Solar Sources of Interplanetary Southward B_z Events Responsible for Major Magnetic Storms (1978-1979)

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Tsurutani et al. [1988] analyzed the 10 intense interplanetary southward B_z events that led to major magnetic storms ($Dst < -100$ nT) during the 500-day interval, August 16, 1978, through December 28, 1979. In this paper we report solar sources of the major storms and discuss their interplanetary effects. Seven of the sources of the 10 major storms are flares and 3 are prominence eruptions. The ratio is consistent with frequency of these two types of events occurring on the Sun during this period. The flares range from M1 to X2 in peak soft X ray emissions. However, the largest of the 10 storms ($Dst = -220$ nT) as well as the two strongest shocks ($M > 3.0$) are associated with prominence eruptions. For three of the five southward B_z events in which the driver gases are the causes of the intense southward field leading to magnetic storms, the photospheric fields of the solar sources have no dominant southward component, indicating the driver gas fields do not always result from a simple outward convection of solar magnetic fields. Finally we compare the solar events and their resulting interplanetary shocks and find that the standard solar parameters do not correlate with the strengths of the resulting shocks at 1 AU. The implications are discussed.

1. INTRODUCTION

Ten intense geomagnetic storms with $Dst < -100$ nT during the 500-day interval, August 16, 1978, through December 28, 1979, have been identified by Gonzalez and Tsurutani [1987]. Using ISEE-3 plasma and field data, Tsurutani et al. [1988] (hereafter called T88) have analyzed the origins of the interplanetary, IP, southward B_z events responsible for the intense storms. In this paper we trace the 10 events backward in time and space to determine the solar sources that gave rise to the IP disturbances. The solar wind-magnetospheric coupling for the 10 major storms is discussed in another follow-up paper by Gonzalez et al. (Solar wind-magnetospheric coupling during intense magnetic storms (1978-1979), submitted to *Journal of Geophysical Research*, 1988).

Solar research of the last few years has revealed the kind of flares most closely associated with phenomena occurring in the high corona and the interplanetary medium, namely, the soft (1-8 Å) X ray long duration events, LDEs. They are found to be associated with optical $\geq$ class I flares, coronal mass ejections [Sheeley et al., 1983a; Munro et al., 1979], metric type II and type IV bursts [Sheeley et al., 1984; Kahler et al., 1984a; Cane and Stone, 1984], interplanetary type II bursts [Cane and Stone, 1984], and interplanetary energetic protons [Bai, 1986; Kahler et al., 1984b, 1978]. Recent analyses of solar hard X ray, HXR, data obtained during the last solar maximum, revealed unique signatures often associated with LDEs — gradual time profile and long duration emission of HXR and microwave (which unlike HXR, is observed by ground-based radio observatories around the world and thus can be used in lieu of HXR data), hard (flat) spectral indices, high and extended HXR emission source, and relatively large ratios of microwave to HXR fluxes

[Tanaka, 1987; Bai, 1986]. Although the physics of the LDEs has yet to be understood, the empirical results are useful in identifying the kind of solar flares responsible for interplanetary shocks used in this study.

For this study we have used a full complement of solar wind plasma and field data from ISEE 3. In searching for the solar sources of the major magnetic storms we consider candidates from the solar point of view as well as suspected candidates suggested by the interplanetary plasma and field data. In section 2 we discuss the solar source(s) in detail for four of the ten events for which the IP southward B_z event have different origins, namely, driver gas, shocked B_z , distorted sheath field and draped fields. In each case, the origin of the B_z event leading to the major storm ($Dst < -100$ nT) is briefly stated. For details of the interplanetary event the reader is referred to T88. In section 3 we summarize the solar events associated with the 10 major storms and review what the Sun had produced during the same period. Finally, we compare the interplanetary effects of the solar events and discuss their implications in solar-interplanetary relationships.

2. CASE STUDY

2.1 September 29, 1978 (Day 272)

The southward B_z event occurs on the above date. The shock occurs at 2040 UT, day 271. Behind the shock is the shocked solar wind plasma (called the sheath), then a discontinuity bounds the driver gas which contains the intense southward magnetic fields responsible for the storm (T88).

The solar source of the shock is uncomplicated. The 2/M3 flare at 1442 UT (maximum) on September 27 located at N27 W19 has many of the characteristics of shock-associated flares. The soft X ray emission lasted a total of 9 hours. Microwave emissions with multiple broad peaks at 2.8 GHz were observed at Ottawa and lasted 46 min. A coronal mass ejection and intense decimetric and metric type IV bursts lasting 105 min were also detected. The flare was observed and filmed in H α at Big Bear Solar Observatory, BBSO. The Coronal loops whose foot points are marked by the flare ribbons, show a predominantly eastward fields which are consistent with the photospheric magnetic fields of the region, but are different from the southwest orientation of the fields at the leading edge of the driver gas detected in the interplanetary space (T88).

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2.2 November 25, 1978 (Day 329)

This IP southward event begins exactly at the shock (see last panel Figure 1), and the field responsible for the magnetic storm is simply shocked interplanetary magnetic fields (T88).

The lack of solar activities during the few days prior to the shock on Nov. 25 (day 329) indicated that the prominence eruption at N35 W55 on Nov. 20 between 1447 and 1545 UT was certainly the most likely source, in agreement with *Joselyn and McIntosh* [1981]. A two-ribbon flare associated with the prominence eruption lasting a minimum of 7 hours was observed at BBSO.

Prominence eruptions have long been suspected as possible causes of interplanetary disturbances. The first definitive proof of the link was provided by a multispacecraft observation of the April 24, 1979, shock (responsible for one of the 10 major storms of our study) and the prominence eruption on the Sun 2 days earlier [*Sanahuja et al.* 1983].

Analyses of IP plasma and field data, however, suggests that the event has the appearance of a corotating interaction region (CIR) boxcar shape: a forward shock and reverse shock bounding the intense fields with a discontinuity in between (1747 UT, Nov. 25) separating the shocked slow plasma that contains the southward B_z , and the fast plasma (T88). Appearances of shocks during possible previous rotations are detected at ISEE 3 on Sept. 5, Oct. 4, and Oct. 29. The IP data for the November shock and those of the suspected previous appearances are shown in Figure 1 in chronological order from left to right. Solar coronal hole data in Hel10830 from Solar Geophysical Data, SGD, for the four rotations are shown in Figure 2. The only long-lasting hole is the one indicated by the arrow. The large positive hole first appeared in Carrington rotation 1671 (not shown here) centered at 300° Carrington longitude. During the next few rotations, the hole gradually decreased in size and its centroid migrated both eastward and equatorward. If the recurrent hole is the source of the above-mentioned shocks, the intervals between the central meridian passages of the trailing eastern edge of the coronal hole and the arrival of the shocks for the four above rotations are approximately 7, 7, 5, and 5 days respectively. A transit time of 7 days would correspond to an average solar wind speed of about 250 km/s, smaller than the observed solar wind speed at 1AU for the Sept. 5 and Oct. 4 shocks (see Figure 1). Other evidence casting doubts on the coronal hole link includes: the small size of the hole in rotation 1675; analysis of ISEE 3 low-frequency radio experiment indicates that the source of the Oct. 4 shock, two rotations earlier, is a 2/M9 flare on Oct. 1 at S13 E57 [*Cane and Stone*, 1984]. We thus conclude that solar data do not seem to support the coronal hole/CIR association of the observed forward and reverse shocks on Nov. 25.

Our best choice for the source is the prominence eruption/flare event discussed earlier. Prominence eruptions are usually not associated with H α emissions; however, all three identified in this study are observed to have flare emissions at BBSO. This may imply the existence of coronal conditions not present in ordinary garden variety prominence eruptions. The interplanetary signature of the Nov. 25 event is reminiscent of the prominence eruption/flare of April 22/23, 1979, and the resultant forward and reverse shocks on April 25 [*Sanahuja et al.* 1983; *Tang*, 1983] that led to one of the other 10 major storms (T88).

2.3 August 29, 1979 (Day 241)

ISEE 3 plasma and field data show that the fluctuating southward B_z event responsible for the intense storm is the distorted sheath fields. *Gosling and McComas* [1987] indicated the possibility of the presence of driver gas starting at 1800 UT, day 242. This, however, occurs at the peak of the *Dst*

value and is associated with the recovery phase of the magnetic storm (T88).

There is little doubt the source of this IP shock is the 2/X2 flare on August 26 at N5 W11. Kilometric type II burst associated with the IP shocks as well as the passage of the shock itself were detected by the ISEE 3 radio experiment [*Cane and Stone*, 1984]. Other characteristics typical of a shock-associated flare include: soft X ray emissions lasting a total of 7 hours; microwave emissions lasting 60 min at 2.8 GHz; intense decimetric and metric type IV burst observed for 105 min; and a coronal mass ejection. The H α flare was observed at BBSO. The coronal fields, inferred from the morphology of the flare, are predominantly southward. However, for this event the cause of the IP southward B_z that led to the intense magnetic storm is not driver gas but the shocked solar wind plasma which probably has a different solar source (T88 and references therein).

2.4 September 18, 1979 (Day 261)

IP plasma and field data for this event is shown in Figure 3. Unlike the others, this disturbance is not associated with a shock, but a noncompressive density enhancement, NCDE. The southward field leading to the storm is interpreted as draped fields over the high density regions and driver gas that began at 0500 UT Sept. 18 (T88).

Gosling et al. [1981] believe that NCDEs with magnetic field reversals in the interplanetary medium are associated with coronal streamers occurring near solar minimum, but are likely to be associated with solar activities during solar maximum.

Although the event occurred during solar maximum and the magnetic field data showed no real field reversal during the NCDE event (T88), we nevertheless searched for coronal streamers that might possibly give rise to the observed NCDE. One coronal streamer located at N20° was observed at east and west limbs on approximately September 4-6 and 18-20, respectively. This would make the central meridian passage of the streamer around September 12 (*R.C. Altrock*, private communication, 1987). However, the 20° latitude was not favorable for the streamer to intercept the Earth. We conclude that there is no compelling reason to believe that the observed coronal streamer is the source of this NCDE.

An excellent flare candidate occurred on September 14. ISEE 3 radio experiment observed kilometric type II burst, emanating from the IP shock associated with the flare for 36 hours but the shock itself was not detected [*Cane et al.* 1982]. In addition, the X2 flare had a soft X ray decay time of 16 hours, an intense microwave burst at 15.4 GHz lasted 93 min, and intense type II/IV bursts lasted 65 min. Although a coronal mass ejection was not observed (due to a gap in the Solwind coronagraph data), one can be assumed based on statistical analysis of the 100% association of CME and soft X ray events with decay time ≥ 6 hours [*Sheeley et al.* 1983a]. The flare was also suspected to be the source for the delayed proton event commencing September 15/1500 UT at 1AU (solar proton events affecting the Earth environment, SGD). In short, the flare has all the characteristics of an IP shock-producing event. The question is why the shock is not observed by ISEE 3.

A closer scrutiny of the solar data reveals that region 16298, from which the X2 flare originated, actually began its prolific flaring activity at 0100 UT on Sept. 16 at E90° (SGD). This means the flare on September 14 most likely originated from about 20° behind the east limb and not at the limb as reported. The flare maximum, deduced from microwave bursts peaks, occurs between 0735 and 0745 UT. H α emission reported over the east limb beginning at 0808 UT was most likely the flaring part high in the atmosphere during the decay stage of the flare. We surmise that the shockless interplane-

Fig. 1. ISEE 3 plasma and field data for the Nov. 25 shock and the preceding three shocks suspected to be part of a corotating structure.

Fig. 2. He 10830 maps showing a long-lasting coronal hole (arrow).

Fig. 3. The interplanetary plasma and field for the NCDE event and the D_{st} value for the storm on September 18, 1979.

tary disturbance in the form of a NCDE originated from the behind-the-limb flare. The IP shock presumably propagated radially outward and thus did not intercept the Earth. It is not uncommon for interplanetary type II bursts to be detected by ISEE 3 but not the passage of the shocks themselves. Besides this one, there were 6 additional cases (4 from the east limb) in the 48 events identified by Cane [1985], all of which had source flares located $> 63^\circ$ from the central meridian. Plasma and field data (Figure 3) beginning at the onset of the southward B_z event at 0600 UT September 18 showed $> 10\%$ He abundance, proton temperature depression, proton density and field strength enhancements—signatures of a driver gas [Zwickl et al., 1983], which supports the notion that the NCDE may be associated with a flare. We speculate that the observed driver gas was not the bulk but a part of the ejected mass that diffused across field lines and then became connected to the Earth. For this reason, an east limb flare will have to be very large in order for its remnant to be observed at Earth. More documented cases in the future may help to evaluate the plausibility of the proposed scenario.

3. SUMMARY AND DISCUSSION

Table 1 summarizes the solar sources of the 10 major magnetic storms for the period August 1978 to December 1979. From left to right, the second column lists the date and time

of the shock. The third column lists the origin of the IP southward B_z event, taken from T88. If the origin is a driver gas, the orientation of the IP field at its leading edge is indicated in the parenthesis. The third column lists the type of solar source event (if it is a flare, the optical and soft X ray sizes are given), time and location of the event, and the dominant orientation of the flare field (which is the inferred coronal field). If two orientations are given it is because the event consists of two episodes with two different orientations. For the Feb. 21 shock (event 4), a particular flare cannot be determined because of insufficient solar data.

3.1 Major Storms Caused by Active Region Flares

Table 1 shows that of the 10 major storms, seven are initiated by active region flares. Three of the six flare sources for which soft X ray data are available, are X class flares, and three are M class flares. A survey of flares observed during the 500 days under study reveals that the Sun produced 35 class X flares, the largest of which is a X6 flare (and a LDE as well). In terms of optical size, 510 class 1, and 80 class 2 (or greater) flares were reported by at least two observatories (source: SGD).

3.2 Major Storms Caused by Prominence Eruptions

Three of the 10 major storms are associated with prominence eruptions in solar quiet regions. Prominence eruptions occur less frequently than flares. An average of about 0.55/day during 1976-1979 can be deduced from a survey by Joselyn and McIntosh [1981]. Class 1 (or greater) flares average 1.19/day during the 16 months period of 1978-1979 (last paragraph). It is interesting to note that the ratio of flare to prominence (7 : 3) for the 10 major magnetic storms in the 500-day interval reflects approximately the same ratio of the two types of events occurring on the Sun.

The number, however, reveals only part of the story of prominence eruptions. In this study two of the most intense shocks as well as the most intense storm are not associated with large/energetic flares but are associated with prominence eruptions, a subject we will discuss further later in the section.

3.3 Solar Field Versus Driver Gas Field

The last column of Table 1 lists the solar field of the source events (two solar events cannot be determined due to insufficient data). Note that in three of the five events where driver gas (believed to have its origin in the transient solar source) is the cause of the IP southward field (indicated in the second column) the (inferred) coronal fields actually have no dominant southward component. Our result suggests that contrary to what has been suspected, the driver gas fields do not (at least not always) result from a simple outward convection of solar magnetic field of the flaring active region.

3.4 Solar Events Versus Interplanetary Effects

Nine of the 10 major magnetic storms discussed here are associated with interplanetary shocks. It is instructive then to learn if there is a correlation between source events on the Sun measured in standard solar parameters and the strengths of the resulting shocks at 1 AU. Table 2 lists the shocks, their magnetosonic Mach numbers, M (from Figure 2 of T88) the solar source event and the optical and soft X ray class, if it is a flare. The list is arranged in descending order of Mach numbers.

Notice that the two strongest shocks with Mach number $M > 3$ are associated with prominence eruptions. Although all three prominence events listed here are accompanied by H α flare brightenings, the associated flares are weak in all stan-

TABLE 1. A Summary of Interplanetary Events Causing the 10 Major Magnetic Storms ($Dst < -100$ nT) and Their Solar Origins

	Shock UT	Cause of Southward B_z	Event	Solar Origin Date/Location	Solar Field
1	Aug. 27, 1978 (02)	driver gas (SE)	prominence eruption	Aug. 23 N15E15	northwest
2	Sept. 28, 1978 (21)	driver gas (SW)	2/M3 flare	Sept. 27 N27W19	east
3	Nov. 25, 1978 (12)	shocked B_z	prominence eruption	Nov. 20 N35W30	southeast
4	Feb. 21, 1979 (02)	driver gas (SW)	(flare)	Feb. 18	...
5	Mar. 9, 1979 (05)	distorted sheath fields	1/M1 flare	Mar. 5 N11E38	east
6	Mar. 28, 1979 (08)	distorted sheath fields	2/X1 flare	Mar. 26 N5W78	northeast
7	April 3, 1979 (09)	driver gas (SE)	1/M1 flare	Mar. 30 S25E31	west
8	April 24, 1979 (23)	distorted sheath fields	prominence eruption	April 22 S25E0	west, southwest
9	Aug. 29, 1979 (05)	distorted sheath fields	2/X2 flare	Aug. 26 N5W11	southeast, southwest
10	Sept. 17, 1979 (NCDE)	draped fields/driver gas (due S)	X2 flare	Sept. 14 >E90	

dard solar parameters, such as weak $H\alpha$ flares, virtually no or minimal 1-8 Å soft X ray emissions above the full Sun background, no hard X ray or microwave bursts that are indicative of acceleration and emissions of high-energy electrons close to the Sun, and weak or no type II/IV radio emissions usually associated with coronal shocks.

For the flare-associated shocks, numbers 3 through 8 in Table 2, it may appear as though the strengths of the flares as indicated by their classes are somewhat correlated with the strengths of the shocks as measured in Mach numbers. However, this is only a coincidence and there is ample evidence that such a simple correlation does not exist. For example, a $M=2.9$ shock on April 5, 1979 is associated with a 1/M4 flare on April 3, whereas the $M=1.7$ shock on August 20, 1979, is associated with a X6 flare (the largest in the 500 days) on August 18. Both flares are LDEs with 1-8 Å soft X ray decay time of 16 hours. Other such examples can be found in flare-associated CMEs and the associated shocks observed by Helios [Sheeley *et al.* 1983b]. The fact that prominence eruptions can be at least

as effective as energetic flares in producing high level of disturbances at 1 AU is consistent with the fact there is a lack of correlation between conventional solar flare parameters near the Sun and the strengths of IP shocks at 1 AU.

This lack of correlation suggests that (1) the telltale solar signatures and parameters for effectively producing an disturbance at 1 AU have yet to be discovered. The physics of the LDEs needs to be understood and may shed light on the matter. (2) The dynamics of the interplanetary medium may play an important role in the cause and effect relationships. Garcia and Dryer [1987] suggest the interplanetary disturbance that led to the intense storm of February 1986 may be the result of the dynamical evolutionary processes in the interplanetary space of successive flares from the same active region. In studying the solar events we noted that 4 of the 10 solar events identified here are observed at BBSO to be two-episode events in which a second maximum is reached after a partial decay of the first episode (a behavior we find to be associated with 60% of the LDEs producing IP type II bursts). These are two prominence

TABLE 2. Interplanetary Shocks in Order of Descending Mach Numbers and Their Associated Solar Sources and Magnetic Storms

	Shock Date	Mach Number	Storm Dst (nT)	Solar Source
1	April 24, 1979	3.5	-140	prominence eruption
2	Aug. 27, 1978	3.3	-220	prominence eruption
3	Aug. 29, 1979	2.3	-140	2/X2 flare
4	Feb. 21, 1979	2.2	-110	(flare)
5	Mar. 28, 1979	1.5	-120	2/X1 flare
6	Sept. 28, 1978	1.3	-215	2/M3 flare
7	Mar. 10, 1979	1.1	-140	1/M1 flare
8	April 3, 1979	1.0	-200	1/M1 flare
9	Nov. 25, 1978	1.0	-150	prominence eruption

eruptions (event 1 and 8 in Table 1) and two flares (event 2 and 9). In addition, a fifth event on Feb. 18, 1979 (event 4), a total of 12 flares occurred in an 8-hour period from two neighboring active regions in the northern hemisphere.

Finally, it is interesting to note that the three most intense of the 10 major storms during this period with $Dst \leq -200$ nT (Table 2) are caused by a prominence eruption, a 2/M3 flare and a 1/M1 flare. Our result shows that for major storms such as the ones during 1978-1979, the solar sources do not have to be large and/or energetic events.

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