronal mass ejections (flarings) are not important. On the contrary, we were surprised to find that this was not the cause for any of the five events. Previously, we had speculated (Tsurutani et al., 1988) that shock compression of either previously shocked fields or of driver gas fields would lead to very intense magnetic fields. Clearly, shock compression of a magnetic cloud could lead to a storm with an intensity much larger than even the events studied here. We plan to continue to search for such events.

Final Comments

We have shown that long duration precursor southward magnetic fields which exist for days prior to the passage of the shock is evidently quite important to the generation of great magnetic storms (at least 60% of them, from this small sample). If one could predict the occurrence of such upstream fields and the intensity of interplanetary shocks, then this would represent a large step forward in being able to forecast the occurrence and intensity of half of the most intense magnetic storms at Earth.

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CORRECTION TO "THE FRICTIONAL BEHAVIOR OF SERPENTINITE: IMPLICATIONS FOR ASEISMIC CREEP ON SHALLOW CRUSTAL FAULTS" BY LINDA A. REINEN, JOHN D. WEEKS, AND TERRY E. TULLIS

In the paper "The Frictional Behavior of Serpentinite: Implications for Aseismic Creep on Shallow Crustal Faults" by Linda A. Reinen, John D. Weeks, and Terry E. Tullis (Geophysical Research Letters, 18, 1921-1924, 1991), part of Figure 1 was omitted. The complete figure and its caption appear below.

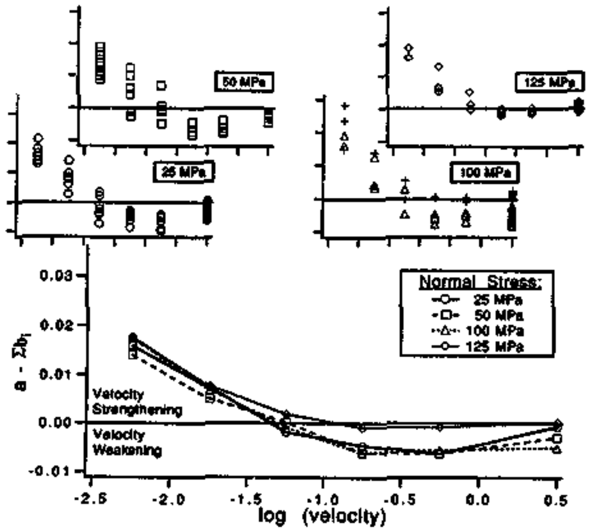

Fig. 1. Steady-state velocity dependence of the frictional strength of serpentinite versus log velocity for the range of load velocities and normal stresses in this study. The symbols connected by lines show the average value of a-Σb_i at each velocity step for a particular normal stress. The insets show all the data at each normal stress. Plus signs in the 100 MPa inset show results after first sliding at 125 MPa; these data were not included in determining the averages for 100 MPa.

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