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An interplanetary cause of large geomagnetic storms: Fast forward shock overtaking preceding magnetic cloud

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[1] In the event that occurred during October 3–6, 2000, at least one magnetosonic wave and one fast forward shock advanced into the preceding magnetic cloud (MC). By using the field and plasma data from the ACE and WIND spacecraft, we analyze the evolution of this event, including the characteristics and changes of the magnetic fields and plasma. At the rear part of the cloud, a large southward magnetic field is caused by a shock compression. The shock intensified a preexisting southward magnetic field. This increased the geoeffectiveness of this event and produced an intense geomagnetic storm with Dst = -175 *nT*. We also describe another event with a shock overtaking a MC on Nov. 6, 2001. A great geomagnetic storm of intensity Dst = 292 *nT* resulted. These observations are used to argue that shock compression of magnetic cloud fields is an important interplanetary cause of large geomagnetic storms. Our analyses suggest that the geoeffectiveness is related to the direction of preexisting magnetic fields, the intensity of overtaking shock, and the amount of shock penetration into the preceding MC. *INDEX TERMS:* 2139 Interplanetary Physics: Interplanetary shocks; 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Wang, Y. M., P. Z. Ye, S. Wang, and X. H. Xue, An interplanetary cause of large geomagnetic storms: Fast forward shock overtaking preceding magnetic cloud, *Geophys. Res. Lett.*, *30*(13), 1700, doi:10.1029/2002GL016861, 2003.

1. Introduction

[2] During this past solar maximum (2000–2001), there were 8 "great" geomagnetic storms with Dst ≤ -200 *nT*. Lesser intensity "intense" geomagnetic storms (Dst $\leq$ -100 *nT*) are more common than great storms. What are the solar and interplanetary causes of great geomagnetic storms? This interesting question has been discussed by many authors [e.g., *Akasofu*, 1981; *Burlaga et al.*, 1987; *Gonzalez and Tsurutani*, 1987; *Tsurutani et al.*, 1988, 1992, 1995; *Gonzalez et al.*, 1989].

[3] Analyzing 10 intense geomagnetic storms with Dst < -100 *nT* from 1978 to 1979, *Gonzalez and Tsurutani* [1987] conclude that the criteria of interplanetary parameters in causing "intense" geomagnetic storms is $B_z < -10$ *nT* with a duration $\Delta T > 3$ *hours*. Further, *Tsurutani et al.* [1988] analyzed the interplanetary causes of these events. Among the 10 intense storms, there were 4 great storms with Dst $\leq$ -200 *nT*, which were all produced by B_s within driver gases (also called magnetic clouds (MCs) [*Burlaga et al.*, 1981]). By studing five very largest geomagnetic storms that occurred between 1971 to 1986, *Tsurutani et al.* [1992] extended their result about the interplanetary causes: 3 of 5 events were caused by shock compression of preexist southward interplanetary magnetic fields, and the other two were caused by intrinsic B_s from MCs. *Gosling and McComas* [1987] have also given evidence that field draping over driver gases can produce IMF B_s, which can be geoeffective.

[4] The idea that the compression of shock of preceding MCs may play an important role in producing intervals of strong B_s field has been discounted by *Tsurutani* [2001] because shocks should not be able to propagate though low β MC plasma. *Tsurutani* [2001] has argued that shock-magnetic cloud events should be rare. This letter studies a complex structure and its development in interplanetary space, which resulted in an intense geomagnetic storm on October 5, 2000 due to shock compressed B_s interval. In this structure, a magnetosonic wave and a fast forward shock overtook and interact with an earlier emitted MC.

2. ACE and WIND Observations

2.1. ACE

[5] Figure 1 shows the plasma observations from the ACE spacecraft. ACE was at about (225, -29, 5)R_E in GSM coordinates. A complex structure was observed from Oct. 3 to 6, 2000. The relatively high ratio of H_e^{++} to proton densities indicates that the structure was mainly of coronal origin. In the complex structure, there was a large scale magnetic cloud beginning at 1018 UT on Oct. 3 and ending at 0534 UT on Oct. 5. The cloud is identified by enhanced magnetic field strengths, large and smooth rotation of the field vectors and low proton temperatures. The front border of the MC can be definitively determined by the sharp decrease in proton temperatures (as denoted by the first vertical dashed line in Figure 1). This MC was preceded by a fast forward shock at 0010 UT on Oct. 3 (indicated by the first vertical line). Within the MC, the field vector rotation basically was in the θ direction and the rotation in the ϕ direction was much smaller. Therefore, the axis of the MC was approximately parallel to the ecliptic plane and perpendicular to the Sun-Earth line.

[6] According to the observations, there were at least two shocks/waves advancing into the cloud (as indicated by 'S1' and 'S2' in Figure 1). The first one was a shock/magnetosonic wave (S1) that arrived ACE at 1336 UT on Oct. 4. Some parameters were discontinuous but weak at S1. The total magnetic field B increased from 11.6 nT to 14.8 nT, and the southward component B_s of magnetic field increased from 10.6 nT to 13.4 nT. The plasma bulk flow

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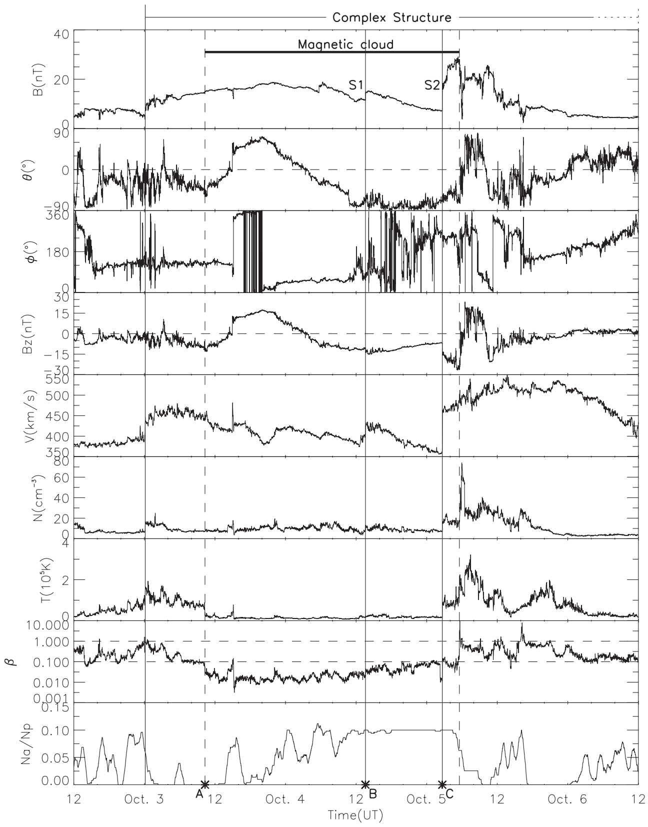

Figure 1. Observations by ACE spacecraft from 1200 UT Oct. 2 to 1200 UT Oct. 6, 2000 (in GSM). From top to bottom are plotted: magnetic field strength *B*, the elevation θ and azimuthal ϕ angles of the field direction, z component field B_z, bulk flow speed *V*, proton density *N*, the proton temperature *T*, the ratio of thermal pressure to magnetic pressure β, and the density ratio of H_e^{++} to proton N_α/N_p.

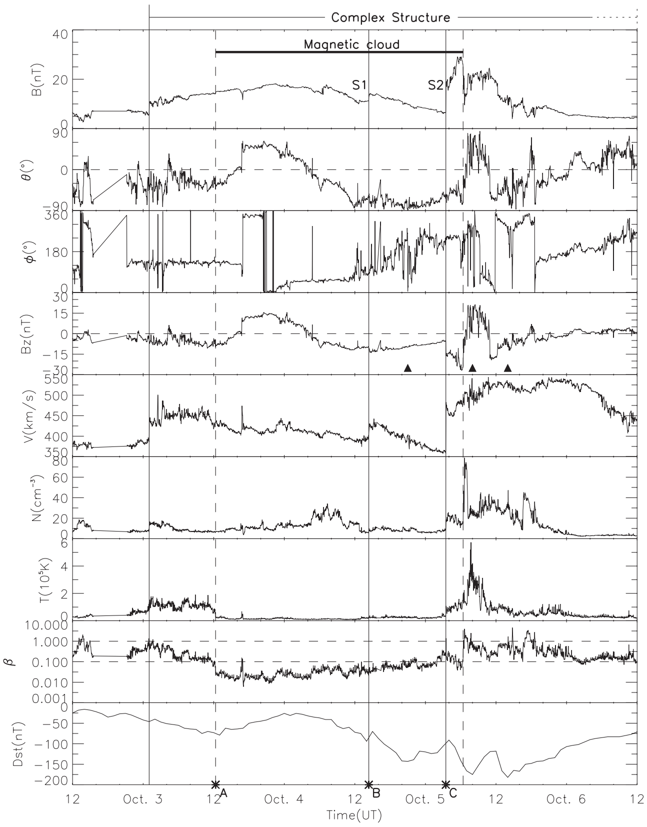

Figure 2. Observations by WIND spacecraft from 1200 UT Oct. 2 to 1200 UT Oct. 6, 2000 (in GSM). The last panel is plotted geomagnetic index *Dst*.

speed V and proton density N, increased from 407.7 km/s and 8.5 cm^{-3} to 432.4 km/s and 12.1 cm^{-3}, respectively. Tentatively, we assume that S1 was a shock. We do not apply coplanarity theorem to calculate the shock normals, because the error in the estimation is great. Instead, we estimate the shock speed by assuming the shock normal direction parallel to the bulk flow velocity. Therefore, the shock speed of S1 is estimated to be ∼491 *km/s* by the continuity equation. As discussed in Section 4, such speed is very close to the estimated local fast magnetosonic speed in the shock frame. Thus, S1 is likely a magnetosonic wave but not a shock. The second one was a shock (S2) clearly that observed at 0240 UT on Oct. 5. It was much more compressive than the S1 event. At the interface of S2, B, B_s, V and N jumped from 7.3 nT, 6.8 nT, 363.6 km/s and 6.9 cm^{-3} to 18.0 nT, 15.6 nT, 459.5 km/s and 15.8 cm^{-3}, respectively. The estimated shock speed of S2 is ∼534 *km/s*. The observational compression ratio and the estimated shock speed are listed in Table 1.

2.2. WIND

[7] Figure 2 shows the solar wind observations from the WIND spacecraft. WIND was at about (32, −220, 110)R_E. The distance between the two spacecraft was ∼193 R_E along the Sun-Earth direction. WIND was farther from the Sun-Earth line than ACE. The observations are similar to those from ACE. The magnetic cloud began at 1219 UT on Oct. 3 and ended at 0625 UT on Oct. 5. A preceding shock occurred at 0100 UT on Oct. 3. Compared with the ACE observations, the overtaking shocks penetrated the preceding MC more deeply.

[8] The first magnetosonic wave (S1) arrived at WIND at 1421 UT on Oct. 4. At S1, the total magnetic field B increased from 11.4 nT to 13.9 nT, and the southward component of magnetic field B_s increased from 9.5 nT to

Table 1. The Comparison Between ACE and WIND Data

	S 1					S 2				
	B_d/B_u	B_{sd}/B_{su}	V_d/V_u	N_d/N_u	V_{sh}	B_d/B_u	B_{sd}/B_{su}	V_d/V_u	N_d/N_u	V_{sh}
ACE	1.28	1.26	1.06	1.42	491 km/s	2.47	2.29	1.26	2.29	534 km/s
WIND	1.22	1.31	1.06	1.35	498 km/s	2.77	3.02	1.34	2.10	590 km/s

The subscript 'u' and 'd' indicate the upstream and downstream respectively. V_{sh} indicates the estimated speed of the shock.

Table 2. The Observations of Three Interfaces

	'A' UT	'B' UT	'C' UT	Position[a] R_E
ACE	10/3, 10:18	10/4, 13:36	10/5, 02:40	(225, −29, 5)
WIND	10/3, 12:19	10/4, 14:21	10/5, 03:28	(32, −220, 110)
V_x[b]	170 km/s	460 km/s	430 km/s	

[a]Position of spacecrafts in GSM.
[b]The speed of the interfaces along the Sun-Earth line.

12.4 nT. The bulk flow speed V and proton density N increased from 400.5 km/s and 6.0 cm^{-3} to 425.8 km/s and 8.1 cm^{-3}, respectively. Following the assumption adopted in last subsection, the assumed shock speed of S1 is estimated to be ∼498 *km/s*, also close to the local fast magnetosonic speed. The second shock (S2) was observed at 0328 UT on Oct. 5. At S2, B, B_s, V and N jumped from 6.5 nT, 5.1 nT, 357.0 km/s and 8.3 cm^{-3} to 18.0 nT, 15.4 nT, 479.0 km/s and 17.4 cm^{-3}, respectively. The shock speed of S2 is ∼590*km/s*. The observed compression ratios and the estimated shock speeds are listed in Table 1.

[9] Refer to the Dst observations (as seen in the bottom panel of Figure 2), this event was responsible for the intense geomagnetic storms during Oct. 4–5. The combination of southward component magnetic field within the MC and the compressed region of S1 produced the first Dst peak (−143 nT) at 2100 UT on Oct. 4. However the S1 compression was weak and The Dst effect small. The compressed southward magnetic field and increased solar wind speed caused by S2 produced the second Dst peak (−175 nT) at 0800 UT on Oct. 5. Double and triple-step storms are quite common [*Tsurutani and Gonzalez*, 1997; *Kamide et al.*, 1998].

3. Comparison

[10] On the basis of the observed data of magnetic fields before S1 and S2, it is found that the fields strength observed by WIND were smaller than those by ACE. This result suggests that the trajectory of ACE within the cloud was closer to the center of the MC than that of WIND.

[11] Table 1 lists the some information of S1 and S2 events. Obviously, the compression ratio of magnetosonic wave S1 observed by WIND is comparable with that at ACE, but the shock S2 observed by WIND is stronger than that at ACE. The increase of observed compression ratio is perhaps due to the different observational positions relative to the MC. WIND should be farther from the center of the cloud and the local Alfvén/magnetosonic speed was therefore smaller, so the compression ratio should be larger.

[12] To further describe the evolution of this event, we consider three special interfaces 'A', 'B' and 'C' (as marked in Figures 1 and 2). Interface 'A', 'B' and 'C' denote the front of the preceding MC, the arrival of S1 and S2 respectively. By comparing the data from ACE and WIND, we evaluate the speed of these interfaces along the Sun-Earth line (V_x). Such speeds of interface 'B' and 'C' are also the x-component of corresponding shock velocities of S1 and S2. The results are listed in Table 2.

[13] The obtained speed of 'A' is 170 km/s and much smaller than the observed speed (∼430 *km/s*). The result suggests that the spacecraft did both not pass through the center of the cloud and the distance between WIND's trajectory and the cloud's center was longer than that between the ACE's trajectory and the cloud's center as mentioned above. The speed of 'B' is 460 km/s approaching the assumed shock speed of S1 as listed in Table 1, which implies that the direction of S1 velocity was approximately parallel to the Sun-Earth line indeed. The speed of 'C' is 430 km/s much smaller than the estimated shock speed of S2, so the direction of shock velocity must be deflected much from the direction of the Sun-Earth line. Thus, we believe that the observed evolution of S2 should be different from that of S1. This can also be a possible reason why the observational compression ratio of S2 increased from ACE to WIND.

4. Summary and Discussion

[14] We have analyzed the evolution of the complex structure in interplanetary medium. In this structure, at least two fast forward shocks/magnetosonic waves advanced into the preceding MC, compressed the preexisting southward magnetic field, and formed compressed field with enhanced solar wind speed.

[15] The likelihood of the existence of shock within magnetic cloud was discussed in previous work [*Tsurutani and Gonzalez*, 1997; *Gonzalez et al.*, 1999]. Generally, the presence of shock is not expected within MCs because of the large Alfvén/magnetosonic speeds in low β clouds. In above instance, the local fast magnetosonic speed is evaluated as approximately 90 km/s. According to the estimated shock speed V_{sh} listed in Table 1, we can obtain that the speeds upstream in the shock frame are ∼83 *km/s* (by ACE) and ∼98 *km/s* (by WIND), respectively at S1, which are around the estimated local fast magnetosonic speed. Thus, S1 likely should not be a shock but a magnetosonic wave.

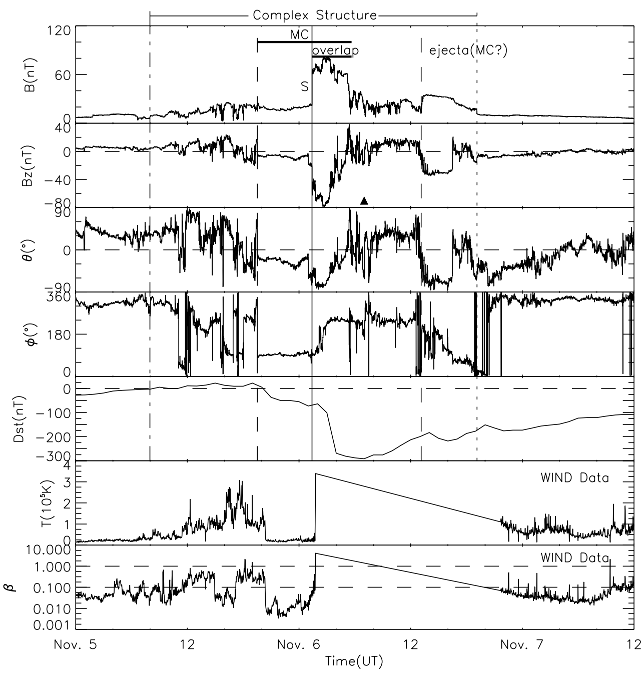

Figure 3. Observations from Nov. 5 to 1200 UT Nov. 7, 2001 (in GSM). Based on the data by ACE, the top four panels are plotted: B, θ, ϕ, and B_z. The fifth panel presents the geomagnetic index *Dst*. The bottom two panels show the plasma parameters: T and β from WIND.

The S1 probably was a fast forward shock before entering the magnetic cloud. After having overtaken the preceding cloud, it decayed into a magnetosonic wave because of the decrease of the local β and the dissipation of S1. As for S2, the upstream speed is larger than the magnetosonic speed. It should be a shock. Thus, as long as the overtaking shock speed is large enough, it is still able to propagate within magnetic cloud. Certainly, it is also possible that S2 decays into a magnetosonic wave as it propagate further.

[16] The interaction of a shock with a MC has been simulated by *Vandas et al.* [1997]. They concluded that the faster shock should slowing down and transfer a part of its energy to the cloud when it penetrated through a cloud. The MC should be compressed in the radial direction and become very oblate. Their results of numerical simulation are approximately consistent with our observations of the first shock because the observational path is approximately along the propagation direction of S1. As for the second shock S2, the situation is complicated because it maybe did not enter the preceding MC completely and the direction of its velocity is not parallel to the Sun-Earth line. The compression ratio of shock is correlative to the local Alfvénic Mach number. At different position within an MC, the corresponding Alfvénic Mach number may be different. Thus, it is possible that the compression ratio increases associated with the energy losing while shock is interacting with a cloud.

[17] Figure 3 shows another example of fast forward shock advancing into magnetic cloud. This event was observed by ACE around November 6, 2001. Since the plasma data by ACE is not available during interesting interval, the corresponding data by WIND is used instead (as shown in Figure 3). The overtaking shock arrived at 0124 UT on Nov. 5. The magnetic fields before the shock have a smooth rotation in θ direction, and actually according to the plasma data by WIND, the proton temperature was low and the β was less than 0.1. Thus, the overtaken object is likely a magnetic cloud. The rear part of this cloud lasting about 5 hours was overlapped by the compressed region of the shock and formed a large B_s event. At this shock arrival, the magnetic field strength B increased from 24 nT to 62 nT sharply. The maximum value of total magnetic field strength B_{max} behind the shock was 82 nT and the southward component B_{smax} was 81 nT. The magnetic field was directed totally southward. This compression between the shock and the MC largely increased the geoeffectiveness of this event. It produced a great geomagnetic storm (Dst = 292 nT) at 0600 UT on Nov. 6, 2001. This event proves again that the compression of shock with preceding MC plays an important role in causing great geomagnetic storms.

[18] The similar events have ever been mentioned, for example the April 5, 1979 event [*Burlaga et al.*, 1987] and the October 19, 1995 event [*Lepping et al.*, 1997]. In those two events, the fields behind the shock were compressed to about 40 nT. Although intense geomagnetic storms occurred in these events, they were both caused by the southward fields intrinsic to the magnetic cloud but not the fields in compressed regions, since the overtaken preexisting magnetic fields at the tail of the preceding MC were northward.

[19] Above analyses suggest that the geoeffectiveness of such event is correlative to many factors, such as the direction of preexisting magnetic fields, the intension of overtaking shock, the amount of shock penetration into the preceding MC, and so on. In which situation does the geoeffectiveness reach the maximum while shock is advancing into preceding MC? Solving this problem is valuable and helpful to improve the level of predicting large geomagnetic storms.

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