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Prediction of Solar-Flare-Caused Geomagnetic Storms

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ABSTRACT

A three-dimensional, time-dependent, MHD model of solar-disturbance-caused storms (Wu, 1993, Wu *et al.*, 1996) is used to predict the turning direction of the interplanetary magnetic field (IMF) at Earth. More explicitly, the authors examine the polarity of B_z caused by solar disturbances on the Sun. A specific solar disturbance, the solar flare, is used in this paper. The data set used is a subset of that used by Smith and Dryer (1995) and is based on observations of coronal shocks as seen in metric type II observations. These observations are associated with both source flares and geomagnetic storms which serve as markers of shock arrival at Earth. The Omni IMF data are used for comparison with the generalized simulation results of the 3D model. Eight events are studied in this paper. The results of six of them are consistent with the prediction model.

(Key words: Solar flare, Geomagnetic storms, IMF turning direction)

1. INTRODUCTION

The configuration of the magnetic field in the disturbed solar wind has become a topic of great interest in the study of the Solar-Interplanetary-Magnetospheric (SIM) coupling problem since the change in direction of the Interplanetary Magnetic Field (IMF) is now known to be one important cause of geomagnetic disturbances. The north-south component of the IMF B_z (in the solar-magnetospheric coordinate system) plays a crucial role in determining the amount of solar wind energy which is transferred to the magnetosphere (Arnold, 1971;

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Meng, 1972; Akasofu, 1981; Akasofu *et al.*, 1985; and Faruggia *et al.*, 1993). More specifically, when the IMF has a large magnitude ($\geq 10\gamma$) and a large southward component, the amount of transferred energy becomes very large. Conversely, when the IMF is directed primarily northward, the transferred energy becomes very small. Gold (1962) suggested that the transient B_z component is associated with the so-called "magnetic tongue". Pudovkin and Chertkov (1976) and Pudovkin *et al.* (1977, 1979) suggested that the polarity of the IMF at Earth can be predicted from the observed polarity of the north-south component of the photospheric magnetic field at the site of a solar flare. However, Tang *et al.* (1985) tested the magnetic tongue model by examining the relationship between the polarity of the transient variation of the IMF B_z component and the associated flare field. They showed that a simple relationship between the orientation of the IMF B_z component and the magnetic orientation of the associated flare region does not in fact appear. The first 3D, time-dependent, magnetohydrodynamic (MHD) simulation model for heliospheric space was given by Han *et al.* (1988) and was employed by Wu (1993) and Wu *et al.* (1992; 1996) to study the relationship between the location of solar activity and the changes in the IMF B_z at 1 AU. Their study put forth an explanation of the reason that a simple relationship between the polarity of the IMF B_z at 1 AU and the magnetic orientation of the associated flare region at the solar activity location *does not* appear. Using two representative heliospheric IMF conditions (unipolar outward polarity and, separately, an initially flat heliospheric current sheet, HCS), they devised a prediction model of the IMF turning direction associated with the initial condition of the IMF and the location of the solar disturbance (Wu, 1993; Wu *et al.*, 1996). In this paper, Section 2 outlines this prediction model. The results of the data analysis are presented in Section 3, and a summary and discussion are provided in Section 4.

2. PREDICTION MODEL OF THE SOLAR-DISTURBANCE - CAUSED IMF TURNING DIRECTION

The prediction model of solar-disturbance-caused storms (Wu, 1993; Wu *et al.*, 1996), is summarized in the six cases listed below. In each case, the initially-flat heliospheric current sheet (HCS) lies in the equatorial plane; a pressure pulse is introduced at the inner boundary, either above, below or in the HCS, and the polarity of the background field is varied. The pressure pulse had a gaussian shape with a width at half maximum, $\Delta p/p$ = 15, which increased in a circular shape (in the heliolatitudinal-heliolongitudinal surface, or θ-ϕ surface) from the initial pressure at 18 solar radii. The temporal duration was a one-hour ramp up to maximum, which was held for four hours before being ramped down to the initial value for the sixth hour. Thus, this pulse was taken to be a representation of a long-duration soft X-ray solar flare and was also used in each of the following cases. The 3D response in the interplanetary medium is represented schematically by a circle in Figures 1-6. Details of the 3D MHD simulations are given by Wu *et al.* (1992, 1996) and Wu (1993).

(i) In the first case, the IMF-lines are disturbed by a pressure pulse propagating into an initial state with outward IMF polarity in the northern hemisphere and inward polarity in the southern hemisphere. The center of the pressure pulse is located in the solar equatorial plane. The IMF-lines turned southward (at the front of the fast-mode wave or shock) either in the southern or northern hemisphere but did not change direction at the solar equatorial plane (see Figure 1).

(ii) The IMF-lines disturbed by a pressure pulse propagating into an initial state of IMF-lines towards the Sun in the northern hemisphere and outwards from the Sun in the southern hemisphere with the center of the pressure pulse in the solar equatorial plane. The IMF-lines turned northward either in the southern or northern hemisphere but did not change direction at the solar equatorial plane (see Figure 2). Again, this turning refers to the front of the propagating disturbance (fast MHD wave or shock).

(iii) The IMF-lines disturbed by a pressure pulse propagating into the northern hemisphere (Figure 3) with an initial state of IMF-lines outwards from the Sun in the northern hemisphere and towards the Sun in the southern hemisphere. This case corresponds to a simulated flare in the northern hemisphere. The IMF-lines turned southward either in the southern hemisphere or in the northern hemisphere at latitudes higher than the central axis of the flare and turned northward in the northern hemisphere at latitudes less than that of the flare- again referring to the front of the interplanetary disturbance.

(iv) The IMF-lines disturbed by a pressure pulse propagating into the southern hemisphere (Figure 4) with an initial state of IMF-lines outwards from the Sun in the northern hemisphere and towards the Sun in the southern hemisphere. The IMF-lines turned southward in the northern hemisphere and at southerly latitudes greater than that of the flare and northward in the southern hemisphere at latitudes less than that of the flare.

(v) The IMF-lines disturbed by a pressure pulse propagating into the northern hemisphere (Figure 5) with an initial state of IMF-lines towards the Sun in the northern hemisphere and outwards from the Sun in the southern hemisphere. The IMF-lines turned northward in the southern hemisphere and at latitudes greater than that for the flare in the northern hemisphere and turned southward at latitudes smaller than that of the flare in the northern hemisphere.

(vi) The IMF-lines disturbed by a pressure pulse propagating into the southern hemisphere (Figure 6) with an initial state of IMF-lines towards the Sun in the northern hemisphere and outwards from the Sun in the southern hemisphere. The IMF-lines turned northward in the northern hemisphere and at latitudes greater than that for the flare in the southern hemisphere. In contrast, they turned southward at latitudes less than that for the flare in the southern hemisphere.

The reader should note that all of the possibilities for the flare's latitude relative to a fundamental initially-flat HCS configuration, regardless of the IMF hemispheric polarity, have been summarized from the 3D MHD results. This initial IMF topology is relevant for solar minimum condition. Future work will consider a warped HCS, which is more appropriate for the rising or falling phases of solar activity. It should also be note that heliolongitudinal displacements of Earth relative to the flare might be expected to attenuate the effects discussed above.

3. DATA ANALYSIS

Within the context of the model results discussed in Section 2, eight events have been studied in this paper under the assumption that an initially-flat HCS is a valid zeroth-order approximation. Table 1 lists the relevant parameters extracted from Smith and Dryer (1995) for eight events which were not associated with sudden substorm commencements (SSC), but with Major Magnetic Storms (MMS) or with observed shocks at ISEE-3 (Event 1). The authors of the present study are not aware of any literature which suggests that the geomagnetic storms, which are discussed below, were associated with coronal mass ejections coming from other solar sources (*e.g.*, high latitude helmet streamer eruptions).

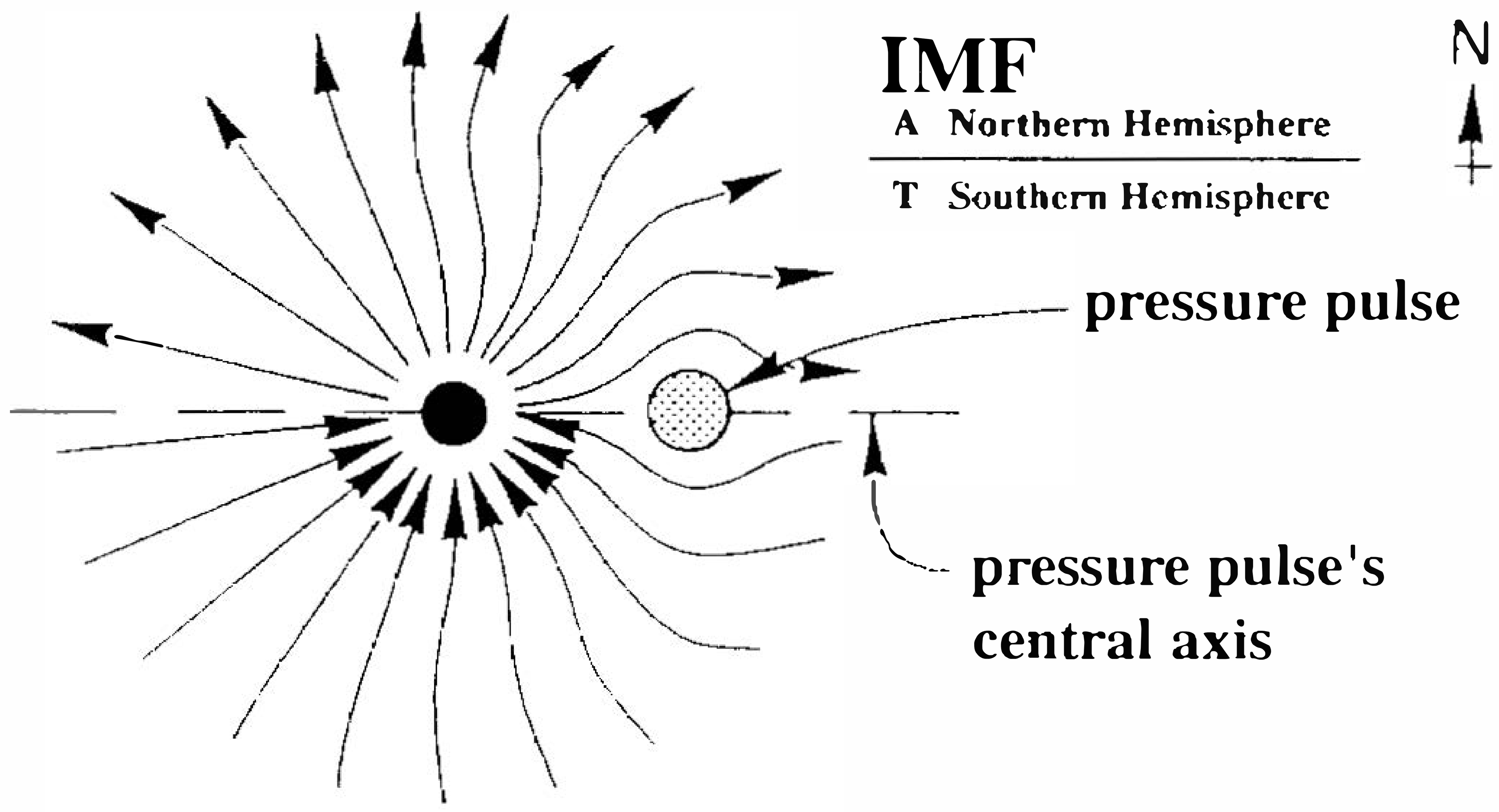

Fig. 1. Schematic IMF-lines disturbed by a pressure pulse propagating into an initial state of IMF-lines outwards from the sun in the northern hemisphere, and towards the sun in the southern hemisphere with the center of the pressure pulse in the solar equatorial plane.

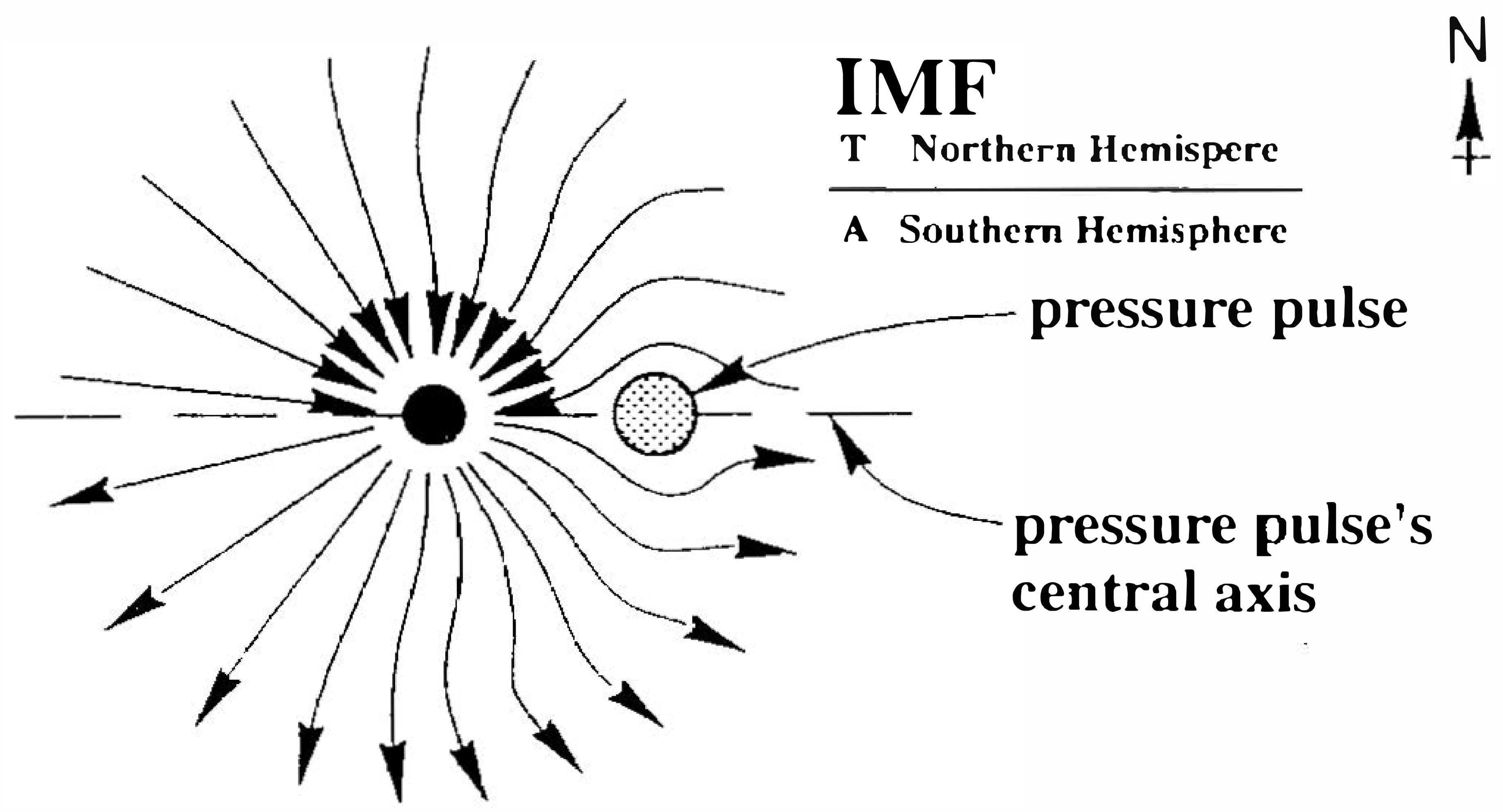

Fig. 2. Schematic IMF-lines disturbed by a pressure pulse propagating into an initial state of IMF-lines towards the sun in the northern hemisphere, and outwards from the sun in the southern hemisphere with the center of the pressure pulse in the solar equatorial plane.

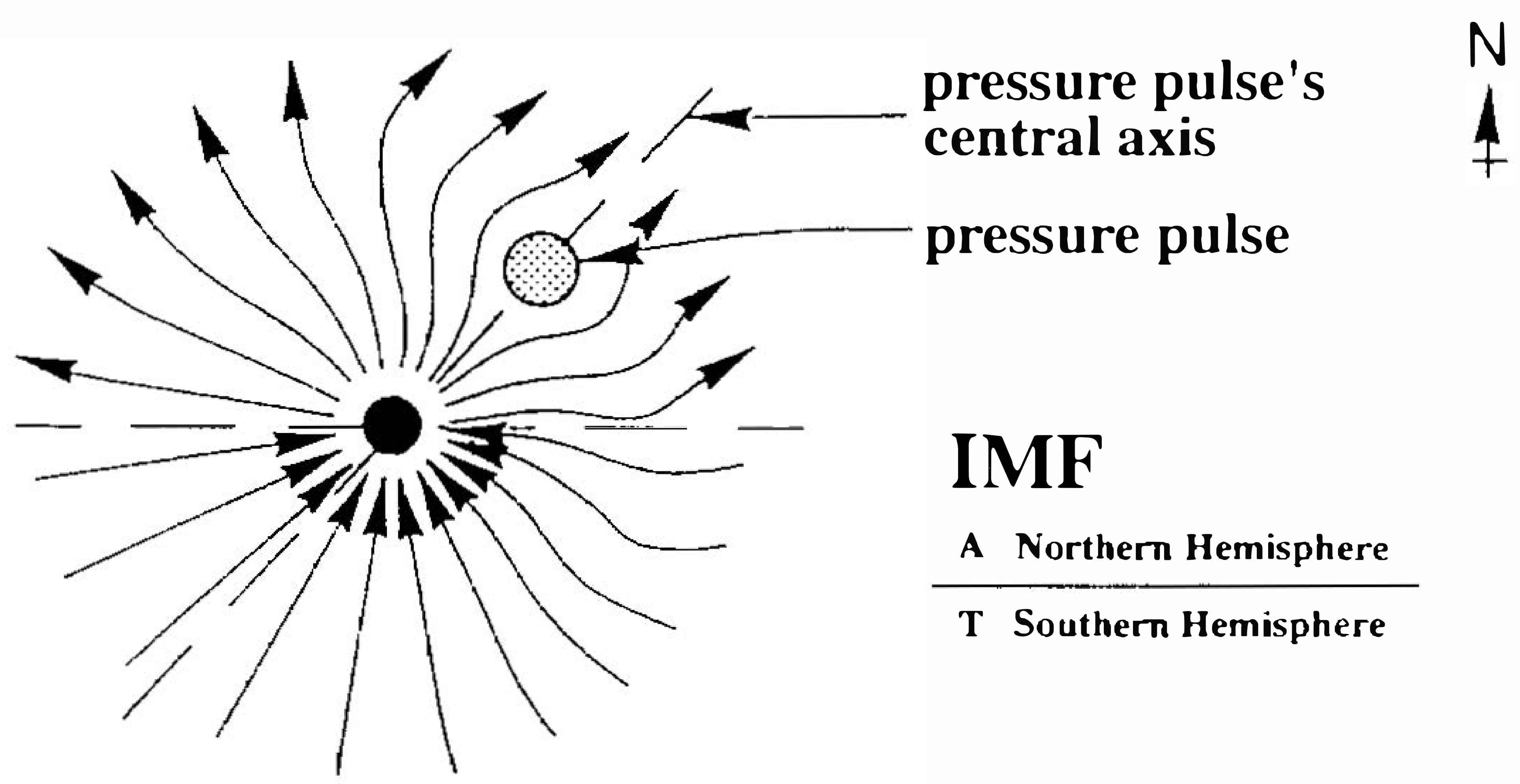

Fig. 3. Schematic IMF-lines disturbed by a pressure pulse propagating into the northern hemisphere with an initial state of IMF-lines outwards from the sun in the northern hemisphere and towards the sun in the southern hemisphere.

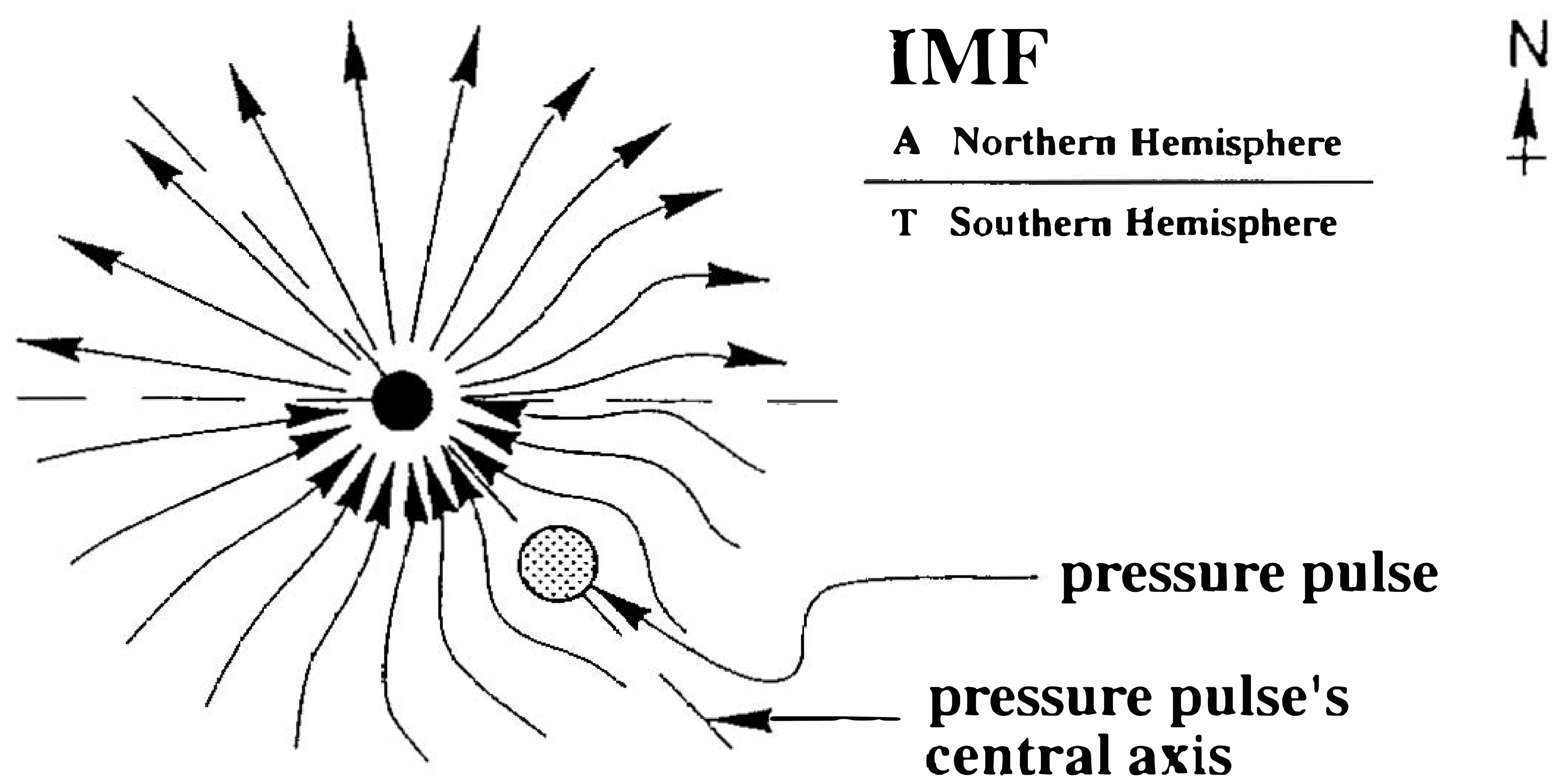

Fig. 4. Schematic IMF-lines disturbed by a pressure pulse propagating into the southern hemisphere with an initial state of IMF-lines outwards from the sun in the northern hemisphere and towards the sun in the southern hemisphere.

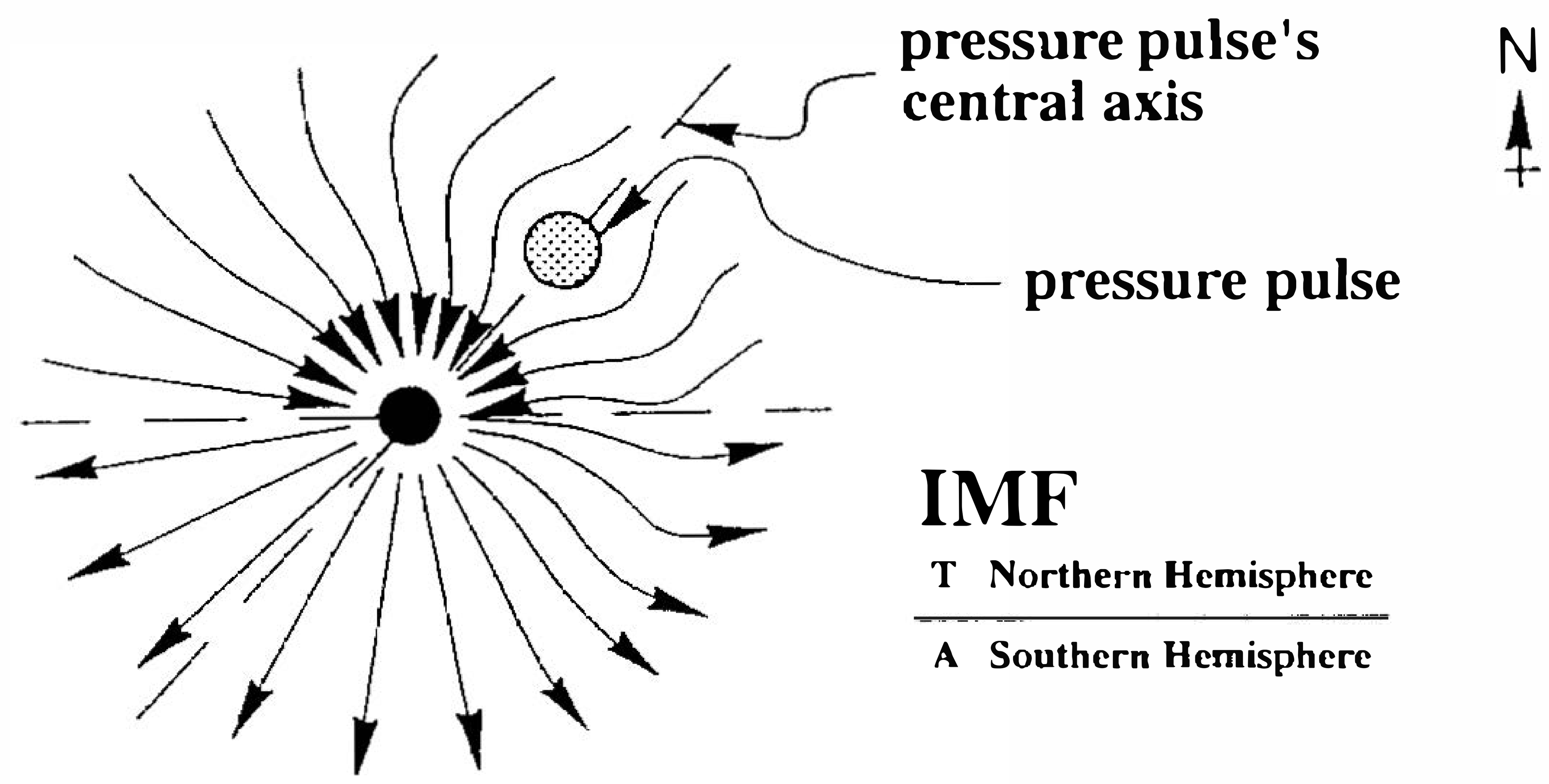

Fig. 5. Schematic IMF-lines disturbed by a pressure pulse propagating into the northern hemisphere with an initial state of IMF-lines towards the sun in the northern hemisphere and outwards from the sun in the southern hemisphere.

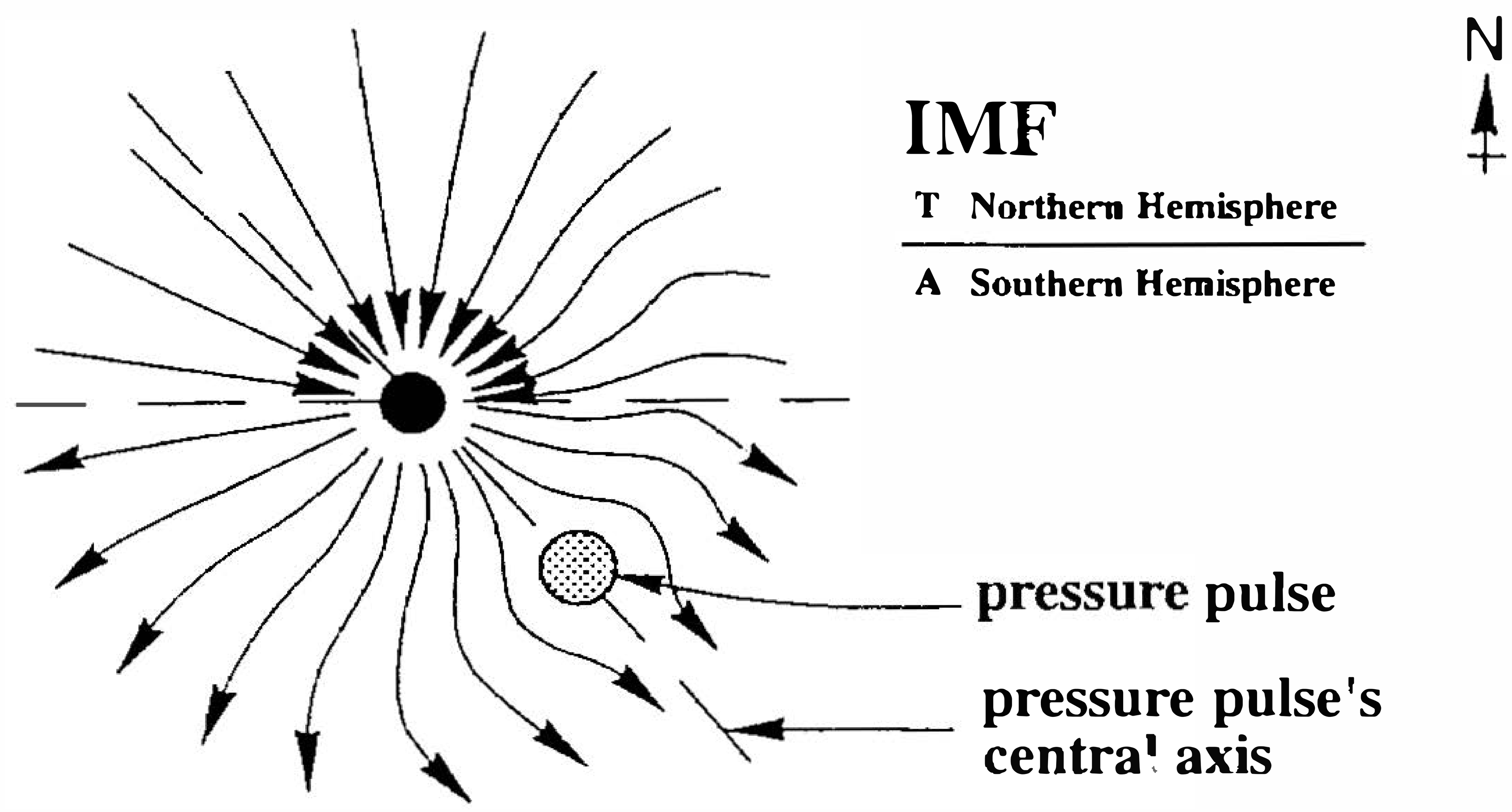

Fig. 6. Schematic IMF-lines disturbed by a pressure pulse propagating into the southern hemisphere with an initial state of IMF-lines towards the sun in the northern hemisphere and outwards from the sun in the southern hemisphere.

Table 1. Data set used to predict the turning direction of IMF.

Event #	YEAR/M/D	XRAY UT	END UT	II STRT	Flare LAT	Flare LON	CLASS OPT	CLASS XR	V(II) KM/S	VSW KM/S	MMS or S/C M	D	UT
1	1979/07/04	0259	0415	0219	7	44	2N	C7*	2500.	309.	7	5	0608
2	1979/12/19	2117	2237	2212	−15	36	2B	X1	1500.	370.	12	22	0500
3	1980/04/09	2233	2359	2237	−10	−90	2B	C7	1500.	424.	4	11	1500
4	1980/05/21	2106	2143	2057	−14	−15	3B	X1	1068.	400.	5	24	0700
5	1980/08/22	0519	0540	0533	9	58	1B	M1	1300.	385.	8	25	2300
6	1981/02/15	1905	1922	1901	15	−71	1B	M1	795.	377.	2	19	1900
7	1982/06/15	1514	1532	1512	−22	66	2B	X1	2750.	310.	6	19	0700
8	1982/07/22	1734	1940	1720	16	−89	1N	M4	2250.	420.	7	24	1500

MMS = Major Magnetic Storm.
S/C = Shock observed at ISEE3, but no SSC. This event is marked by a "*" in the X-ray class column, XR.
II = Type II radio burst.
V(II) = Coronal Type II shock velocity.
VSW = Solar wind velocity measured by ISEE-3.
LON = East of central meridian is positive; west, negative.

Table 2 lists all the IMF data used in this paper on the basis of ground-based-inferred IMF polarities for each day, starting with the solar event and ending with the commencement of the storm for 4 events; the IMF polarities for several days after the storm commencement are also listed for the other 4 events. The inferred interplanetary magnetic field (IMF) was prepared from Vostok observations for the first half-day by the Institute for Terrestrial Magnetism, Ionosphere and Radio Propagation, Moscow, USSR and from Thule observations for the second half-day by the Space Environment Services Center, NOAA, Boulder, Colorado, USA. "T" denotes the IMF toward the Sun, while "A" denotes the IMF away from the Sun, as determined from the predominant half-day values from either IZMIRAN or from NOAA/SESC. Mixed polarities are indicated as predominantely "TA" or "AT" during the first-half of the UT data.

Table 2. Data set of IMF used to predict the MMS.

Event	FLARE		Interplanetary Magnetic Field								MMS or S/C	Predicted	Time Delay Sun-to-Earth
#	Year/M/D	LAT,LON	M,D	Pol.	M,D	Pol.	M,D	Pol.	M,D	Pol.	M,D,UT	IMF	D/H/Min
1	1979/7/4	7,44	7,5	TA A	7,6	TA A	7,7	AT A	7,8	A T	7,5,0608	N	1/3/49
2	1979/12/19	−15,36	12,20	A A	12,21	TA A	12,22	A A	12,23	T A	12,22,0500	S	2/6/48
3	1980/4/09	−10,−90	4,9	A A	4,10	AT A	4,11	T A	4,12	T A	4,11,1500	S	1/16/23
4	1980/5/21	−14,−15	5,21	AT A	5,22	* A	5,23	TA A	5,24	A A	5,24,0700	S	2/09/03
5	1980/8/22	9,58	8,22	T T	8,23	T T	8,24	T A	8,25	T T	8,25,2300	S	3/17/27
6	1980/2/15	15,−71	2,16	A A	2,17	TA A	2,18	A A	2,19	A A	2,19,1900	N	4/00/00
7	1980/6/15	−22,66	6,16	− −	6,17	A −	6,18	TA −	6,19	A −	6,19,0700	S	3/15/48
8	1982/7/22	16,−89	7,22	T −	7,23	A −	7,24	T −	7,25	T −	7,24,1500	−	1/21/40

Inferred interplanetary magnetic field (IMF) prepared from Vostok observations for first half-day by the Institute for Terrestrial Magnetism, Ionosphere and Radio Propagation, Moscow, USSR; and from Thule observations for second half-day by Space Environment Services Center, NOAA, Boulder, Colorado, USA. T = Toward the sun, A = Away from the sun, as determined from the predominant half-day values from either IZMIRAN or from NOAA/SESC. Mixed polarities are indicated as predominantely "TA" or "AT" during the first-half of the UT day.
* = Effect doubtful or not discernible, − = Missing Data. M, D = Month, Day. UT = Universal Time.
D/H/Min (Day/Hour/Minute) = The time delays between the peak of the flares' X-ray flux and MMS or S/C.

3.1 Events 2, 3, 4 and 7

These events all had flare locations in the southern hemisphere of the Sun. During the period of the associated commencement of the MMS, the IMF was always directed outward from the Sun. Therefore, based on Case (vi) above, the IMF was predicted to turn southward before the commencement of the MMS.

3.2 Event 5

For Event 5, the flare was located in the northern hemisphere, and the IMF is inferred to be towards the Sun before the commencement of the MMS. Therefore, based on Case (v), the IMF should turn southward before the commencement of the MMS.

3.3 Events 1 and 6

For Event 1, during the early part of July 5, 1979, the IMF was first inferred to be towards the Sun; however, later in the day, it was outwards ("A") from the Sun (see "TA" symbol in Table 2). Because the IMF was directed predominantly away from the Sun before the shock arrival at ISEE-3, the IMF was predicted to turn northward near 1 AU in accordance with Case (iii). This meant that a storm was not predicted and, in fact, none was actually observed. The location of the flare for Event 6 was also in the northern hemisphere, and the IMF polarity, it was inferred, would be outwards from the Sun. Therefore, the IMF as per Case (iii), would be expected, to also turn northward near 1 AU without any MMS. Event 6 is discussed in Section 4 in more detail.

3.4 Event 8

The location of the flare was in the northern hemisphere, and the IMF polarity is toward the Sun most of the time prior to and during the commencement of the MMS. The commencement of the MMS was at July 24, 15:00UT, and the IMF polarity was towards the Sun during the first half of July 24 and 25, 1982. If it is assumed that the IMF polarity is towards the sun during the rest of the time on July 24, the IMF should turn southward near 1 AU in keeping with Case (v).

4. SUMMARY AND DISCUSSION

The maximum excursion of Earth in its annual motion around the Sun relative to the solar equatorial plane is $\pm 7.25°$. Using the simple flat HCS model as an approximation to solar minimum heliospheric topology, it is easy to predict the turning direction of the IMF near Earth when the location of the flare or other disturbance is greater than 7.25° or less than -7.25°.

(1) When the flare is located at more than 7.25° in the north hemisphere:
   (i) the IMF turns southward if the initial polarity of the IMF is towards the Sun, and
   (ii) the IMF turns northward if the initial polarity of the IMF is outwards from the Sun.

(2) When the flare is located at more than 7.25° in the southern hemisphere:
   (iii) the IMF turns southward if the initial polarity of the IMF is outwards from the Sun, and
   (iv) the IMF turns northward if the initial polarity of the IMF is towards the Sun.

Table 3 summarizes the recipe for the initial turning propensity of the B_z component of the IMF for the case of a pre-event flat HCS which is discussed in this paper. Eight events have been studied by using the 3D MHD model (Han *et al.*, 1988) and the applications of that study by Wu (1993) and Wu *et al.* (1996) to predict the turning direction of the IMF near 1 AU. For Events 2, 3, 4, 5 and 7, the IMF was predicted (retroactively) to turn southward before the commencement of the MMS. For Event 6, the IMF was predicted to

Table 3. Summary for a B_z turning Recipe: Pre-Event Flat Heliospheric Current Sheet.

	Pre-Event HCS in Solar Equatorial Plane				Pre-Event HCS North of Solar Eq. Plane		Pre-Event HCS South of Solar Eq. Plane	
Source Location Relative to HCS	N		S		Source aligned w/HCS		Source aligned w/HCS	
Observer's IMF polarity before SSC	T	A	T	A	T	A	T	A
Predicted turning of Bz at Observer's position								
Ident relative to Solar Eq. Plane	S	N	N	S	S	N	N	S
Case #	(v)	(iii)	(iv)	(vi)	(i)	(ii)	(ii)	(i)
Figure in this paper	5	3	4	6	1	2	2	1

Note: Nature of the solar pulse (flare, eruptive prominence, destabilized coronal helment streamer) is not essential for the *initial* turning of the Bz component of the IMF. The energy release, heliolongitudes, and nature of the pulse *are* essential vis-a-vis the magnitude (severity) and duration of a possible ensuing geomagnetic storm. Topological nature of extraneous solar ejecta (Plasmoids, magnetic clouds, flux ropes) is not considered in this study.

turn northward before the commencement of the MMS. For Event 1, which was only marked at Earth by a shock, the IMF polarity, by prediction, would turn northward. Therefore, a storm was not expected, and none was observed. The results of six of the events (Events 1, 2, 3, 4, 5 and 7) are consistent with the prediction model, whereas for one (Event 6), it is not. The data are missing for Event 8.

The time delays between the peak of the X-ray flux of the flares and the MMS for each event are :

Event 1: one day, three hours and forty-nine minutes,
Event 2: two days, six hours and forty-eight minutes,
Event 3: one day, sixteen hours and twenty-three minutes,
Event 4: two days, nine hours and three minutes,
Event 5: three days, seventeen hours and twenty-seven minutes,
Event 6: four days,
Event 7: three days, fifteen hours and fourty-eight minutes, and
Evnet 8: one day, twenty-one hours and forty minutes.

Based on the prediction model, the turning direction of the IMF will be northward for Event 6, and there should be no MMS during the period between Feb. 16 and 19, 1980 except for the early part of Feb. 17 when the initial IMF was towards the Sun. In addition, the average time for the delay between the flare and the commencement of the MMS is about two days, fourteen hours and thirty-five minutes. For Event 6, the candidate flare (Table 2) takes almost four days, presumably to generate an MMS *via* its interplanetary disturbance. This delay is much longer than those for the other events. Therefore, one might suspect that this association was in error, and that the MMS might have been associated with another form of solar activity.

The present study involves the use of ground-based inferred "toward" or "away" IMF polarity at Earth. The *in situ* polarities as found from the Omni data base are now considered here. Table 4 lists a summary of the IMF polarity data (for the days of the commencement of the MMS) from the Omni data base for the flares that were associated with the storms as listed in Tables 1 and 2 from Smith and Dryer (1995). "T" denotes the IMF toward the

Table 4. Data set of IMF (Omni data) used to predict the polarity of IMF B_z.

Event #	Year/Mon/Day	FLARE LAT,LON	IMF Bx	Obs. Bz	Pred. Bz
1	1979/7/4	7,44	A	N	N
2	1979/12/19	-15,36	A	N	S
3	1980/4/9	-10,-90	A	S	S
4	1980/5/21	-14,-15	A	S	S
5	1980/8/22	9,58	T	S	S
6	1980/2/15	15,-71	A	N	N
7	1980/6/15	-22,66	A	S	S
8	1982/7/22	16,-89	T	S	S

LON = East of central meridian is positive.
Bx = "T" is toward the sun; "A" is away as determined by the predominant polarity provided in the hourly-averaged OMNI data for the days of the commencement of the MMS.

sun and "A" away from the sun, as determined by the predominant polarity provided in the hourly-averaged Omni data for the day that includes the beginning of the MMS (or the Shock for Event 1). According to the 3D MHD model (Wu, 1993; Wu *et al.*, 1996), the predicted IMF would turn southward for Events 2, 3, 4, 5, 7 and 8, but northward for Events 1 and 6. When compared to the actual hourly-averaged IMF data of Omni, only Event 2 has the opposite result. The results of the other seven events all match the prediction.

Altogether, the studies presented here have demonstrated that a simple relationship between the location of flares and the initial condition of the IMF is apparent for the basic heliospheric topology that has a flat HCS prior to a disturbance. It is possible to predict, for this approximation to solar minimum conditions, not only the polarity of the IMF B_z component by using the initial polarity of the IMF but also the location of flares by using the recipe given here, as provided from the explicit results of the 3D MHD model (Wu, 1993; Wu *et al.*, 1996).

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