CAWSES November 7–8, 2004, superstorm: Complex solar and interplanetary features in the post-solar maximum phase

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[1] The complex interplanetary structures during 7 to 8 Nov 2004 are analyzed to identify their properties as well as resultant geomagnetic effects and the solar origins. Three fast forward shocks, three directional discontinuities and two reverse waves were detected and analyzed in detail. The three fast forward shocks "pump" up the interplanetary magnetic field from a value of ~4 nT to ~44 nT. However, the fields after the shocks were northward, and magnetic storms did not result. The three ram pressure increases were associated with major sudden impulses (SI + s) at Earth. A magnetic cloud followed the third forward shock and the southward Bz associated with the latter was responsible for the superstorm. Two reverse waves were detected, one at the edge and one near the center of the magnetic cloud (MC). It is suspected that these "waves" were once reverse shocks which were becoming evanescent when they propagated into the low plasma beta MC. The second reverse wave caused a decrease in the southward component of the IMF and initiated the storm recovery phase. It is determined that flares located at large longitudinal distances from the subsolar point were the most likely causes of the first two shocks without associated magnetic clouds. It is thus unlikely that the shocks were "blast waves" or that magnetic reconnection eroded away the two associated MCs. This interplanetary/solar event is an example of the extremely complex magnetic storms which can occur in the post-solar maximum phase. **Citation:** Tsurutani, B. T., E. Echer, F. L. Guarnieri, and J. U. Kozyra (2008), CAWSES November 7–8, 2004, superstorm: Complex solar and interplanetary features in the post-solar maximum phase, *Geophys. Res. Lett.*, *35*, L06S05, doi:10.1029/2007GL031473.

1. Introduction

[2] Although the sunspot number cycle typically shows a single maximum, the occurrence frequency of large magnetic storms (Dst < −100 nT) often has two peaks. The first one occurs at or near solar maximum and the second occurs two or three years after solar maximum [*Gonzalez et al.*, 1990; E. E. Echer et al., On the solar cycle dependence of interplanetary drivers causing intense magnetic storms (Dst < −100 nT), submitted to *Journal of Geophysical Research*, 2007].

[3] Previous works have focused on magnetic storms that are caused by a single fast interplanetary coronal mass ejection (ICME). There are two fundamental plasma regions where there can be intense magnetic fields for long durations (hrs). These are the interplanetary sheaths behind (sunward of) fast forward shocks, and driver gas/magnetic cloud portions of the ICMEs proper [*Tsurutani et al.*, 1988]. If the fields are intensely southward during these intervals, reconnection with the Earth's magnetopause fields will occur [*Dungey*, 1961], and a magnetic storm will result [*Gonzalez and Tsurutani*, 1987; *Gonzalez et al.*, 1994]. If there are southwardly directed magnetic fields in both of these regions, then a "double storm" will occur [*Kamide et al.*, 1998].

[4] Very little attention has been paid to more complex interplanetary events. [*Burlaga et al.*, 1987] have indicated that "compound streams" (solar wind streams running into other streams) are a means for creating unusual interplanetary structures. However *Tsurutani and Gonzalez* [1997] and *Tsurutani et al.* [1999] have argued that shock compression of extremely low plasma beta ($<10^{-1}$ and sometimes as low as $\sim 10^{-3}$) magnetic cloud regions will not be possible. Shocks should become evanescent within these low beta regions. On the other hand, shock compression of the sheath regions should be possible. The study of these features is one of the goals of the present paper.

[5] After the solar cycle 23 maximum (around years 2000–2001), there were many complex active regions (ARs) on the sun (particularly during the years 2003 to 2005 [*Tsurutani et al.*, 2005; *Gopalswamy et al.*, 2006]). These regions produced multiple flaring each day. Presumably CMEs are produced concurrently with many of the most intense flares. Thus, the interplanetary medium might be expected to be complex due to the interaction of the many ICMEs propagating from the sun to 1 AU during this interval of solar activity.

[6] It is the purpose of this paper to examine the solar and interplanetary causes of one of the CAWSES super magnetic storm events, the event that occurred on 7–8 Nov 2004. Solar flare events will be studied to attempt to identify the related sources of interplanetary shocks and ICMEs. We will demonstrate that this magnetic storm interval is particularly interesting from a space weather viewpoint.

2. Results

[7] The solar activity during Nov 1 through 12, 2004 (days 306 through 317) is shown in Figure 1. Figure 1 (top) contains two GOES x-ray channels: 1–8 Å (in blue) and 0.5

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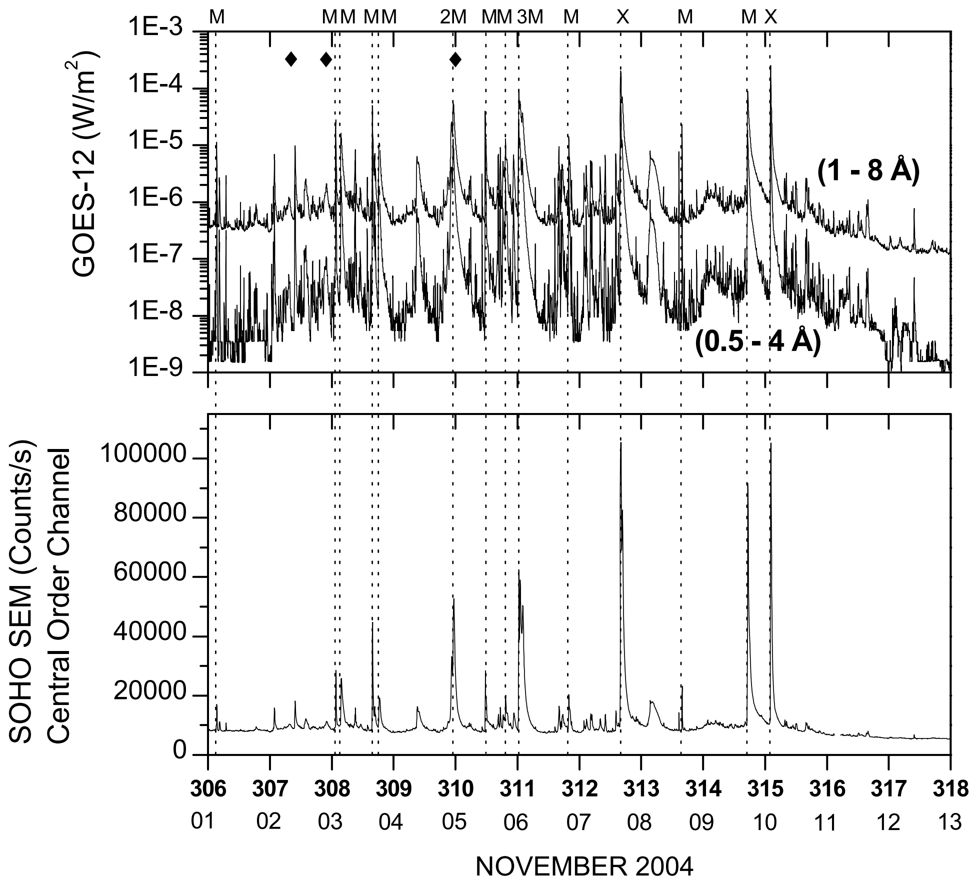

Figure 1. GOES-12 X-ray fluxes (1–8 A and 0.5–4 A channels) and SOHO SEM (central order channel) EUV count rates for the interval Nov 1 to 12, 2004. Major solar flares are indicated by dashed lines.

to 4 Å. Figure 1 (bottom) contains the SOHO SEM broadband EUV channel covering 1 to 50 nm photons [*Judge*, 1998]. The vertical axes for the two panels are given in energy flux (in Wm^{-2}) and in counts/s, respectively. The former is given in a logarithmical scale and the latter by a linear scale. All of the M-class and X-class flares that occurred during the interval are indicated by vertical dotted or dashed lines. The flare classifications come from the NOAA GOES website. Intervals where several flares have occurred and overlap each other are indicated at the top of Figure 1. For example, "3M" indicates that three M-class flares have occurred and are overlapping each other. The overlap is not possible to see in this figure due to the low time resolution used. There are 17 X- and M-class flares in the interval 1–12 Nov 2004. Detailed information about the flare sites are given in Table S1 of the auxiliary material.[1]

[8] Figure 1 shows a very close correspondence between X-ray M- and X-Class flares and EUV flares. For each and every major flare noted in X-rays, there are major EUV enhancements as well. It should be noted that the X-ray enhancements for these flares are orders of magnitude greater than the background. The EUV flare enhancements, on the other hand, are far less intense. Visible enhancements (not shown) are even less variable than EUV enhancements. This very strongly falling spectra (decreasing flux with increasing wavelength) is typical for flares. The greatest variability occurs at the highest frequency end of the spectrum.

[9] The details of these M- and X-class flares are given in Table S1: the time of maximum (flare) flux, the intensity, and the associated active region. What is particularly interesting is that all flares in Figure 1 (except the first two events) come from the same active region (AR696). It is also noted that there are many smaller flares (C-class) which we have not identified in detail. The origin of the C-class flares is much more varied in the source regions (not shown for brevity).

[10] Figure 2 shows the solar wind consequences of some of this solar (and CME) activity. The top three panels are the temperature, velocity, and density of the solar wind for Nov 7 and 8, 2004. The plasma data come from the ACE satellite [*Stone et al.*, 1998]. The next four panels are the interplanetary magnetic field values (also from ACE) given in GSM coordinates. Next are the derived solar wind parameters: the y-component of the interplanetary electric field, the solar wind ram pressure and the plasma beta (the plasma thermal pressure divided by the magnetic pressure). The bottom panel is the 1-min SYM-H index. The SYM-H values have not been time-shifted to remove the solar wind propagation delays. A superstorm occurs at the end of November 7 and the beginning of Nov 8. The peak SYM-H intensity was −394 nT at ~0700 UT, Nov 8.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031473.

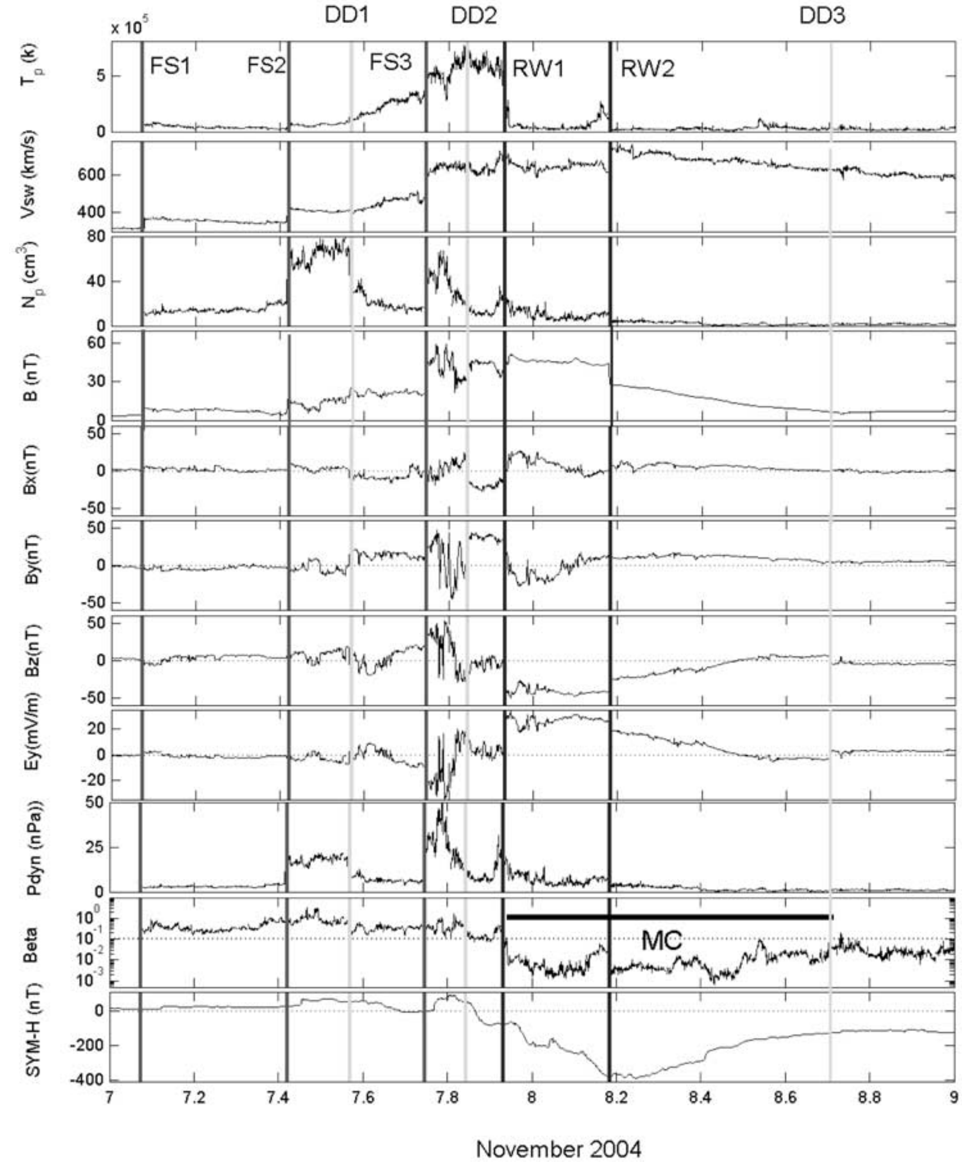

Figure 2. Interplanetary plasma and magnetic field data, and the SYM-H geomagnetic indices for the interval 7–8 Nov 2004. Fast forward shocks (FS), interplanetary directional discontinuities (DD), and reverse waves (RW) are indicated. The MC interval is marked with the heavy black bar.

[11] Significant interplanetary discontinuities are indicated in Figure 2 by vertical lines. At 0155 UT 7 Nov there is a fast forward shock (FS1) identified by sharp increases in solar wind velocity, density, temperature and magnetic field magnitude. This shock compresses the interplanetary magnetic field from a value of ~4 nT to ~9 nT. The shock normal angle was 68° calculated using the magnetic coplanarity method [*Colburn and Sonnett*, 1966]. The shock direction relative to the Earth-sun line was 78°. Unfortunately there was no high resolution plasma density available for this event to apply other methods of shock normal determination. There is a corresponding sudden impulse (SI+) noted in the SYM-H index. The SYM-H index indicates that the SI was a +15 nT field increase at Earth (see discussion about SIs and SSCs by *Joselyn and Tsurutani* [1990]).

[12] At ~1000 UT 7 Nov, there is a second fast forward shock (FS2). This shock compressed the upstream (sheath from the previous shock) magnetic field from ~5 nT to ~15 nT. The shock normal was calculated in two different ways. Assumption of coplanarity gives a shock normal angle of 24°. The *Abraham-Shrauner and Yun* [1976] (hereinafter referred to as AS) method give a value of 39°. The angle that the shock normal made to the Earth-sun line was 88° and 68°, respectively. The fast magnetosonic Mach number (last line in Table S2) was 4.1. This shock caused a second SI+. This can also be noted in the SYM-H panel. The magnetic field jump was ~+35 nT.

[13] There is a third fast forward shock (FS3) at 1755 UT 7 Nov. The shock compressed the sheath fields from ~20 nT to ~44 nT. The shock normal angles were found to be 77° and 85° for the coplanarity and AS methods, respectively. The fast magnetosonic Mach numbers were both

~2.0. This third fast forward shock created a third SI+. The magnitude of the SI+ increase was ~+40 nT.

[14] The details of the shock calculations are given in Table S2. The various upstream (1) and downstream (2) plasma parameters used in the calculations are presented. We provide this information for the reader who wishes to check the input numbers/results.

[15] What is particularly interesting is that the sequence of three fast forward shocks (FS1, FS2 and FS3) compressed the interplanetary magnetic field from the nominal quiet time value of ~4 nT to a very high value of ~44 nT. Each shock compressed sheath plasma (not MC plasma) further. The latter value is the same as the magnetic field strength of the MC that follows (discussed later). The directions of the upstream magnetic field for the second and third shocks were northward. Shock compression [*Tsurutani et al.*, 1988] created more intense northward magnetic fields. This field direction is not conducive for magnetic reconnection. Thus the sheath fields behind the shocks did not create magnetic storms.

[16] A magnetic cloud is indicated by a black horizontal bar (by the label MC) in the next to bottom panel (plasma beta) of Figure 2. The plasma beta is less than 10^{-1} throughout the cloud (it decreases to almost 10^{-3}). The MC is characterized by low proton temperatures (top panel), and high, smooth magnetic fields [*Tsurutani and Gonzalez*, 1997]. There is a general absence of waves and discontinuities. The magnetic cloud starts at ~2225 UT 7 Nov (or earlier) (RW1) and ends at ~1640 UT 8 Nov (DD3). There are discontinuities at both boundaries of the MC. The former is a reverse wave (RW1) The angle of propagation relative to the upstream magnetic field is 80° based on the AS method. There are no jumps in the magnetic field magnitude, velocity and plasma density. There is however a large increase in temperature. RW1 does not cause a noticeable SI.

[17] The parameters associated with the discontinuity at the end of the MC (DD3) are given in Table S3. The normal to the discontinuity is perpendicular to the magnetic field (89°) determined by the minimum variance method [*Sonnerup and Cahill*, 1967]. It is a tangential discontinuity.

[18] The magnetic cloud has a south-then-zero Bz configuration. The initial southward component is responsible for the main phase of the intense magnetic storm (the storm main phase onset is caused by smaller southward magnetic fields that begins near the DD2 discontinuity at ~2020 UT 7 Nov). The SYM-H index reaches a peak value of −394 nT (the hourly average Dst value was −373 nT), one of the largest magnetic storms of this solar cycle.

[19] At first glance, the interplanetary cause of this magnetic storm appears to be a simple magnetic cloud. However, it is more complex than that. A vertical line at 0420 UT 8 Nov indicates the occurrence of a fast reverse wave (RW2). This event is characterized by an increase in solar wind speed, and a decrease in temperature, density and magnetic field strength with time. The coplanarity and AS methods indicate that the wave normal angle was 50° (Table S2). A Rankine-Hugoniot analysis of this event indicates that the speed of the wave is ~171 km propagating into an upstream region where the magnetosonic speed was ~312 km/s. Thus this wave was propagating at a submagnetosonic speed and is a reverse wave and not a shock. It is most probably was a reverse shock which became "subsonic" as it propagated into the low beta MC.

[20] What is significant about RW2 in a geomagnetic sense is that the reverse wave causes a decrease in the MC field strength from ~43 nT to ~27 nT. The Bz component increased from −37 to −21 nT. This sudden Bz increase caused/triggered the recovery phase of the magnetic storm. No obvious related SI was noted in the SYM-H indices.

[21] There are other directional discontinuities (DD1 and DD2) indicated in Figure 2 and Table S3. The first discontinuity (DD1) at 1330 UT 7 Nov has a density decrease from ~80 to ~30 particles/cm^3 across the discontinuity. The IMF Bx component changes from ~+3 nT to ~−8 nT across the DD and the By component changes from −7 to +12 nT across the surface. This field change indicates that the magnetic field polarity reversed from an outward positive polarity (from the sun) to an inward negative polarity field. This is most probably a heliospheric current sheet (HCS) crossing [*Smith et al.*, 1978]. There is no resultant geomagnetic activity associated with this crossing.

[22] The second DD event occurred on 2020 UT 7 Nov and had a similar Bx and By switching as DD1. Bx changed from ~+15 nT to ~−20 nT and By changed from ~−20 nT to ~+40 nT. It is thus possible that this was a second HCS crossing. This second event had large IMF Bz components, but the duration was less than 1 hr. The southward IMF initiated the onset of the super magnetic storm, but the main driver of the storm main phase was the IMF Bz of the MC, as discussed earlier.

[23] Both DD1 and DD2 had large normal angles relative to the magnetic field, 86° and 84°, respectively. They are tangential discontinuities. The plasma densities surrounding them are relatively high. Thus, DD1 and DD2 are most likely HCSs that have been swept up by the forward shocks FS2 and FS3.

[24] It is of interest to try to relate the solar flares at the sun to the fast shocks detected at 1 AU (ACE). Can we identify solar flares that presumably launched ejecta which formed fast forward shocks in the interplanetary medium? Is there a one-to-one relationship? Why are there three fast forward shocks and only one MC detected at 1 AU? Could any of these shocks be "blast waves" that do not have associated driver gases/MCs? If not, where are the other two MCs? Could magnetic reconnection have played a role in their dissipation? We will try to answer these questions in the following section.

[25] To study this, we have used the measured solar wind speeds upstream of each of the three fast forward shocks, the calculated shock speeds and the shock normal directions (Table S2) to determine the transit time of each of the shocks. This is done assuming no solar wind deceleration between the sun and 1 AU. The extrapolated times are indicated by diamonds in the top panel of Figure 1. The times of the shocks are ~08 UT 2 Nov, ~22 UT 2 Nov and ~00 UT 5 Nov. Assuming that there is only deceleration of the bulk plasma in transit, the flare times for the three shocks would be later than the times given above e.g., the actual transit times were shorter than that calculated.

[26] There are several significant features to note in Figure 1 and Table S1. The fast forward shocks that were responsible for the large Sudden Impulses and the magnetic cloud, responsible for the superstorm, were not associated

with X-class flares. The only X-class flares occurred on 7 Nov and 10 Nov, times too late to be responsible for these interplanetary events.

[27] The extrapolated times do coincide with/are near flare events. The first triangle at ~08 UT 2 Nov is close to both a C1.8 flare at 0122 UT from AR 693 (S17E10) and a C6.9 flare at 0143 UT from AR 687 (N11W92). The second diamond at ~22 UT 2 Nov is close in time to the M2.8 flare at 0128 UT on 3 Nov (AR 691) or to a M1.6 flare at 0332 UT (AR696). The location of the latter flare was N09E45. Finally the diamond at ~00 UT 5 Nov is close in time to the double flare event at 2300 UT (M2.5 at N11E19) and the 2309 UT M5.4 flare. Both of these latter flares had their origins in AR 696.

[28] Of course other possibilities exist. If there is significant plasma/shock deceleration, the first shock could be associated with the two M class flares at the beginning of 3 Nov and the second shock with the two M class flares towards the end of day 3 Nov. Then the third shock could be related to the same double flare event discussed above. In this scenario, all three shocks would be associated with M-class flares and all three events were related to double flare events. We find this latter possibility intriguing. We follow this train of thought to understand the lack of detection of three ICMEs.

[29] Table S1 gives the location for all of the M-class flares discussed in the above scenarios. It is noted that for both FS1 and FS2, the potential candidate flare locations are not well connected to Earth. Thus it is highly probable that the associated ICMEs missed the Earth and only the envelope shocks were sensed. For the FS3 case, the double flare location was N11E19 (AR696). This is close to central meridian and thus one would expect both shock and ejecta to hit the Earth's magnetosphere, as observed.

3. Discussion and Conclusion

3.1. Identification of Discontinuities

[30] The post-solar maximum phase is characterized by many large, complex active regions (ARs). Intense M- and X- class solar flares occur frequently (multiple times a day), with less intense C-class flares occurring even more frequently. We have illustrated one particular interval investigated by CAWSES: 1 to 12 Nov 2004 using GOES X-rays and SOHO/SEM EUV flare data.

[31] Three distinct fast forward shocks were associated with the interplanetary event that caused the superstorm. They were all Mach >2 shocks that caused large SI+s. The shocks were oblique to quasiperpendicular in nature. The three shocks "pumped" up the interplanetary magnetic field from ~4 nT to ~44 nT. The upstream magnetic fields were however northward in orientation so no magnetic storms resulted.

[32] There were two tangential discontinuities embedded within the plasma sheaths that appear to be heliospheric current sheets. They were most probably swept up by the second and third fast forward shocks. The HCS crossings were not geomagnetically effective.

[33] The main cause of the superstorm was southwardly directed magnetic fields within a magnetic cloud. The MC was identified by its low plasma beta ranging from 10^{-1} to 10^{-3}. This cloud followed the third forward shock. The MC was bounded by two discontinuities which were found to be tangential in nature. The antisunward boundary was noted to be a reverse wave and not a shock. One interpretation is that this was a reverse shock which has propagated into the low beta MC and was becoming an evanescent wave.

[34] Another reverse wave was identified within the MC. This wave caused a decrease in the MC southward Bz and initiated the recovery of the magnetic storm. It is possible that this wave was once a reverse shock which propagated into the MC and became dissipative in nature.

[35] Fast ICMEs can generate a pair of shocks, one propagating forward (antisunward) and another propagating in the reverse direction. The two reverse waves detected in the event could possibly be associated with the forward shocks FS1 and FS2, respectively. As the shocks propagate into regions where their speeds are less than the ambient magnetosonic speeds, they will become subsonic waves, as the case here. It is noted that the dissipation of these reverse waves are slow. They do have (de)compressional effects within MCs at 1 AU, with important resultant geomagnetic consequences, such as the triggering of the storm recovery phase shown here [see also *Lepping et al.*, 1997].

3.2. Solar Origin of Fast Shocks

[36] We have attempted to identify the solar/interplanetary origins of the three fast forward shocks and the magnetic cloud. We find that only M- and C-class flares could have been responsible. Of possible flare candidates for the first two shocks, we find that reasonable locations are longitudinally remote and the MCs launched from these sites most likely missed the Earth. For the third fast forward shock, a double (M-class) flare event was identified as a likely solar source (of the related ICME). The flare site was near central meridian allowing the MC to reach the Earth. The above scenario is our current hypothesis. This could be further checked by using CME observations. However accurate modeling of the CME speeds, deceleration rates as they propagate through the interplanetary medium to 1AU and speeds at the flanks of the envelope shock structures need be considered in some detail. Work on this topic is currently in progress.

[37] We have illustrated the complexity of interplanetary events and geomagnetic activity that occurs during the post-solar maximum phase. Multiple flaring/CME releases will lead to magnetic storms with multiple initial phases and complex recovery phases. We expect that other events, depending on the interplanetary interactions of their causative phenomena, will have complex storm main phases as well.

[38] As a final comment it is noted that the great August 4–5, 1972 event with the highest solar wind speed on record [*Vaisberg and Zastenker*, 1973], had multiple forward shocks but only one magnetic cloud detected [*Tsurutani et al.*, 1992]. During the period near the September 1–2, 1859 Carrington solar flare/magnetic storm [*Carrington*, 1859], there was again multiple flaring taking place at the sun and continuous geomagnetic activity for many days [*Tsurutani et al.*, 2003]. The post-maximum phase of the solar cycle thus may in general be an interval of very complex interplanetary structures and complex geomagnetic activity. It is possible that such complexities will need to be

understood to gain further insight on the solar and interplanetary causes of extreme magnetic storms at Earth.

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