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

X.H. Xue*, Yuming Wang, P.Z. Ye, S. Wang, M. Xiong

School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui Province 230026, China

Received 28 October 2003; received in revised form 1 June 2004; accepted 19 October 2004

Abstract

In this paper, we analyze the interplanetary causes of eight great geomagnetic storms ($D_{st} \leq -200 \text{nT}$) 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 $(-V_B \Delta \tau)^{\alpha}$ gives the weights of $-V_B$ and $\Delta \tau$ 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 $D_{st} \leq -100 \text{nT}$ 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
Great magnetic storms ($D_a \leq -200 \text{nT}$) 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 ($-288 \text{nT}$), July 16, 2000 ($-301 \text{nT}$), August 12, 2000 ($-235 \text{nT}$), September 17, 2000 ($-201 \text{nT}$), March 31, 2001 ($-387, -284 \text{nT}$), April 11, 2001 ($-271 \text{nT}$), November 6, 2001 ($-292 \text{nT}$), November 24, 2001 ($-221 \text{nT}$), according to the $D_a$ 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 $D_a$ curve, the peak value of the great geomagnetic storm was $-288 \text{nT}$ 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 $VB_s \geq 0.5 \text{mV/m}$ (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 $B_d/B_s = 2.9$ ($B_d$ is the downstream magnetic field strength and $B_s$ is the upstream magnetic field strength); it suggested that the shock was strong. At the rear part of this $B_s$ interval, $D_a$ reached a minimal value. Besides, before the shock, the $z$-component of the interplanetary magnetic field was almost southward and the average value was $-3.5 \text{nT}$ for a large duration ($\sim 16 \text{h}$). 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 $\beta$ 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 ($\sim 5 \text{nT}$) 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.
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 $\beta$. Generally, $T_p$ decreases suddenly at the front boundary and continues at a low value throughout the cloud and proton $\beta$ also drops to $\approx 0.1$ at the front boundary correspondingly (Burlaga et al., 1981, 2001). Then $T_p$ and proton $\beta$ 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 $\beta$ 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 defined.

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...
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 $\geq 1100$ km/s during this period (Lepping et al., 2001), and the magnetic field magnitude increased to a maximum value of $\sim 60$ 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 ($\pm 235$ 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 $\theta$ direction, low proton temperatures ($\sim 0.2 \times 10^5$ K), low proton $\beta$ value ($\sim 0.005$), and a relatively high $N_s/N_p$ value ($> 0.08$). The maximum value of southward IMF in MC was 29.9 nT, and the duration of $VB_s \geq 0.5$ 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.
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 $\beta_p < 0.1$, and a high ratio of $N_{\text{He}}/N_p (> 0.05)$. The front boundary of the complex ejecta began at about 2300 UT on September 17, with a corresponding maximum speed of $\sim 883$ km/s, and declined nearly monotonically to a minimum at midday 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
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 $\beta$ value.

From the $D_{st}$ curve on Fig. 4, the great geomagnetic storm began at 2000 UT on September 17, and $D_{st}$ minimum ($\sim$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 $VB_s \geq 0.5$ 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 $B_s$ 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 $B_s/B_0 = 1.38$ 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 $-387 \text{nT}$ occurred at 0900 UT. Thereafter, the $D_{st}$ began to recover gradually. However, it decreased again at 1800 UT and another minimal value of $-284 \text{nT}$ 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 $B_{\text{max}}$ was 49.1 nT and the southward component $B_s$ reached 47.9 nT. The density ratio $N_a/N_p$ was about 0.1 and proton $\beta$ was around 0.074. The duration of $VB_s \geq 0.5 \text{mV/m}$ was nearly 3.4 h. It was responsible for the first minimum in the $D_{st}$ curve $(-387 \text{nT})$. During 1235–2140 UT, the spacecraft passed through the second MC. Within MC2, proton $\beta \sim 0.075$, $N_a/N_p \sim 0.1$, $B_{\text{max}}$, $B_{\text{smax}}$ and duration of $VB_s \geq 0.5 \text{mV/m}$ were 41.4 nT, 36.8 nT and 5.8 h, respectively. This MC produced the second $D_{st}$ peak value of $-284 \text{nT}$.

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 $\beta$ 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).](image-url)
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 solar wind plasma made the field line draping.
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 $B_s = 34.1 \text{nT}$, 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 $D_s$ curve to drop further and reach a minimum value of $-271 \text{nT}$.

In summary, the great geomagnetic storm was a triple-step storm and the causes of this event were: (1) 5.9h duration of $V B_s \geq 0.5 \text{mV/m}$, (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 1AU. $D_s$ dropped at about 2000 UT on November 5. Several hours later, $D_s$ changed slowly. At 0300 UT on November 6, $D_s$ dropped again suddenly, and the $D_s$ minimal value ($-292 \text{nT}$) 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 $\theta$ direction, low proton temperature ($\sim 0.14 \times 10^5 \text{K}$), and low proton $\beta$ value ($\sim 0.1$). The magnetic field component $B_z$ in this structure was southward, and it caused the $D_s$ 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 5h, 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...
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 $B_{s\text{max}}$ was 81 nT, thus the magnetic field was directed almost totally southward. With the compression of the overtaking shock, the field component $B_s \geq 10$ nT lasted about 5.4 h (because of solar wind speed data gap, we cannot calculate the duration of $VB_s \geq 0.5$ 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 $D_{st}(-92$ nT) occurred, then at 1300 UT another minimum of $D_{st}(-196$ nT) occurred, and the main minimum of $D_{st}(-221$ 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 $D_{st}(-92$ 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.](image)
November 24 with the identifications: the enhanced magnetic field strength, the rotation of field vector in the \( \phi \) direction, low temperature (\( \sim 1.2 \times 10^4 \) K), a low proton \( \beta \) value (\( \sim 0.006 \)), high density ratio of \( N_e/N_p \) (\( \sim 0.08 \)).

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 \( B_s \leq 18 \) 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 \( V B_s > 0.5 \text{mV/m} \) 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 \( D_{st} \leq -200 \) 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

<table>
<thead>
<tr>
<th>Date</th>
<th>( V ) (km/s)(^a)</th>
<th>( B_{max} ) (nT)(^c)</th>
<th>( V B_s ) (mV/m)</th>
<th>( \Delta t ) (h)(^b)</th>
<th>( D_{min} ) (nT)</th>
<th>IP Causes</th>
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<tr>
<td>April 7, 2000</td>
<td>636 (sheath)</td>
<td>33.3</td>
<td>13.299</td>
<td>7.299</td>
<td>-288</td>
<td>SC(^d)</td>
</tr>
<tr>
<td>June 12, 2000</td>
<td>Data gap</td>
<td>59.5</td>
<td>7.949</td>
<td>-301</td>
<td>MC</td>
<td></td>
</tr>
<tr>
<td>August 12, 2000</td>
<td>722</td>
<td>29.9</td>
<td>13.276</td>
<td>2.549</td>
<td>-201</td>
<td>SC, MC</td>
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<tr>
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<td>36.6</td>
<td>13.113</td>
<td>3.400</td>
<td>-387</td>
<td>High speed compression</td>
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<tr>
<td>March 31, 2001</td>
<td>844</td>
<td>47.9</td>
<td>23.506</td>
<td></td>
<td>Multi-MCs</td>
<td></td>
</tr>
<tr>
<td>April 11, 2001</td>
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<td>36.8</td>
<td>16.871</td>
<td>5.799</td>
<td>-284</td>
<td>SC, Draping and Multi-MCs</td>
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<tr>
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<td>7.050</td>
<td>-271</td>
<td>SC, Draping and Multi-MCs</td>
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<td>11.914</td>
<td>3.900</td>
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\(^a\) data gap of solar wind speed \( V \) during \( \Delta t \).

\(^b\) \( \Delta t \) means the duration of \( V B_s > 0.5 \text{mV/m} \).

\(^c\) The maximum value of southward magnetic field during the time interval of \( \Delta t \).

\(^d\) Shock compression.
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 ($V \sim 490 \text{ km/s}$) 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 $\sim 660 \text{ km/s}$, the density dropped to $3.8 \text{ cm}^{-3}$ lower than the origin value of density, the temperature rose and the velocity $V_s$ 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 $\sim 27.6 \text{ nT}$ 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 $\Delta t_{\text{min}}$ and the interplanetary parameters $\Delta t$ (the duration of $\nabla B_s > 0.5 \text{ mV/m}$) and $-\nabla B_z$ through 105 geomagnetic storms with $\Delta t \leq \sim 50 \text{ nT}$ during 1998–2001 and found a simple empirical formula which suggests that $-\nabla B_z$ is much more important than $\Delta t$. Here we follow their work to study the relationship between $\Delta t_{\text{min}}$, $\Delta t$ and $-\nabla B_z$ for the great geomagnetic storms. Fig. 10a, b shows the scatter plots of the $\Delta t_{\text{min}}$, $\Delta t$ versus $\nabla B_z$, 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 $\Delta t$ and $\Delta t_{\text{min}}$. On the other hand, a relatively better relation between the $-\nabla B_z$ and $\Delta t_{\text{min}}$ is given in Fig. 10b.

**Table 2**

The possible solar regions relative to the geomagnetic storms

<table>
<thead>
<tr>
<th>Geomagnetic events</th>
<th>Solar region</th>
<th>Day</th>
<th>Time (UT)</th>
<th>Source</th>
<th>Speed (km/s)</th>
<th>AR$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 7, 2000</td>
<td>N16W60</td>
<td>0404</td>
<td>1632</td>
<td>N16W60</td>
<td>1188</td>
<td>8933</td>
</tr>
<tr>
<td>July 16, 2000</td>
<td>N17W02</td>
<td>0714</td>
<td>1054</td>
<td>N17W02</td>
<td>1674</td>
<td>9077</td>
</tr>
<tr>
<td>August 12, 2000</td>
<td>N20E12</td>
<td>0809</td>
<td>1630</td>
<td>N20E12</td>
<td>702</td>
<td>9114</td>
</tr>
<tr>
<td>September 17, 2000b</td>
<td>N14E07</td>
<td>0915</td>
<td>1206</td>
<td>N14E07</td>
<td>377</td>
<td>9165</td>
</tr>
<tr>
<td></td>
<td>N14E05</td>
<td>0915</td>
<td>1526</td>
<td>N14E05</td>
<td>467</td>
<td>9165</td>
</tr>
<tr>
<td></td>
<td>N14E01</td>
<td>0915</td>
<td>2150</td>
<td>N14E01</td>
<td>370</td>
<td>9165</td>
</tr>
<tr>
<td></td>
<td>N14W02</td>
<td>0916</td>
<td>0518</td>
<td>N14W02</td>
<td>692</td>
<td>9165</td>
</tr>
<tr>
<td>March 31, 2001</td>
<td>N20E12</td>
<td>0328</td>
<td>0127</td>
<td>N20E12</td>
<td>427</td>
<td>9401?</td>
</tr>
<tr>
<td>April 11, 2001</td>
<td>N15E04</td>
<td>0328</td>
<td>1250</td>
<td>N15E04</td>
<td>519</td>
<td>9393</td>
</tr>
<tr>
<td>November 6, 2001</td>
<td>N15W12</td>
<td>0329</td>
<td>1026</td>
<td>N15W12</td>
<td>942</td>
<td>9393</td>
</tr>
<tr>
<td>November 24, 2001</td>
<td>S20W05</td>
<td>0409</td>
<td>1554</td>
<td>S20W05</td>
<td>1192</td>
<td>9415</td>
</tr>
<tr>
<td></td>
<td>S25W10</td>
<td>0410</td>
<td>0530</td>
<td>S25W10</td>
<td>2411</td>
<td>9415</td>
</tr>
<tr>
<td></td>
<td>N11W21</td>
<td>1101</td>
<td>2230</td>
<td>N11W21</td>
<td>1053</td>
<td>9682</td>
</tr>
<tr>
<td></td>
<td>N14W12</td>
<td>1104</td>
<td>1635</td>
<td>data gap</td>
<td>1810</td>
<td>9684</td>
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<tr>
<td></td>
<td>S12W35</td>
<td>1122</td>
<td>2330</td>
<td>S12W35</td>
<td>1437</td>
<td>9704</td>
</tr>
</tbody>
</table>

$^a$Solar Active Region, obtained from the flare reports.

$^b$Burlaga et al. (2001).
Further, \( \phi = \nabla B_\lambda \Delta t \) is considered the magnetic flux per unit length transferred from the interplanetary medium into the inner magnetosphere. Assuming the magnetic flux \( \phi \) is conserved by a frozen field, the \( \Delta t \) will shorten correspondingly while \( -\nabla B_\lambda \) is enhanced due to the compression. If the \( -\nabla B_\lambda \) and the duration of \( \Delta t \) change inversely, the geoeffectiveness should be invariant. However, from Fig. 10c the linear correlation (CC = 0.4392) between \( -\nabla B_\lambda \Delta t \) is weak. This might suggest that the weights of \( -\nabla B_\lambda \) and \( \Delta t \) should be different. Using the variable \( (-\nabla B_\lambda)^\alpha (\Delta t)^\beta \) 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 \( B_\xi \) may be more geoeffective than its duration \( \Delta t \).

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

\[
D_{st\min} = -19.01 - 8.43(-\nabla B_\lambda)^{1.09}(\Delta t)^{0.30} \text{ nT.} \tag{1}
\]

They also gave another empirical relationship for 35 large storms with \( D_{st} \leq -100 \) nT

\[
D_{st\min} = -66.31 - 3.21(-\nabla B_\lambda)^{1.35}(\Delta t)^{0.33} \text{ nT.} \tag{2}
\]

Our result is consistent with theirs. Note the change of the exponents of \( -\nabla B_\lambda \) and \( \Delta t \) in three linear fittings for different levels of \( D_{st\min} \), we can find that the weight of \( -\nabla B_\lambda \) relative to \( \Delta t \) should be different. Using the variable \( (-\nabla B_\lambda)^\alpha (\Delta t)^\beta \) 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 \( B_\xi \) may be more geoeffective than its duration \( \Delta t \).

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

Acknowledgements

We acknowledge the use of the data from ACE, Wind, SOHO spacecraft, the D<sub>s</sub> index from World Data Center and Wind MFI website (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html). We thank the referees for the constructive comments. The research was supported by the Chinese Academy of Sciences (KZCX2-SW-136), the National Natural Science Foundation of China (40404014, 40336052, 40336053) and the State Ministry of Science and Technology of China (G2000078405).

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