Interplanetary causes of great magnetic storms: Further insights

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Interplanetary causes of great magnetic storms: Further insights

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Abstract. We discuss possible interplanetary mechanisms for the creation of the great ($D_{ST} < -250$ nT) magnetic storms at the Earth. We consider the effects of interplanetary shock events on magnetic cloud and sheath plasma, leading to potentially stronger interplanetary magnetic field (IMF) magnitudes. We also examine the effects of a combination of a long-duration southward sheath magnetic field, followed by a magnetic cloud B_S event. The profiles of the most intense storms for which interplanetary data exist will be discussed in light of these mechanisms.

1 Introduction

The purpose of this paper is to examine the causes of the largest magnetic storms at Earth. We know the energy transfer mechanism from the solar wind to the magnetosphere for magnetic storms is magnetic reconnection between the interplanetary magnetic fields and the Earth's fields, where the interplanetary dawn-dusk electric field is given by $V_{SW} \times B_S$ (Dungey, 1961; Gonzalez et al., 1994). In the above expression, V_{SW} is the solar wind velocity and B_S is the southward component of the interplanetary magnetic field (IMF). However, there has been little effort placed to date on understanding the detailed causes of the very largest magnetic storms. Are the velocities unusually high? Are the magnetic fields unusually intense or do both the velocity and magnetic fields have to be large to create superintense storms? Are double (or triple) shock events creating very high magnetic fields? Or are there other causes of these unusually intense storm events?

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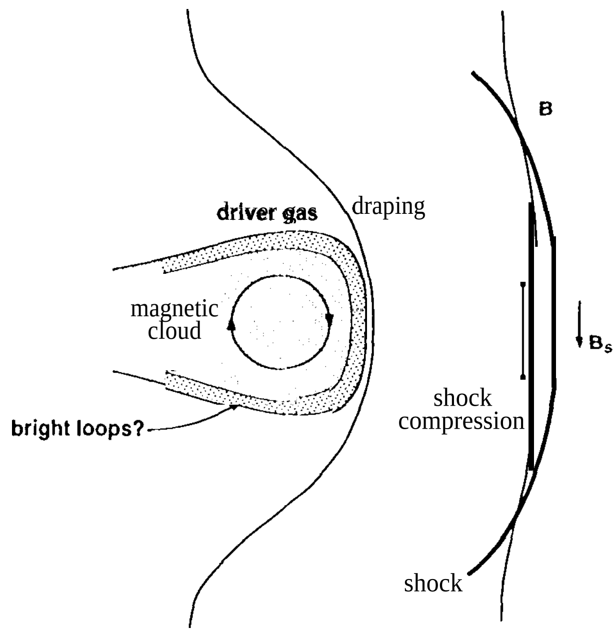

Fig. 1. Schematic showing geometry of a magnetic cloud and upstream sheath

2 Sheath/ICME Magnetic Fields

It has been shown that a southward IMF ≤ -10 nT (≥ 5 mV/m) for T>3 hours is necessary for the creation of an intense ($D_{ST} \leq -100$ nT) magnetic storm (Gonzalez and Tsurutani, 1987). The southward IMF events can be located either in the sheath fields ahead of fast interplanetary coronal mass ejections (ICMEs) or within the ICMEs themselves. The latter case, B_S within an ICME, is usually in the form of a magnetic cloud (Burlaga et al., 1981) (However, it should be pointed out that 5 out of 6 fast solar ejecta do not contain magnetic clouds: Tsurutani et al., 1988). A schematic of this overall geometry is given in Figure 1.

There are reasons to expect stronger magnetic fields in both interplanetary regions for fast ICMEs. A fast driver gas will in general lead to stronger shock-compressed magnetic fields (depending on the upstream flow conditions). The magnetic field compression across the shock can be up to a maximum of 4 (Kennel et al., 1985). If the upstream IMF has a southward orientation, the shock leads to intensification of this component.

In previous data analyses results, there is a general relationship between the speed of the ICME and the magnetic field intensity in the magnetic cloud. From the Burlaga et al. (1978) data set, we note that the magnetic field intensity of slow speed streams was only -10 nT, whereas tbc faster clouds have intensities of 20-30 n-l'. 'l'his relationship has not been previously pointed out and no theoretical explanation has been offered, 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_{SW} relationship may give important clues as to these mechanisms. This topic will be examined in greater detail in Tsurutani et al. ('l'his issue).

One mechanism to create even higher field strengths would be for a second interplanetary shock to (further) compress the high fields existing in the ICME/sheath regions (of Figure 1). An argument was presented in Tsurutani and Gonzalez (1997) that the presence of shocks/strong compressions may not be possible within magnetic clouds because of the low beta conditions present there. Typical beta values in clouds are -0.1 with consequential Al fvén/magnetosonic speeds of 300-700 km S-l. These high, speeds necessary for shock formation, should ordinarily preclude the formation of such structures within magnetic clouds.

It is unclear what will happen to this compressional wave when it reaches the other side of the cloud. It may be sufficiently dispersed or it may possibly reform as a shock. Another 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 tbc possibility of each of these mechanisms might be, simulation efforts are recommended.

3 Double Storms

Another way to get large D_{ST} events is to have two storm main phases with the second closely following the first. Kamide et al. (1997) in an analysis of more than 1200 magnetic storms has shown that such events are quilt common and are caused by two IMF southward field events of' approximately equal strength. This is shown in Figure 2. Kamide et al. argue that this could also be

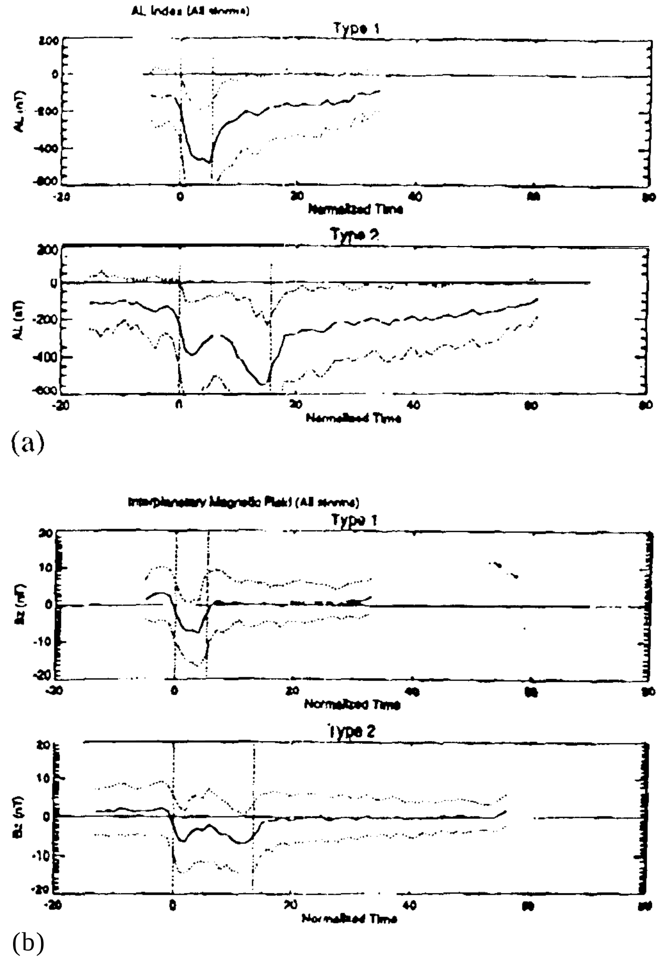

Fig. 2. Normalized time series of (a) the AL index showing the development of single (top panel) and double (second panel) geomagnetic storms, nnd (h) the corresponding IMF B_z components showing the southward turning of the field which induces the response in the AL index shown in (a).

viewed as two moderate magnetic storms with the D_{ST} base of the second well below that of the first.

Grande et al. (1996) and Daglis et al. (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 [he second by Fe^{+16}. A likely explanation is 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), -['ill' peak D_{ST} for the first event was - – 100 nT and - –300 nT for the second event. We note however that these values were not solar wind ram pressure-corrcc(cd. The field at the storm initial phase was - +60 nT, indicating that the correction will be substantial.

We reexamine the interplanetary causes of great magnetic storms (D_{ST} ≤ -250 nT) which have corresponding interplanetary data (reported in Tsurutani et al., 1992). The D_{ST} profiles are shown in Figure 3.

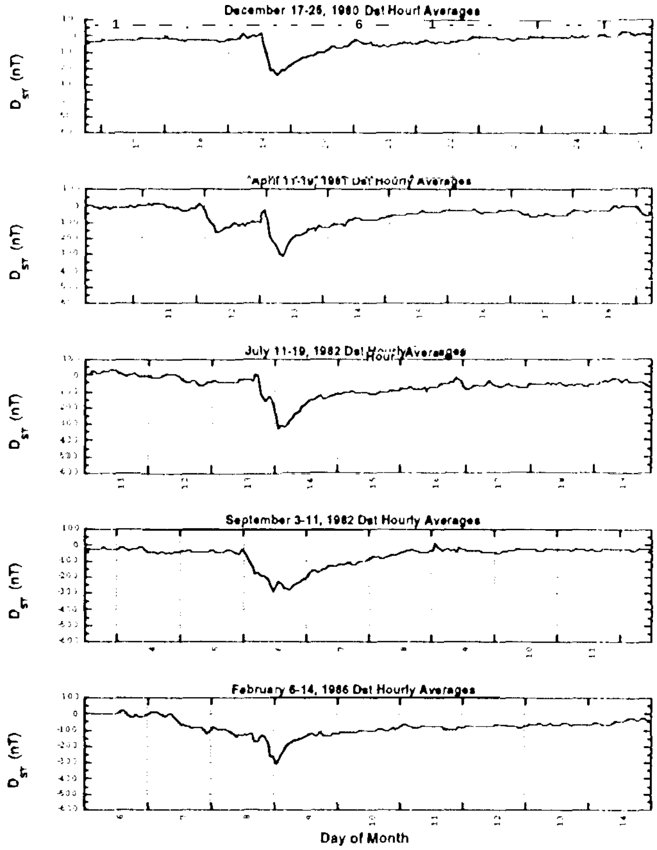

Fig. 3. The five largest magnetic storms during the period from 1980 through 1986.

Three of the four largest events have. complex main phases. The April 12-13, 1981 and July 13-14, 1982 events are double main phase storms. The February 7-9, 1986 storm had a main phase that took 1 1/2 days to develop, then an abrupt further decrease. The former could be due to a complex ICME sheath region.

4 Conclusions

It is found that double main phase events are quite common for great magnetic storms ($D_{ST} \leq -250$ nT). The two (or more) ring current injections lead to the exceptionally large D_{ST} values as suggested by Kamide et al. (1997). A reexamination of the IMF B_S features leading these five storm events would be illuminating.

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