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Analysis on the interplanetary causes of the great magnetic storms in solar maximum (2000–2001)

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Abstract

In this paper, we analyze the interplanetary causes of eight great geomagnetic storms ($D_{st} \leqslant -200$ nT) during the solar maximum (2000–2001). The result shows that the interplanetary causes were the intense southward magnetic field and the notable characteristic among the causal mechanism is compression. Six of eight great geomagnetic storms were associated with the compression of southward magnetic field, which can be classified into (1) the compression between ICMEs (2) the compression between ICMEs and interplanetary medium. It suggests that the compressed magnetic field would be more geoeffective. At the same time, we also find that half of all great storms were related to successive halo CMEs, most of which originated from the same active region. The interactions between successive halo CMEs usually can lead to greater geoeffectiveness by enhancing their southward field B_s interval either in the sheath region of the ejecta or within magnetic clouds (MCs). The types of them included: the compression between the fast speed transient flow and the slow speed background flow, the multiple MCs, besides shock compression. Further, the linear fit of the D_{st} versus $(-\overline{VB_z})^{\alpha}(\Delta t)^{\beta}$ gives the weights of $-\overline{VB_z}$ and Δt as $\alpha = 2.51$ and $\beta = 0.75$, respectively. This may suggest that the compression mechanism, with associated intense B_s, rather than duration, is the main factor in causing a great geomagnetic storm.

Keywords: Geomagnetic storms; CMEs; Interplanetary shocks; Field draping; ICMEs; Magnetic clouds; Interplanetary magnetic field

1. Introduction

Geomagnetic disturbances occur in response to the Sun's activity (Richardson et al., 2000). Solar wind coupling with the magnetosphere can cause the enhancement of westward ring current through magnetic reconnection of the southward interplanetary magnetic field B_s with the Earth's magnetic field near the Earth's equator, and a geomagnetic storm will happen as a result. During solar minimum, the Earth is located in high speed streams 55% of the time versus 10% for the transient structures associated with coronal mass ejections (CMEs) (Richardson et al., 2002). So high speed streams from coronal holes dominate interplanetary medium activity (Gonzalez et al., 1999). Geomagnetic disturbances are generally weak during solar minimum and the intense geomagnetic storms with $D_{st} \leqslant -100$ nT are few, and majority are the moderate recurrent storms caused by the corotating interaction regions (CIRs) (Sheeley et al., 1976; Burlaga and Lepping, 1977; McAllister and Crooker, 1997; Webb et al., 2001); but some strong B_s also occur during the solar minimum period. During solar maximum, when the Earth is located in transient structures associated with CMEs 30% of the time (Richardson et al., 2002), the dominant interplanetary phenomena causing magnetic storms are the interplanetary manifestations of fast CMEs. Two interplanetary structures are associated with intense southward interplanetary magnetic fields (IMFs) (Gonzalez et al., 1999): the sheath region behind the forward

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shock (Tsurutani et al., 1988; Tsurutani and Gonzalez, 1997), and the interplanetary coronal mass ejection (ICME) itself, e.g., magnetic cloud (MC) (Klein and Burlaga, 1982).

Great magnetic storms ($D_{st} \leqslant -200$ nT) are one of the most prominent disastrous phenomena in space weather. Studying the interplanetary mechanism in the creation of great magnetic storms is meaningful for space weather forecasting. Tsurutani et al. (1992) studied five events of great geomagnetic storms during 1971–1986 and analyzed the interplanetary causes of them. They found: (1) the intense southward IMFs are the important causes of great geomagnetic storms, (2) three great geomagnetic storms were caused by shock compression and field draping (intense southward IMFs in sheath), the other two were caused by the intense southward IMFs in ejecta (MC), (3) precursor southward fields ahead of the high speed streams allow the shock compression mechanism to be particularly geoeffective.

From the 1990s, we can get more precise data by many satellites such as ACE, WIND, and SOHO etc., which give us a very good opportunity to study the interplanetary causes of great geomagnetic storms. In the recent solar maximum (2000–2001), there are eight great geomagnetic storms observed: April 7, 2000 (-288 nT), July 16, 2000 (-301 nT), August 12, 2000 (-235 nT), September 17, 2000 (-201 nT), March 31, 2001 ($-387, -284$ nT), April 11, 2001 (-271 nT), November 6, 2001 (-292 nT), November 24, 2001 (-221 nT), according to the D_{st} data from World Data Center for Geomagnetism (WDC). Four of these eight great geomagnetic storms have recently been discussed in the literature. The July 16, 2000 great geomagnetic storm was caused by the Bastille Day event. A monograph of *Solar Physics* (Volume 204, Issue 1/2, 2001) is devoted to this event. The September 17, 2000 great magnetic storm was associated with interplanetary complex ejecta. These complex ejecta have been mentioned by Burlaga et al. (2001). They considered that the complex ejecta were the result of interactions between four successive halo CMEs with different speeds which formed a single fast stream that had only one peak in the solar wind speed profile (Burlaga et al., 2001). The March 31, 2001 great geomagnetic storm was caused by another type complex structure—multiple magnetic clouds (multi-MCs) identified by Wang et al. (2002, 2003a), which were due to the overtaking of successive magnetic clouds and comprised of several relatively isolated sub-clouds satisfying the criteria of the MC. And the November 6, 2001 great geomagnetic storm was caused by forward shocks overtaking preceding MCs, in which the southward field within the MCs was enhanced by the compression of the shock. Wang et al. (2003b) have also discussed this case. We will discuss in Section 3.

In this paper, we discuss the interplanetary causes of these eight great geomagnetic storms based on the observations from ACE and WIND spacecraft, and try to find some notable characteristics of interplanetary causes of the great geomagnetic storms during solar maximum.

2. Observations

2.1. The April 7, 2000 event

Fig. 1 shows observations from the ACE spacecraft and the related geomagnetic disturbance for this event.

From D_{st} curve, the peak value of the great geomagnetic storm was -288 nT occurring at 0100 UT on April 7. The intense southward magnetic field B_s interval beginning at 1610 UT on April 6 was responsible for the great geomagnetic storm (see the filled region in the second panel). Its average value and maximum value were 21.04 and 33.31 nT, respectively, in this region and the duration of $VB_s \geqslant 0.5$ mV/m (Burton et al., 1975) was nearly 7.3 h.

The intense southward field was located in the shock sheath; evidently, it was the result of shock compression. This shock arrived at 1601 UT on April 6 with a compression ratio of $B_d/B_u = 2.9$ (B_d is the downstream magnetic field strength and B_u is the upstream magnetic field strength); it suggested that the shock was strong. At the rear part of this B_s interval, D_{st} reached a minimal value. Besides, before the shock, the z-component of the interplanetary magnetic field was almost southward and the average value was -3.5 nT for a large duration (~ 16 h). Such a general southward tilt of the IMF makes a shock's compression enhance the preexisting B_s and allows it to be particularly geoeffective.

By examining the SOHO/EIT images, we consider that the halo CME originated from N16W60 at 1632 UT on April 4, 3 days ahead of the geomagnetic storm, with the linear fit for a speed of 1188 km/s, was responsible for the shock. The location of the CME on the solar disk was far from the center meridian, and it was not a well Earth-directed ejecta. However, we can observe the low proton temperature and a relatively low proton β value starting about 0800 UT on April 7, which suggested the body of an ICME arrival (also reported by Cane and Richardson (2003)). The characteristics of a relatively long duration between the shock arrival and the start of the ICME, the much weaker magnetic field (~ 5 nT) within the ICME, and the departure of the source location from the center meridian implied that the ACE satellite only passed through the edge of the ICME. Since the shock driven by the ejecta was much broader than the ejecta itself, we may still observe the strong shock versus the weaker ICME. In this event the compressed intense southward IMF in the sheath was the cause of this great geomagnetic storm.

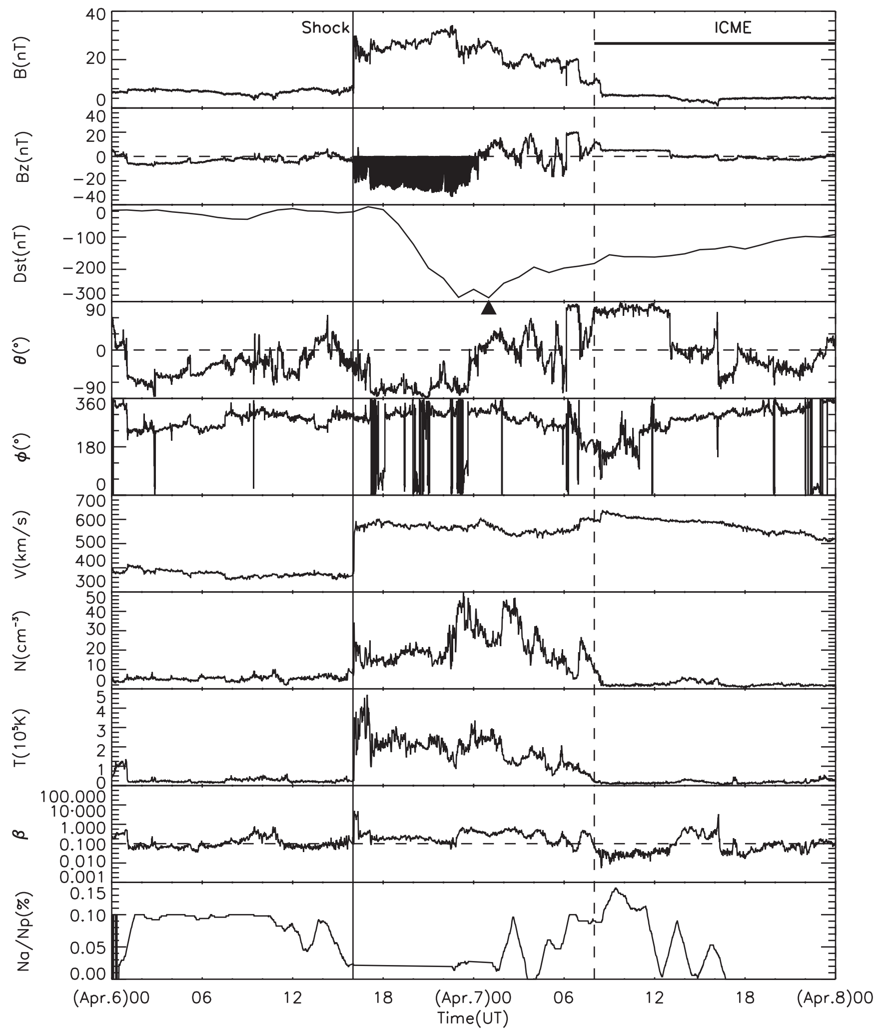

Fig. 1. The observations by the ACE spacecraft from April 6 to 7, 2000 (in GSM). From top to bottom, it shows the magnetic field strength (B), the z-component of the magnetic field (B_z), D_{st} curve, the elevation θ and azimuthal ϕ angles of field direction, the solar wind speed (V), the density (N), the proton temperature (T), the proton β value, and the density ratio of N_α/N_p. The horizontal dashed line denotes $\beta = 0.1$.

2.2. The July 16, 2000 event

A monograph of *Solar Physics* (Volume 204, Issue 1/2, 2001) is devoted to this event. Many authors have discussed its solar origin and the interplanetary properties associated with the storm caused by this so-called Bastille Day event in detail (e.g., Andrews, 2001; Araujo-Pradere and Fuller-Rowell, 2001; Lepping et al., 2001; Raeder et al., 2001; Smith et al., 2001). So we summarize this event concisely.

Fig. 2 shows ACE observations of this event at 1 AU. From the D_{st} curve, the great geomagnetic storm began at 2100 UT on July 15, and its minimal value reached −301 nT at 0100 UT on July 16. The cause of this great geomagnetic storm was the intense southward IMF in the magnetic cloud (MC).

The magnetic cloud boundaries are determined by the changes of the proton temperature (T_p) and proton β. Generally, T_p decreases suddenly at the front boundary and continues at a low value throughout the cloud and proton β also drops to ~ 0.1 at the front boundary correspondingly (Burlaga et al., 1981, 2001). Then T_p and proton β will increase at the rear boundary. In some cases, the T_p within cloud is not as low as that within a typical magnetic cloud due to compression (e.g., multiple magnetic clouds), but proton β still has the typical value. Sometimes, the rear boundary is difficult to identify because of ambiguous signatures. In all cases of the magnetic clouds examined by this paper, the front boundaries are well definited.

According to the criteria of MC boundaries, the MC started at 1900 UT on July 15 and ended at 1000 UT on July 16 (marked by dashed lines). The maximum value of the southward IMF was 59.55 nT, and 4.5 h just after this value the D_{st} minimal value occurred.

Previous statistical study showed a relationship of the peak magnetic field magnitude within an ICME at 1 AU in direct proportion to its velocity (Tsurutani, 2001). It

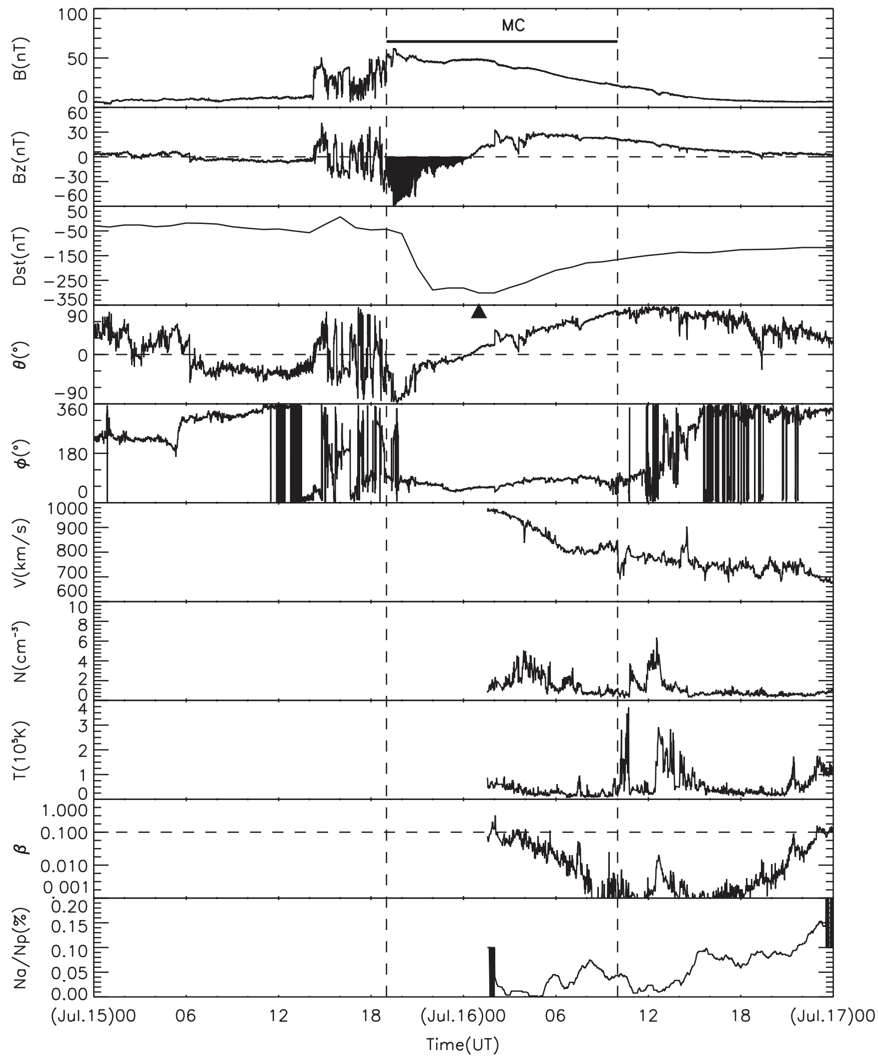

Fig. 2. Observations by the ACE spacecraft from July 15 to 16, 2000 (in GSM).

should be noted that this general $V_{sw} - |B|$ relationship also held for this event. The interplanetary solar wind had a very high speed of $\geqslant 1100$ km/s during this period (Lepping et al., 2001), and the magnetic field magnitude increased to a maximum value of ~ 60 nT (shown in Fig. 2). So the very high speed solar wind is also an important parameter, which may result in the intense magnetic field magnitude in ICME.

2.3. The August 12, 2000 event

Fig. 3 shows ACE observations of this event at 1 AU. The main phase of this great geomagnetic storm began at 0300 UT on August 12, and D_{st} minimal value (-235 nT) occurred at 1000 UT on the same day. The southward IMF B_s associated with this great geomagnetic storm was mostly within the MC, which was observed from 0517 UT on August 12 to 2200 UT on August 13. It is identified by enhanced magnetic field strengths (the peak value is 34.3 nT), large and smooth rotation of the field vectors in the θ direction, low proton temperatures ($\sim 0.2 \times 10^5$ K), low proton β value (~ 0.005), and a relatively high N_α/N_p value (>0.08). The maximum value of southward IMF in MC was 29.9 nT, and the duration of $VB_s \geqslant 0.5$ mV/m lasted 7.9 h (shown in Fig. 3). About 4 h after the peak value of B_s, the D_{st} minimal value occurred.

We also note that there was a field draping structure near the leading portion of the ejecta in the sheath. Draping is a consequence of two facts: (1) the magnetized plasma cannot significantly penetrate the obstacle and thus is forced to flow around it, and (2) the magnetic field links plasma elements which, at any particular moment, have experienced different amounts of slowing and deflection as the plasma is bent around the obstacle (Gosling and McComas, 1987). From Fig. 3 (the filled part between the first two dashed lines), the draping structure approximately began at 0130 UT on August 12, and contained a small B_s interval. This B_s event lasted about 2 h with a minimal value of 17.82 nT,

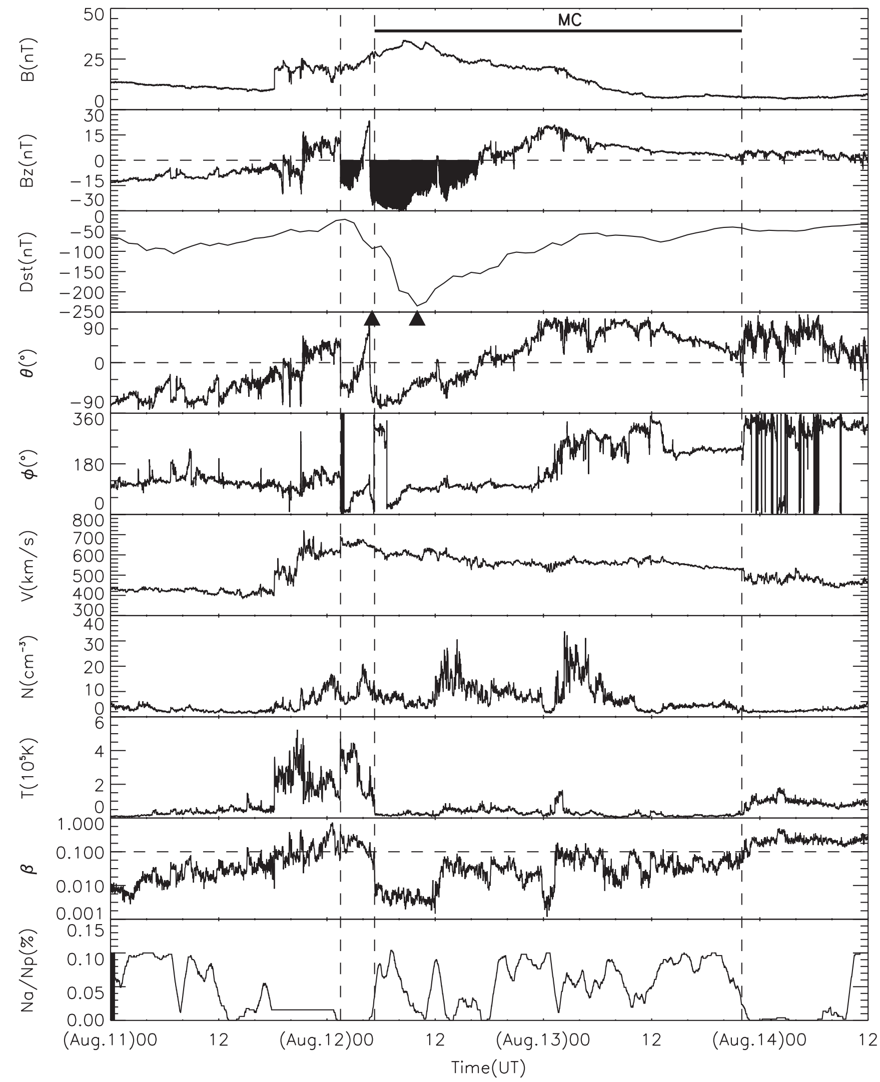

Fig. 3. Observations by the ACE spacecraft from August 11 to 1200 UT August 14, 2000 (in GSM). The draping field is marked by first two dashed lines.

and caused the minor D_{st} minimum (-93 nT) at 0500 UT on August 12.

This event was a double-peak geomagnetic storm, the double-peak structure of a geomagnetic storm has been discussed by Kamide et al. (1998). According to the facts above, this great geomagnetic storm was mostly caused by the intense southward IMF in the MC, and the field draping in the sheath contributed to the early portion. Wu and Lepping (2002) also discussed the two-step storms caused by cloud complexes and gave the conditions which were required for a two-step storm: (1) The two dips in D_{st} must be separated by more than 3 h, and the value of the earlier DST dip must be less than -30 nT, (2) the later dip of D_{st} must be greater than the earlier one, (3) there must be no storm sudden commencement (SSC) or sudden impulse (SI) between the two dips of D_{st}. This case was consistent with all the conditions that mentioned by Wu and Lepping (2002).

2.4. The September 17, 2000 event

Fig. 4 shows ACE observations of this event at 1 AU. Burlaga et al. (2001) pointed out four successive halo CMEs, which happened at 1150 UT, 1506 UT, 2150 UT on September 15 and 0526 UT on September 16, and whose projected speeds were 377, 467, 370, 692 km/s, respectively. They formed a single fast transient stream with one maximum velocity (see the part between two dashed lines) and the characteristics of a relatively low temperature, low proton $\beta(\leqslant 0.1)$, and a high ratio of $N_\alpha/N_p(>0.05)$. The front boundary of the complex ejecta began at about 2300 UT on September 17, with a corresponding maximum speed of ~ 883 km/s, and declined nearly monotonically to a minimum at mid-day of September 21 (this also agreed with Cane and Richardson, 2003), approximately four days later. The passage of time of this stream was approximately four

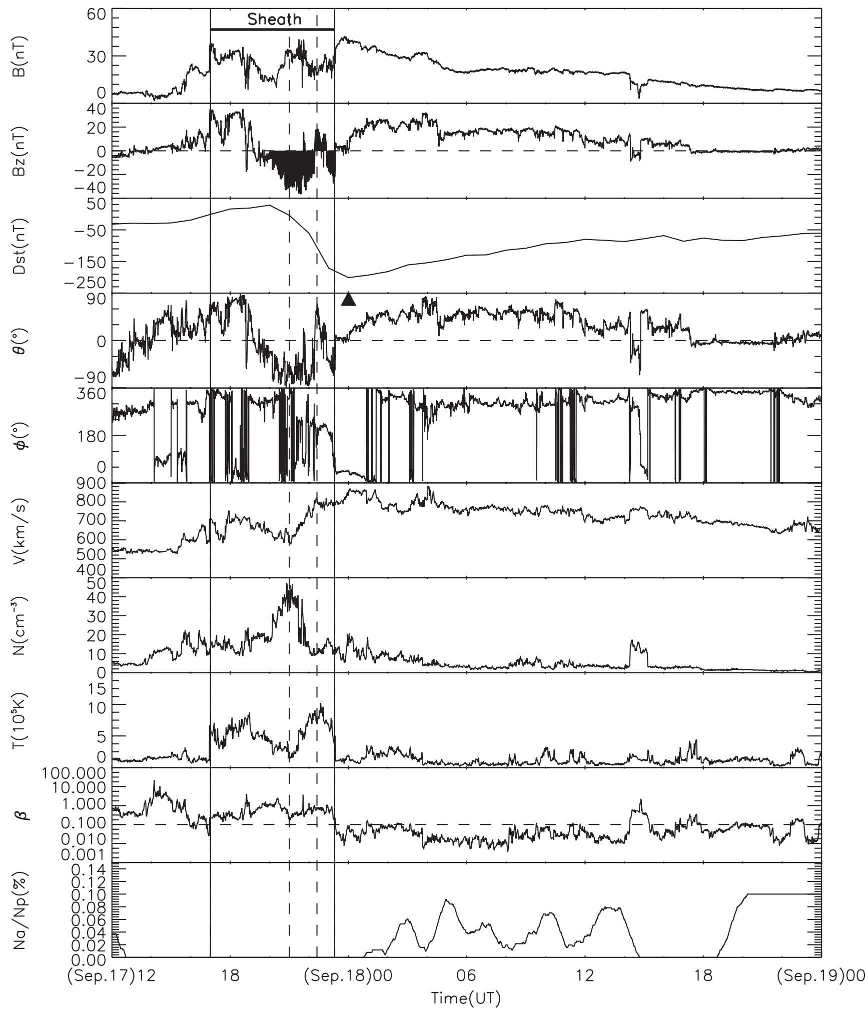

Fig. 4. Observations by the ACE spacecraft from 1200 UT September 17 to 18, 2000 (in GSM). The region of the large speed gradient is marked by the two dashed lines.

times that of a typical MC, which indicated the complexity of the interactions between the successive halo CMEs. However, the front part of this complex ejecta on September 18 contained a magnetic cloud-like structure (which is listed in the MC list of Wind MFI website http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html) with low proton temperature and a low proton β value.

From the D_{st} curve on Fig. 4, the great geomagnetic storm began at 2000 UT on September 17, and D_{st} minimum (-201 nT) arrived at 2400 UT. The IMF associated with the event turned to south at 1900 UT on September 17 and the peak value of B_s(36.58 nT) occurred at 2130 UT. The duration of $VB_s \geqslant 0.5$ mV/m was about 3.4 h, which caused the great geomagnetic storm.

The shock arrived at 1656 UT on September 17 and is indicated by the first vertical solid line in Fig. 4. The intense southward IMF mentioned above was located in the sheath of the shock. Comparing the curve of B_z with the speed profile, one can find that the intense southward magnetic field was associated with the large speed gradient (marked by the two dashed lines) which indicated the compressive mechanism. Because of the relatively high speed of the background solar wind ($\sim$ 550 km/s), the shock with the compressional ratio of $B_d/B_u = 1.38$ was not strong; thus, the speed after the shock was only approximately 700 km/s a little higher than the background solar wind, and then dropped down gradually. The complex ejecta formed by the four halo CMEs had the very high speed ($\sim$ 880 km/s). As a result of this interaction between the high speed complex ejecta and the relative slow speed background stream, from 2100 UT to 2224 UT on September 17 (as denoted by the two vertical dashed line in Fig. 4), the speed in the sheath increased from 579 to 825 km/s abruptly and caused a large speed gradient. Thus, the high speed transient stream compressed the preexisting southward B_s interval and formed the intense southward IMF. Here, we call the cause of this B_s event a compressive mechanism between the high speed transient stream and the upstream solar wind.

2.5. The March 31, 2001 event

Fig. 5 shows ACE observations of this event at 1 AU.

The D_{st} curve of this storm also showed a double-peak structure. The main phase of a great geomagnetic storm began at 0500 UT on March 31 and the D_{st} minimal value of −387 nT occurred at 0900 UT. Thereafter, the D_{st} began to recover gradually. However, it decreased again at 1800 UT and another minimal value of −284 nT occurred at 2200 UT.

The interplanetary cause of this great geomagnetic storm has been discussed by Wang et al. (2003a) in their research of multiple magnetic clouds (multi-MCs), so we simply summarize it here.

They have concluded that this event was due to the southward IMF in each sub-cloud made intense by the compressive interactions of a double-MCs. The first MC was observed from 0505 to 1015 UT on March 31. The maximum magnetic field strength B_{max} was 49.1 nT and the southward component B_s reached 47.9 nT. The density ratio N_α/N_p was about 0.1 and proton β was around 0.074. The duration of $VB_s \geqslant 0.5$ mV/m was nearly 3.4 h. It was responsible for the first minimum in the D_{st} curve (−387 nT). During 1235–2140 UT, the spacecraft passed through the second MC. Within MC2, proton $\beta \sim 0.075$, $N_\alpha/N_p \sim 0.1$, B_{max}, $B_{s_{max}}$ and duration of $VB_s \geqslant 0.5$ mV/m were 41.4 nT, 36.8 nT and 5.8 h, respectively. This MC produced the second D_{st} peak value of −284 nT.

Berdichevsky et al. (2003), who also studied this event, considered that the fast halo CME on March 29 (listed in Table 2) overtook the preceding slow one at 1250 UT on March 28 (also listed in Table 2), and formed interplanetary shocks S_I at 2330 UT on March 30 and S_{II} at 0111 UT on March 31, as well as two distinct regions of very strong magnetic fields of low variance separated by a narrower region where the field was weak and proton β was high. This point of view is consistent with ours.

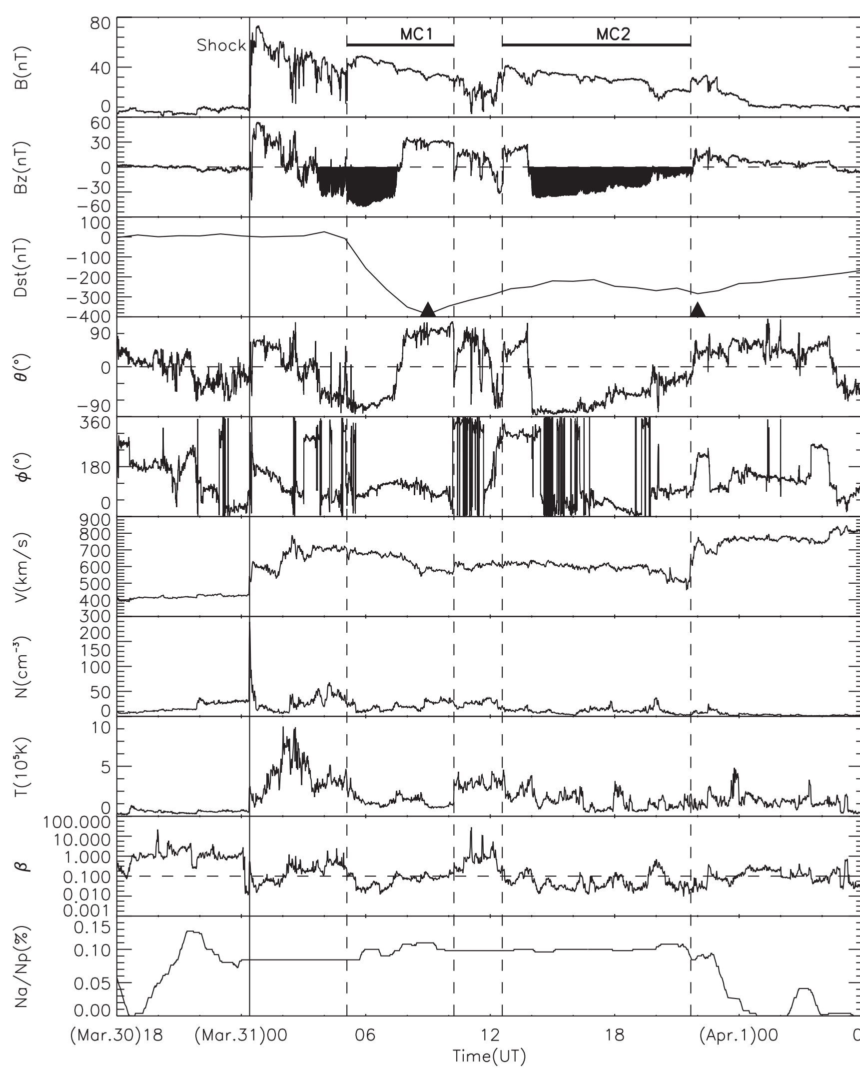

Fig. 5. Observations by the ACE spacecraft from 1800 UT March 30 to 31, 2001 (in GSM).

2.6. The April 11, 2001 event

Fig. 6 shows ACE observations of this event at 1 AU. Wang et al. (2003a) has concluded that the interplanetary structure of this event was also multi-MC (shown in Fig. 6). The first cloud (MC1) was observed from 2215 UT on April 11 to 0355 UT on April 12, and the second cloud (MC2) was observed from 0855 UT on April 12 to 0705 UT on April 13. The z-component of the magnetic field in MC2 was nearly northward, so there was no geomagnetic storm following the MC2.

From the D_{st} curve, the main phase of a great geomagnetic storm began at 1600 UT on April 11 and D_{st} minimal value of -271 nT occurred at 2400 UT on that day. The southward magnetic field associated with it consisted of three parts (Fig. 6): (1) the shock compressed turbulence beginning at 1600 UT on April 11 (2) the field draping structure beginning at 1943 UT (noted by the first dashed line) and (3) the intense southward field structure near the leading portion of MC1 which began at 2210 UT.

The Shock arrived at about 1300 UT on April 11. The z-component of the magnetic field after the shock showed long-period ~ 6 h oscillations and was only ~ -6 nT on average, this was probably due to turbulence, waves or discontinuities (Tsurutani et al., 1988). During this interval the D_{st} curve had dropped starting from 1600 UT and formed a minimum about -105 nT. As we know, the draping structures were due to the high speeds of ejecta as shown in the speed profile. The speed of fast ejecta reached up to about 760, 280 km/s higher than the ambient solar wind speed. On the one hand, the fast ejecta with so large a speed difference caused the field line draping by the stream interaction with the ambient solar wind plasma, which made the intense southward field component in the sheath with the maximum $B_s = 30.5$ nT. On the other hand, the fast multi-MC interacting with the ambient

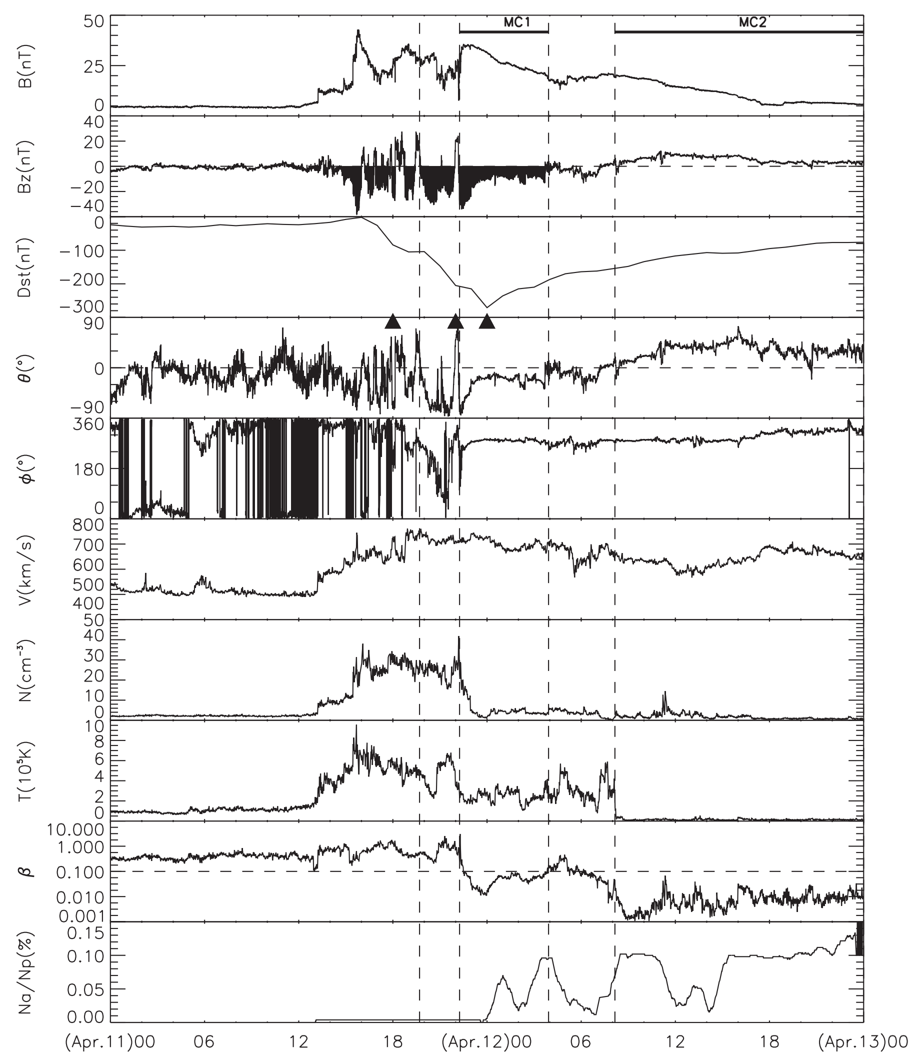

Fig. 6. Observations by the ACE spacecraft from April 11 to 12, 2001 (in GSM). The first dashed line indicates the start of the draping field.

solar wind and the resulting compressed sub-clouds also led to substantial compression of the leading portion of the MC1, which made the southward field component in the leading portion of MC1 so intense, i.e., the maximum $B_s = 34.1\,\mathrm{nT}$, and similarly for the relatively higher density and temperature. The field draping in the sheath together with the compressed intense southward field in MC1 caused the D_{st} curve to drop further and reach a minimum value of $-271\,\mathrm{nT}$.

In summary, the great geomagnetic storm was a triple-step storm and the causes of this event were: (1) 5.9 h duration of $VB_s \geqslant 0.5\,\mathrm{mV/m}$, (2) shock compression together with the field draping in the sheath, and (3) the intense southward field within Multi-MCs.

2.7. The November 6, 2001 event

Fig. 7 shows ACE observations of this event at 1 AU. D_{st} dropped at about 2000 UT on November 5. Several hours later, D_{st} changed slowly. At 0300 UT on November 6, D_{st} dropped again suddenly, and the D_{st} minimal value ($-292\,\mathrm{nT}$) was reached at 0700 UT.

Wang et al. (2003b) have also analyzed this event, and concluded that it was the result of a fast forward shock overtaking a preceding magnetic-cloud-like structure and compressing the precursor southward field. The preceding MC-like structure began at 1930 UT on November 5 and can be identified by: the rotation of field component in θ direction, low proton temperature ($\sim 0.14 \times 10^5\,\mathrm{K}$), and low proton β value (~ 0.1). The magnetic field component B_z in this structure was southward, and it caused the D_{st} to decline at 2100 UT on November 5. The overtaking shock was observed at 0124 UT on November 6. The rear part of this structure, lasting about 5 h, overlapped the compressed region of the shock, which caused the southward field B_s to increase sharply. At the shock arrival, the magnetic field strength B increased

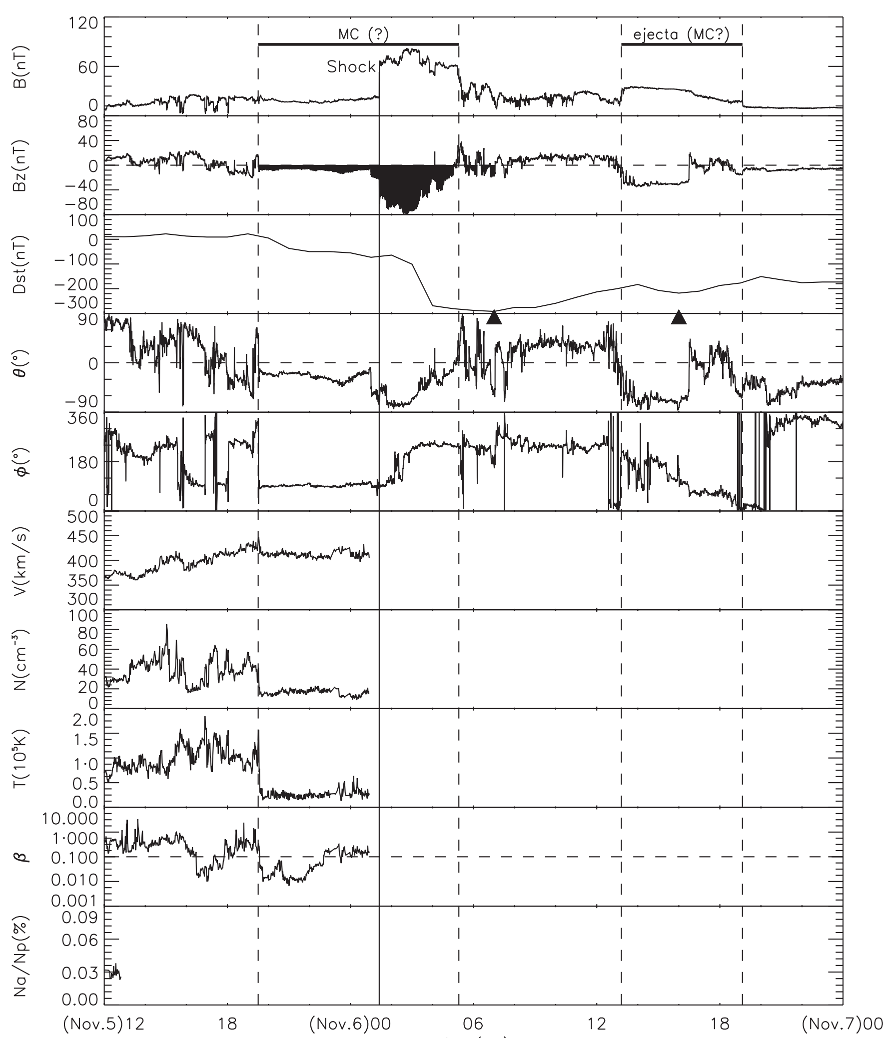

Fig. 7. Observations by the ACE spacecraft from 1200 UT November 5 to 6, 2001 (in GSM).

from 24 to 62 nT suddenly, and the southward field B_s jumped from 22.3 to 55.8 nT, correspondingly. The maximum value of the magnetic field was 82 nT and the southward component $B_{s\max}$ was 81 nT, thus the magnetic field was directed almost totally southward. With the compression of the overtaking shock, the field component $B_s \geqslant 10$ nT lasted about 5.4 h (because of solar wind speed data gap, we cannot calculate the duration of $VB_s \geqslant 0.5$ mV/m), and the great geomagnetic storm formed.

We should note that the D_{st} dropped again and formed a minor minimum of −176 nT at 1600 UT on November 6. So this geomagnetic storm had a double-phase structure, too. The cause of the minor D_{st} minimum due to the ejecta from 1312 to 1906 UT on November 6 which also looks like a MC structure.

2.8. The November 24, 2001 event

The great geomagnetic storm began at 0800 UT on November 24. At 0900 UT a minor minimum of $D_{st}(-92\,\mathrm{nT})$ occurred, then at 1300 UT another minimum of $D_{st}(-196\,\mathrm{nT})$ occurred, and the main minimum of $D_{st}(-221\,\mathrm{nT})$ occurred at 1700 UT. Evidently, this storm was a triple-step storm.

Fig. 8 shows the WIND spacecraft observation of the event on November 24, 2001, ACE data could not be used because of a data gap during this period. A strong shock arrived at 0554 UT on November 24. Because the fluctuations of field component B_z ahead of the shock and the B_z was nearly zero, the shock compression was not intense enough to cause a magnetic storm. It only triggered the decline of the D_{st} and formed the minor minimum of $D_{st}(-92\,\mathrm{nT})$. MC began at 1330 UT on

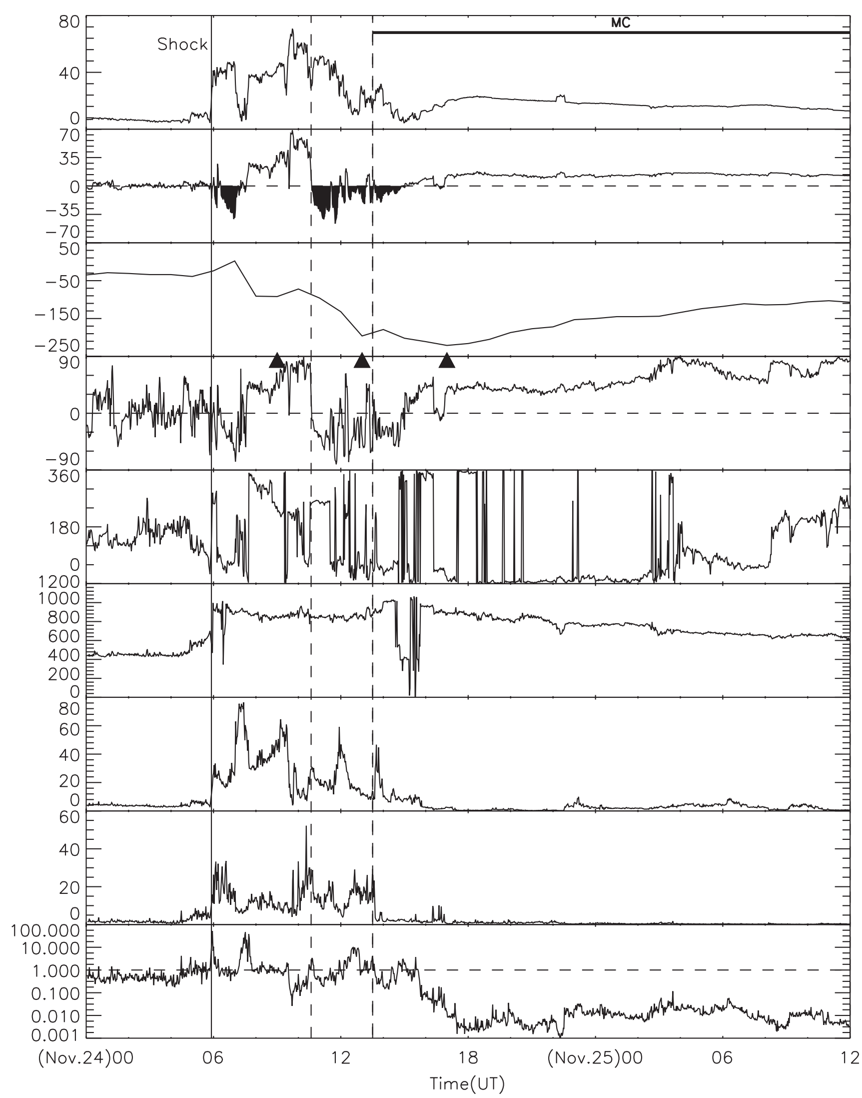

Fig. 8. Observations by the ACE spacecraft from November 24 to 1200 UT November 25, 2001 (in GSM). The first dashed line indicates the start of the draping field.

November 24 with the identifications: the enhanced magnetic field strength, the rotation of field vector in the ϕ direction, low temperature ($\sim 1.2 \times 10^5$ K), a low proton β value (~ 0.006), high density ratio of N_α/N_p (~ 0.08).

Field draping in the sheath between the shock and the MC began at 1036 UT (noted by the first dashed line in Fig. 8) on November 24, it caused the maximum value of B_s to reach 46.4 nT. The intense field in the sheath caused the D_{st} to drop down and reach the minimal value of -196 nT. We should also notice that the field in the front of the MC was southward with the maximum $B_s \leqslant 18$ nT (and it turned to northward quickly). This southward field might have contributed to the great geomagnetic storm; it made the D_{st} drop further and reach a value of -221 nT.

Summarily, the duration of $VB_s \geqslant 0.5$ mV/m was about 3.9 h and three parts of the interplanetary structure contribute to this great geomagnetic storm: the compression of the shock, the field draping, and the southward magnetic field within MC.

3. Discussion

The total of eight great geomagnetic storms with $D_{st} \leqslant -200$ nT in solar maximum (2000–2001) are studied as well as their interplanetary causes. The interplanetary parameters and the causes of the eight storms are summarized in Table 1. Obviously, the fundamental interplanetary origins of the great geomagnetic storms are strong B_s intervals. According to the above analyses, these intense southward magnetic field B_s intervals exist within two regions. One is located within the sheath between the shock and the ejecta, and another is within the ejecta itself. It should be noted that the ejecta carrying strong B_s interval are all magnetic clouds in these cases: April 7, 2000 event, August 12, 2000 event, and March 31, 2001 event. So, MC can play a very important role in causing great magnetic storm.

We should notice that the intense B_s was involved in the compression mechanism of the original southward fields in all cases, except the July 16, 2000 event and the August 12, 2000 event which were caused by the intense magnetic field within MCs. The compressive mechanism includes: (1) the compression between ICMEs, e.g., Multi-MCs, and the forward shock overtaking precede MC, (2) the compression between ICMEs and the interplanetary medium, e.g., shock compression, high speed stream's compression and the field draping.

We also examine the possible corresponding halo CMEs in each of these cases, the results including the eruption times, the locations, the linear fit speeds, and the active regions of these halo CMEs, all of which, are summarized in Table 2.

From Table 2, it should be noted that four of the eight great geomagnetic storms were associated with successive halo CMEs and all involved the compression mechanism (1) and (2) mentioned above, that is, the event of September 17, 2000, March 31, 2001, April 11, 2001 and November 6, 2001. We can see that these four events were related to multiple solar sources. Successive CMEs with different speeds may overtake, interact and intermingle with each other as they propagate in interplanetary medium. As the merging process is nonlinear, the results (that is, the types of complex structures) of their interactions may be different, such as, multi-MCs, the forward shock overtaking the MC, the large speed gradient caused by flow interaction, and so on. It is important to note that, if the subsequent ICME and its driving shock have higher speed than previous ones, they might bring higher kinematic

Table 1
The interplanetary parameters and the causes of eight great geomagnetic storms

Date	V (km/s)[a]	$B_{s_{max}}$ (nT)[c]	$\overline{VB}_s$ (mV/m)	Δt (h)[b]	$D_{st_{min}}$ (nT)	IP Causes
April 7, 2000	636 (sheath)	33.3	13.299	7.299	−288	SC[d]
July 16, 2000	Data gap	59.5	–	–	−301	MC
August 12, 2000	722	29.9	13.276	7.949	−235	SC, MC
September 17, 2000	883	36.6	13.113	2.549	−201	High speed stream compression
		47.9	23.506	3.400	−387	
March 31, 2001	844					Multi-MCs
		36.8	16.871	5.799	−284	
April 11, 2001	761	34.1	11.387	7.050	−271	SC, Draping and Multi-MCs
November 6, 2001	Data gap	78.9	–	–	−292	Shock overtaking upstream MC
November 24, 2001	1065	46.4	11.914	3.900	−221	SC, draping and MC

–data gap of solar wind speed V during Δt.

[a]The maximum speed of ICME, the event of April 7, 2000 has no evident main body, so V is the maximum speed in the sheath.

[b]Δt means the duration of $\overline{VB}_s > 0.5$ mV/m.

[c]The maximum value of southward magnetic field during the time interval of Δt.

[d]Shock compression.

Table 2
The possible solar regions relative to the geomagnetic storms

Geomagnetic events	Solar region				
	Day	Time (UT)	Source	Speed (km/s)	AR[a]
April 7, 2000	0404	1632	N16W60	1188	8933
July 16, 2000	0714	1054	N17W02	1674	9077
August 12, 2000	0809	1630	N20E12	702	9114
September 17, 2000[b]	0915	1206	N14E07	377	9165
	0915	1526	N14E05	467	9165
	0915	2150	N14E01	370	9165
	0916	0518	N14W02	692	9165
March 31, 2001	0328	0127	N20E22?	427	9401?
	0328	1250	N15E04	519	9393
	0329	1026	N15W12	942	9393
April 11, 2001	0409	1554	S20W05	1192	9415
	0410	0530	S25W10	2411	9415
November 6, 2001	1101	2230	N11W21	1053	9682
	1104	1635	data gap	1810	9684
November 24, 2001	1122	2330	S12W35	1437	9704

[a]Solar Active Region, obtained from the flare reports.
[b]Burlaga et al. (2001).

pressure, and then the fields in the leading ICME or its sheath could be compressed forming an intensification of B_s (if the magnetic fields in the previous ICME or its sheath were southward). This effect would contribute to a further increase in the associated storm intensity. Therefore, the geo-effects due to the interactions of successive CMEs during solar maximum will be more notable, and a more intense geomagnetic storm could be expected.

We also should note that most successive CMEs which caused the great magnetic storms originated from the same solar active regions. We can imagine that when a frequently eruptible active region rotates near the center of the solar disk, its successive ejections (CMEs) could cause the more intense geomagnetic effect through their interactions, and it may give us a possible way for predicting the geomagnetic storms by observations of the changes within active regions during solar maximum.

As mentioned in the Introduction, high speed streams from coronal holes dominate the interplanetary medium during solar minimum. They can cause the great geomagnetic storms too. For example, considering the October 22, 1999 (-237 nT) event shown in Fig. 9. At the forward shock located at 0215 UT on October 21, marked by the first solid line in Fig. 9, the jumps in plasma parameters T_p, N_p, V and B were not very large, indicating a weak event. It was driven by slow speed ejecta ($V \sim 490$ km/s) and lasted from 0800 UT on October 21 to about 0700 UT on October 22 (Cane and Richardson, 2003) and carried southward field at the rear part. On the other hand, note that after 0648 UT on October 22, the velocity maintained a high value ~ 660 km/s, the density dropped to 3.8 cm^{-3} lower than the origin value of density, the temperature rose and the velocity V_y changed its direction just at that moment; these were the typical characteristics of a high speed stream and the interface (IF) (IF was marked by the second solid line in Fig. 9). Southward field between the ejecta and the high-speed stream increased evidently with average value ~ 27.6 nT and was responsible for this great geomagnetic storm. It suggested that high-speed stream is interacting with the slower ejecta, compressing the rear part of the ejecta and leading to the formation of a CIR behind the slow ejecta. Thus, the great storm was due to the compression of the southward field within the ejecta by the interaction with the corotating high speed stream. It is obvious that the great geomagnetic storms were also associated with the compression mechanism.

The result that most of geomagnetic storms (6/8) were caused by the intense compressed B_s illuminates that compressed B_s interval has more geoeffectiveness. Wang et al. (2003c) have studied the relationship between the $D_{st_{min}}$ and the interplanetary parameters Δt (the duration of $\overline{VB}_s > 0.5$ mV/m) and $-\overline{VB}_z$ through 105 geomagnetic storms with $D_{st} \leqslant -50$ nT during 1998–2001 and found a simple empirical formula which suggests that $-VB_z$ is much more important than Δt. Here we follow their work to study the relationship between $D_{st_{min}}$, Δt and $-\overline{VB}_z$ for the great geomagnetic storms. Fig. 10a, b shows the scatter plots of the $D_{st_{min}}$ versus Δt, $-\overline{VB}_z$, for six great geomagnetic storms listed in Table 1 (the other two were excluded due to data gaps). Obviously, there is a non-linear relation between the Δt and $D_{st_{min}}$. On the other hand, a relatively better relation between the $-\overline{VB}_z$ and $D_{st_{min}}$ is given in Fig. 10b.

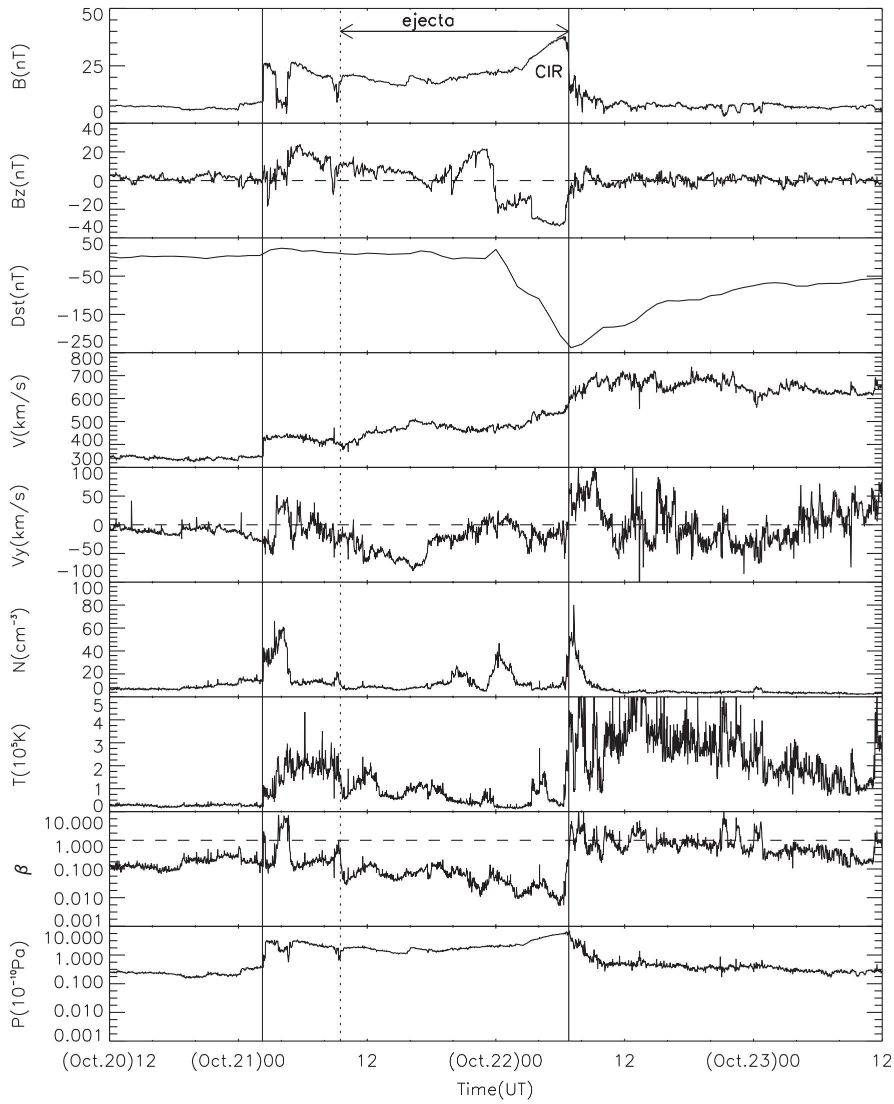

Fig. 9. Observations by the WIND spacecraft from 1200 UT October 20 to 1200 UT October 23, 1999 (in GSM).

Further, $\phi = \overline{VB}_s\Delta t$ is considered the magnetic flux per unit length transferred from the interplanetary medium into the inner magnetosphere. Assuming the magnetic flux ϕ is conserved by a frozen field, the Δt will shorten correspondingly while $-\overline{VB}_z$ is enhanced due to the compression. If the $-\overline{VB}_z$ and the duration of Δt change inversely, the geoeffectiveness should be invariant. However, from Fig. 10c the linear correlation ($CC = 0.4392$) between $-\overline{VB}_z\Delta t$ is weak. This might suggest that the weights of $-\overline{VB}_z$ and Δt should be different. Using the variable $(-\overline{VB}_z)^\alpha(\Delta t)^\beta$ to fit the D_{st} data, we get $\alpha = 2.51$, $\beta = 0.75$ and a minimum correlation coefficient of 0.9242 as shown in Fig. 10d. It implies that B_s may be more geoeffective than its duration Δt.

Wang et al. (2003c) gave an empirical formula statistically for $D_{st} \leqslant -50\,\mathrm{nT}$ as

$$D_{st_{min}} = -19.01 - 8.43(-\overline{VB}_z)^{1.09}(\Delta t)^{0.30}\,\mathrm{nT}. \quad (1)$$

They also gave another empirical relationship for 35 large storms with $D_{st} \leqslant -100\,\mathrm{nT}$

$$D_{st_{min}} = -66.31 - 3.21(-\overline{VB}_z)^{1.35}(\Delta t)^{0.33}\,\mathrm{nT}. \quad (2)$$

Our result is consistent with theirs. Note the change of the exponents of $-\overline{VB}_z$ and Δt in three linear fittings for different levels of $D_{st_{min}}$, we can find that the weight of $-\overline{VB}_z$ relative to Δt will increase, while the storm's intensity becomes larger. This may suggest that the compression mechanism is more geoeffective, and that the intense B_s rather than its duration is the main factor causing the great geomagnetic storms.

Summarily, the interplanetary origins of the eight great storms were various. Obviously, the frequent occurrence of coronal mass ejections during solar maximum plays an important role. Most great geomagnetic storms ($>60\%$) during solar maximum 2000–2001 were due to interactions between ICMEs. This might cause the predictions of great geomagnetic storms to be

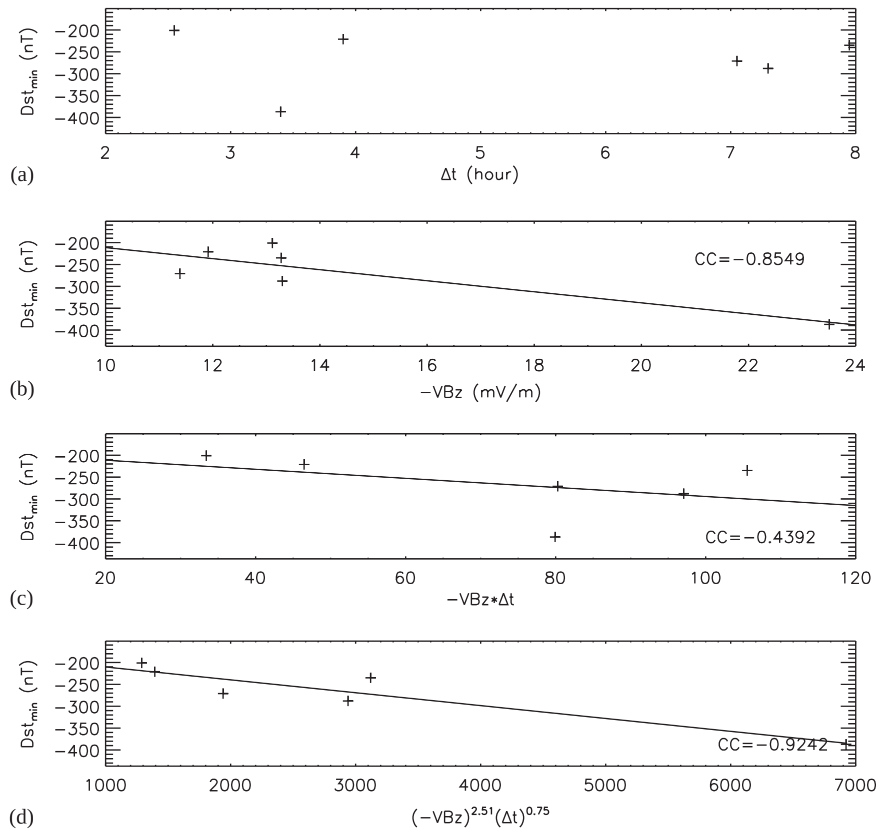

Fig. 10. The scatter plots of $D_{st_{min}}$ versus Δt (the duration of $\overline{VB}_s > 0.5\,\text{mV/m}$), $-\overline{VB}_z$, $-\overline{VB}_z\Delta t$ and $(-\overline{VB}_z)^{2.51}(\Delta t)^{0.75}$ for six cases listed in Table 1 (which have no data gaps). The solid lines are the linear fitting curves.

more complicated and difficult. Studying the solar origins, activities, and the processes of ICMEs' interactions will be essential and helpful.

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