Long-lived geomagnetic storms and coronal mass ejections

H. Xie,1,2 N. Gopalswamy,3 P. K. Manoharan,4 A. Lara,5 S. Yashiro, and S. T. Leprí6

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[1] Coronal mass ejections (CMEs) are major solar events that are known to cause large geomagnetic storms (Dst < −100 nT). Isolated geomagnetic storms typically have a main phase of 3–12 hours and a recovery phase of around 1 day. However, there are some storms with main and recovery phases exceeding ~3 days. We trace the origin of these long-lived geomagnetic storms (LLGMS) to frontside halo CMEs. We studied 37 LLGMS events with Dst < −100 nT and the associated CMEs which occurred during 1998–2002. It is found that LLGMS events are caused by (1) successive CMEs, accounting for ~64.9% (24 of 37); (2) single CMEs, accounting for ~21.6% (8 of 37); and (3) high-speed streams (HSS) in corotating interaction regions (CIRs) with no related CME, accounting for ~13.5% (5 of 37). The long duration of the LLGMS events was found to be due to successive CMEs and HSS events; the high intensity of the LLGMS events was related to the interaction of CMEs with other CMEs and HSS events. We find that the duration of LLGMS is well correlated to the number of participating CMEs (correlation coefficient r = 0.78). We also find that the intensity of LLGMS has a good correlation with the degree of interaction (the number of CMEs interacting with a HSS event or with themselves) (r = 0.67). The role of preconditioning in LLGMS events, where the Dst development occurred in multiple steps in the main and recovery phases, has been investigated. It is found that preconditioning does not affect the main phase of the LLGMS events, while it plays an important role during the recovery phase of the LLGMS events.


1. Introduction

[2] Intense geomagnetic storms generally occur when solar wind with intense, long-duration southward interplanetary magnetic field (IMF) impacts Earth’s magnetosphere. During geomagnetic storms, southward IMF reconnects with Earth’s geomagnetic field at the dayside magnetopause, resulting in a chain of events leading to the dramatic increase of the ring current westward, which induces a magnetic field opposite to the geomagnetic field and causes global depression in the horizontal component (H) of the geomagnetic field. It has been known since the work of Burton et al. [1975] that the intensity of geomagnetic storms is proportional to the interplanetary dawn-dusk electric field

\[ E = -V_{sw} \times B_{z}/c, \]

where \( V_{sw} \) is the solar wind flow speed and \( B_{z} \) is the southward component of the IMF [e.g., Tsurutani and Gonzalez, 1997; Gonzalez et al., 1994].

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Burton et al. [1975] provided a simple formula describing the dependence of the energy injection into the ring current system as a function of the solar wind electric field E, indicating that the duskward E is generally associated with the observed negative Dst peak (an index proportional to the kinetic energy of the ring current particles) during the storm. Using an empirical model, O’Brien and McPherron [2000] found that this energy injection is proportional to \( E - E_{c} \), where the threshold to the electric field \( E_{c} = 0.49 \) mV/m. Large-intensity storms are expected to be a more direct response to the interplanetary conditions, where their long life is mainly from the large value reached by \( |Dst| \).

[3] The Dst (disturbance storm time) index is based on the H-component of the geomagnetic field averaged over four near-equatorial observatories. The strength of geomagnetic storms can be measured by the Dst index. In the case of an isolated magnetic storm, the Dst decreases drastically in the main phase and then recovers gradually to its quiet time level in the recovery phase. An isolated magnetic storm normally lasts for 1 day with a typical main phase of 3–12 hours and a recovery phase lasting ~14 ± 4 hours [e.g., Dasso et al., 2002; Tsurutani and Gonzalez, 1997]. However, there are some geomagnetic storms, which have more complex structure and show multiple-step decreases in Dst in the main phase and/or recovery phases. These geomagnetic storms often have longer duration and higher intensity. We refer to geomagnetic storms with total duration exceeding 3 days as long-lived geomagnetic storms (LLGMS).
index data from the World Data Center in Kyoto (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/) to identify the geomagnetic storms. The associated CMEs observed by the Solar and Heliospheric Observatory (SOHO) mission’s coronagraphs were obtained from the CME catalog (http://cdaw.gsfc.nasa.gov/CME_list) [Yashiro et al., 2004]. The solar source regions of the CME were identified from the online Solar Geophysical Data (SGD) as the location of the associated GOES X-ray flares in order to see if CMEs were frontside and traveling toward Earth. When GOES X-ray flare information was not available, we used movies from the Extreme-ultraviolet Imaging Telescope (EIT) on board SOHO and Yohkoh mission’s soft X-ray telescope to identify the location of the eruption. In order to identify the ICMEs, we use Fe charge state data from Advanced Composition Explorer/Solar Wind Ion Composition Spectrometer (ACE/SWICS), the solar wind plasma density, temperature, and flow speed from the Solar Wind Experiment (SWE) aboard the Wind spacecraft; and the magnitude $|B|$ and the $B_z$ component of the interplanetary magnetic field from Wind Magnetic Field Investigation (MFI). Also, we used the IP shocks from Wind online shock list (http://pwg.gsfc.nasa.gov/wind/current_listIPS.htm), the MC list from Lepping et al. [2005], the MC-like (MCL) structures from Wind MFI online list (http://lepmmf.gsfc.nasa.gov/mfi/MCL1.html), and the CME trajectories obtained from empirical CME arrival (ECA) model [Gopalswamy et al., 2000, 2001] to identify the arrival of successive CMEs at 1 AU.

The ECA model is based on the empirical interplanetary acceleration of CME, which was found to be

$$a = 2.193 - 0.0054u_0(s < d_i)$$

$$a = 0(s > d_i)$$

(1)
where \( a \) is acceleration in units of \( \text{m s}^{-2} \), and \( u_0 \) is initial CME speed in units of \( \text{km s}^{-1} \), \( s \) is the heliocentric distance along the line of sight, \( d_1 \) is the acceleration ceasing distance. The ECA model assumed that the acceleration ceases at a distance \( d_1 \) in interplanetary space when the CME speed is the same as the ambient solar wind speed. Assuming \( d_2 = 1 \text{ AU} - d_1 \), the CME travel time is computed as the sum of time \( t_1 \) to travel \( d_1 \) and \( t_2 \) to \( d_2 \): 

\[
t_1 = \frac{-u + \sqrt{u^2 + 2ad_1}}{a}, \quad t_2 = \frac{d_2}{\sqrt{u^2 + 2ad_1}}.
\]

[10] The CME trajectories can be obtained from the basic kinematic equations:

\[
s = u_0 t + at^2/2 (t < t_1) \\
s = u_1 t + d_1 (t > t_1)
\]

The ECA model requires the initial radial speed of a CME as input parameter. One of the difficulties in obtaining the CME initial speed is the uncertainty due to projection effects. Even though Earth-impacting CMEs typically originate from close to the Sun center [Gopalswamy et al., 2000], there is no easy way to determine whether a halo or partial halo CME would reach Earth. In this work, we attempt to correct for the projection effect and resolve the criterion for a CME to reach Earth by an improved CME cone model [Xie et al., 2004].

In the cone model, the orientation of a CME is defined by the longitude angle \( \alpha \) and the latitude angle \( \theta \) (or \( \lambda \)); the angular width of the CME is defined by \( 2\omega \), as shown in Figure 1. The actual radial speed of the CME is given by

\[
V_r = \frac{dr}{dt} = \frac{V_{r,c}}{\cos \omega \cos \theta - \sin \omega \sin \theta \sin \delta}
\]

or

\[
V_r = \frac{dr}{dt} = \frac{V_{r,c}}{\sin \omega \cos \delta}
\]

where \( V_{r,c} \) and \( V_{r,c} \) are the components of the CME projection speed along \( x_c \) and \( y_c \) axes in the plane of the sky (POS), respectively, \( \delta \) is the azimuthal angle defined as \( \delta = \)

\[
\text{Figure 1. Topology of the cone model. The coordinate (} x_h, y_h, z_h \text{) is the heliocentric coordinate system, where } z_h \text{ points to Earth, } y_h \text{ points north, and the } x_h - y_h \text{ plane defines the plane of the sky (POS). The coordinate (} x_c, y_c, z_c \text{) is the cone coordinate system, where } x_c \text{ is the cone axis, and the } y_c - z_c \text{ plane is parallel to the base of the right cone. The angles } (\phi, \lambda) \text{ are the longitude and latitude relative to the ecliptic plane. } \lambda \text{ is the angle between the cone axis } x_c \text{ and the } x_h - y_h \text{ plane and } \phi \text{ is the angle between projection of } x_c \text{ on the } x_h - y_h \text{ plane and the } z_h - \text{axis. The angles } (\alpha, \theta) \text{ are defined as the longitude and latitude relative to POS for conveniently determining the cone model parameters, where } \theta \text{ is the angle between } x_c \text{ and POS and } \alpha \text{ is the angle between the cone axis projection on POS and } x_h - \text{axis.}
\]

The ECA model assumes that the acceleration ceases at a distance \( d_1 \) in interplanetary space when the CME speed is the same as the ambient solar wind speed. Assuming \( d_2 = 1 \text{ AU} - d_1 \), the CME travel time is computed as the sum of time \( t_1 \) to travel \( d_1 \) and \( t_2 \) to \( d_2 \): 

\[
t_1 = \frac{-u + \sqrt{u^2 + 2ad_1}}{a}, \quad t_2 = \frac{d_2}{\sqrt{u^2 + 2ad_1}}.
\]

\[
\text{Figure 2. Illustration of the constraint } \omega \geq \beta + \Delta \text{ between the angular width } 2\omega \text{ and orientation } (\beta, \Delta) \text{ for a front-side halo } (\Delta = 0) \text{ or partial halo CME to encounter Earth. } O \text{ is the solar disk center. } O' \text{ is any arbitrary point on the solar surface near the disk center. Here } \beta \text{ is the angle between the cone central axis and the line-of-sight (LOS). Here } \theta \text{ is the angle between the cone central axis and the plane of the sky. } L \text{ is the distance of } O' \text{ to the LOS, and } \Delta \text{ is the angle between the LOS and one (Earth-directed) of the cone lateral projections.}
\]
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\[
\tan^{-1}(z/y) \quad \text{in the cone coordinate. The projection speed } V_r' \quad \text{on POS along the position angle (PA) is related to } V_{rc}' \quad \text{and } V_{sc}' \quad \text{as follows: } V_{sc}' = V_r' \sin(\alpha - PA) \quad \text{and } V_{sc}' = V_r' \cos(\alpha - PA).
\]

\[\begin{align*}
\omega & \geq \beta + \Delta, \\
\end{align*}\]

where $\beta$ is the angle between the cone central axis and the line-of-sight (LOS), L is the displacement of the CME source region to LOS, and $\Delta$ is the angle between the LOS and one (earthward) of the cone lateral projections, $\Delta = L/1$ AU (see Figure 2) [Xie et al., 2004].

3. Data

Table 1 lists the 37 LLGMS events. In the table, the $D_{st}$ minimum ($D_{st_{min}}$) time, $D_{st_{min}}$ value, storm onset time, storm end time, storm duration, IP driver, CME first appearance time in C2, associated solar source location, storm category, and comments are listed. The storm onset time is defined by the occurrence time of storm sudden commencement (SSC), which is caused by an intensification of the magnetopause current as the enhanced solar wind dynamic pressure (due to the IP shock) drives the magnetopause inward. The SSC is normally associated with the occurrence of IP shocks but may not be recognizable when the geomagnetic field is already depressed (preconditioning). When there is no clear identification of an SSC, we define the storm onset time as the time when $D_{st}$ starts decreasing. The storm end time is defined by the time when the $D_{st}$ recover to $D_{st_{0}}$ at $D_{st_{0}}$ where $D_{st_{0}}$ is $-50$ nT, the minimum intensity of modest storms. The LLGMS events are classified as (1) multiple CME (M) type, (2) single CME (S) type, and (3) CIR (C) type. In column 10, the first number in parentheses represents the number of participating CMEs in an LLGMS. The criterion to determine the number of participating CMEs in the LLGMS is to examine whether the arrival time of CMEs from the ECA model falls into the interval of LLGMS plus an error of $\pm 21.4$ hours, i.e., two times of root-mean-square (rms) of ECA model, where the average prediction error (rms) was estimated as 10.7 hours [Gopalswamy et al., 2001]. The second number in column 10 represents the degree of interaction, which is defined as follows: if the interaction occurs between a CME and a HSS, the interaction is of degree 1; otherwise, the degree is equal to the number of CMEs involved in the possible interaction, $h$ = cases involving HSS events.

\begin{table*}[ht]
\centering
\caption{Table 1. \textit{continued}}
\begin{tabular}{cccccccccc}
\hline
\text{Num} & \text{D$t_{min}$ Time, UT} & \text{D$t_{min}$, nT} & \text{Start, UT} & \text{End, UT} & \text{Dur, day} & \text{IP Driver} & \text{CME} & \text{Source Loc.} & \text{Category and Comments} \\
\hline
28 & 0420 0900 & -149 & 0417 1200 & 0423 0500 & ~5.7 & Sh. + MC + HSS + MCL & 0415 0350 (H) & SI$\text{S}$W01 & M: (2, 1, h) \\
29 & 0523 1800 & -109 & 0522 0200 & 0526 0200 & ~4.0 & C. Sh. + HSS & 0522 0350 (H) & SI$\text{W}$434 & M: (3, 0, h) \\
30 & 0821 0700 & -106 & 0819 0000 & 0822 1900 & ~3.8 & Sh. + C. ICME (2 MCs) & 0816 1230 (H) & SI$\text{E}$738 & M: (4, 0) \\
31 & 0904 0600 & -109 & 0903 2000 & 0907 0000 & ~3.2 & HSS in CIR & 0905 1654 (H) & SI$\text{N}$928 & M: (4, 2, h) \\
32 & 0908 0100 & -181 & 0907 0100 & 0915 1000 & ~10.4 & Sh. + C. ICME + HSS & 0906 1331 (H) & SI$\text{N}$1W54 & M: (0, h) \\
33 & 1001 1700 & -176 & 0930 200 & 1003 1000 & ~3.3 & Sh. + MC & 0928 1131(89) & SI$\text{E}$907 & M: (3, 3) \\
34 & 1004 0900 & -146 & 1003 1000 & 1006 1500 & ~3.2 & Sh. + 2 MCs & 0929 0806 (106) & SI$\text{N}$2E76 & M: (3, 0) \\
35 & 1007 0800 & -115 & 1006 1500 & 1013 1300 & ~6.9 & HSS in CIR & 1002 0731 (pH) & SI$\text{N}$1E36 & Pre. - 27 nT \\
36 & 1014 1400 & -100 & 1013 1300 & 1021 0600 & ~7.7 & HSS in CIR & 1003 0534 (pH) & SI$\text{E}$907 & M: (0, h) \\
37 & 1121 1100 & -128 & 1121 300 & 1126 2200 & ~5.8 & HSS in CIR & 1003 0554 (pH) & SI$\text{N}$3W29 & M: (0, h) \\
\hline
\end{tabular}
\end{table*}

\textsuperscript{5}D$t_{min}$ minimum time of the LLGMS.

\textsuperscript{6}D$t_{min}$ minimum value of the LLGMS.

\textsuperscript{7}Start time of the LLGMS.

\textsuperscript{8}End time of the LLGMS.

\textsuperscript{9}Duration of the LLGMS.

\textsuperscript{10}Interplanetary driver causing southward IMFs. MCL = Magnetic Cloud Like, Sh. = Sheath, C. = Compressed or Compound.

\textsuperscript{11}Associated CME first appearance time in C2. Halo = Full Halo CME, pH = Partial Halo CME. If related CMEs are neither Halo or partial Halo, then their angular width are listed. DG = Data Gap.

\textsuperscript{12}Solar source location of the associated CMEs.

\textsuperscript{13}M = Multiple CME, S = Single CME, C = CIR. The first number in parentheses is the number of associated CMEs, second number is the degree of interaction: the degree of 1 represents interaction between a CME and a HSS, otherwise, the degree is equal to the number of CMEs involved in the possible interaction, $h$ = cases involving HSS events.
interaction has occurred between the two CMEs (the distance where the CME interaction occurs is indicated in the y-axis of the CME height-time plot). The third letter “h” in parentheses of column 10 denotes cases involving an HSS event.

Figures 3a, 3b, 5, and 6 present four examples of LLGMS events, in which we show the associated $D_{st}$ variation and related solar wind parameters. Figure 3a shows the $D_{st}$ index, Fe charge state, $|B|$, $B_z$, $N$, $T$, $V$ and CME height-time profile, respectively. The vertical solid lines indicate the ICME shock front ($F_1$, $F_2$, $F_3$, $F_4$, $F$ denotes forward fast shock). The number on the bottom panel indicates the associated CMEs. The arrows show the dips in complex structures of $D_{st}$ and $B_z$. Note that the drop in $\langle Q_{Fe} \rangle$ near $F_2$ is due to the instrumental noise produced by the impact of the shock.

Figure 3a. A LLGMS associated with successive CMEs. From top to bottom: the panels are $D_{st}$ Index, Fe charge state, $|B|$, $B_z$, $N$, $T$, $V$ and CME height-time profile, respectively. The vertical solid lines indicate the ICME shock front ($F_1$, $F_2$, $F_3$, $F_4$, $F$ denotes forward fast shock). The number on the bottom panel indicates the associated CMEs. The arrows show the dips in complex structures of $D_{st}$ and $B_z$. Note that the drop in $\langle Q_{Fe} \rangle$ near $F_2$ is due to the instrumental noise produced by the impact of the shock.
Dip “A” in the main phase was caused by the compressed $B_r$ in the rear part of ICME 1. Dip “B” followed by a small dip was produced by the $B_s$ structures in the sheath region and the MC, respectively. The MC was followed by a HSS-like structure with high $T$ and low $N$, causing Dip “C” in the recovery phase, where the $Dst$ value was nearly constant for more than 10 hours. However, this HSS-like structure could also likely be the extension of the ICME 2, since no apparent coronal hole was observed at low latitude near the Sun disk (ICME interval is typically featured with low $T$ and reduced field fluctuations, but such features may not be present in some ICMEs [Cane and Richardson, 2003]). CME 1, CME 3, and CME 4 originated from the active region AR8858 when it was at N25E26, N31E04, and N26W26 as the Sun rotated westward. CME 2 originated from AR8853 at S17W40. Figure 3b shows the LASCO images of the four successive CMEs associated with this event, superposed with EIT images.

Figure 3b. LASCO C2 images of CMEs associated with the event. From top left to bottom right: CME 1, CME 2, CME 3, and CME 4.
the MC 1 and MC 2, respectively. The MC 1 produced a typical two-step ring current intensification, i.e., dip “A” and dip “B” in the $D_s t$ plot of Figure 4a, caused by the $B_s$ in the sheath region and the cloud, respectively. This two-step feature was not seen in the second storm; only dip “D” was produced by the $B_s$ in the sheath region of shock $F_2$. The solar origin of dip “C” was difficult to define since we did not find any reported CME on the Sun. It might be either due to a short HSS-like structure or an ejecta associated with a missing CME. Two CMEs, which caused the two MCs, respectively, were observed to be associated with this event. CME 1 originated from active region AR 9905 at S15W01 with an M1.2 flare and CME 2 originated from active region AR 9906 at S14W34 with an M2.6 flare. Fe charge state data showed two clear anomalous stages for this event, and their onsets are in near coincidence with the leading edge of the MCs. Figure 4b shows LASCO C2 images of CME 1 and CME 2.

Figure 4a. A LLGMS associated with two IMCs. From top to bottom the panels are $D_s t$ index, Fe charge state, $|B|$, $B_z$, $N$, $T$, $V$, and CME height-time profile, respectively. The vertical solid lines indicate the ICME shock front ($F_1$, $F_2$, $R_2$, $F$ denote forward fast shock and $R$ denotes reverse shock). The number on the bottom panel indicates the associated CMEs. The arrows show the dips in complex structures of $D_s t$ and $B_z$. Note that the drop in $Q_{Fe}$ near $F_1$ due to the instrumental noise produced by the impact of the shocks.
has caused the long recovery phase of the LLGMS. Shock $F_1$ was associated with a fast halo CME with actual speed of 1139 km/s and actual angular width of 128° obtained by the cone model.

[16] Figure 6 shows the corresponding data for the LLGMS from 6 October 2002 to 13 October 2002. The LLGMS had lasted for ~6.9 days with modest intensity of the minimum $D_{st}$ ~ −115 nT. It was produced by a HSS emanating from a low-latitude coronal hole, which was present a few days earlier near the disk center at 2200 UT on the 5 October 2002 EIT image.

4. Statistical Results

4.1. Associations

[17] First of all we find that the LLGMS events were produced by complex $B_s$ structures in various interaction regions: (1) IP shocks and complex ICMEs related to successive CMEs; (2) single IP shock and ICME (MC); (3) HSS events in CIRs. Note that both type 1 and type 2 might be mixing with possible HSS events. Of the 37 LLGMS events, 24 (64.9%) were associated with multiple CMEs, 8 (21.6%) were caused by single CMEs, and 5 (13.5%) were related to CIRs with no CME involvement.

4.2. LLGMS Properties

4.2.1. LLGMS Duration

[18] In order to study the relationship between the duration of LLGMS and successive CMEs and their interaction with HSS events, the LLGMS events were divided into the following six groups: (1) all multiple CME cases; (2) all single CME cases; (3) all CIR cases with no related CME; (4) multiple CME cases with >3 CMEs; (5) all cases involving HSS; (6) cases with no HSS and ≤ 2 CMEs. Note that the classification of the groups (1–6) does not imply disjunct sets, e.g., in this case group 4 is a subset of group 1. We use group 4 to study the effects of multiple CMEs (>3) on the duration ($Dur$) of LLGMS, and group 5 to study the effects of HSS events on $Dur$. Group 6 is used to study the cases without either multiple CMEs or HSS. Figure 7 presents the distribution of the duration of LLGMS for six different groups. The median durations for the above six groups are 4.1, 4.6, 6.9, 5.4, 5.8, and 3.4 days, respectively. In the multiple CME group, the LLGMS events were associated with more than one $B_s$ structure and the $D_{st}$ developed in multiple consecutive steps, causing the long duration. The median durations for the multiple CME type 1 and 4 are 4.1 and 5.4 days, respectively. The median duration for the CIR group is the longest with a median value of 6.9 days. The second-longest duration is for all the LLGMS events involving HSS. The nature of the duration in the events involving HSS is due to the long periods of $B_s$ fluctuations within HSS. As expected, the median duration for group 6 with no HSS and ≤2 CME is the shortest among the six groups, with a median value of 3.5 days. Therefore the CIRs and HSS are associated with the largest duration LLGMS events. If an LLGMS is associated with successive CMEs, the duration of the storm increases with the number of the participating CMEs. Figure 9a shows the relationship between the LLGMS duration and the number ($nc$) of participating CMEs. We find that there is a good correlation between the duration and $nc$ with correlation coefficient ($r$) of 0.78.

[19] Note that some single CMEs (with no HSS) events can reach long durations (~3 days) because of the very large storm intensity in these events, which caused relatively long recovery phase of the storms.

4.2.2. LLGMS Intensity

[20] To study the effect of the interaction CMEs with other CMEs and HSS on the intensity of LLGMS, we group the LLGMS events as in subsection 4.2.1, except that group 6 is classified as cases with no CME interaction. We extrapolated the CME trajectories from the Sun to 1 AU (see bottom panel in Figure 3a) to decide if two CMEs...
interact and applied criterion 5 to identify if a CME would reach Earth [Xie et al., 2004]. Figure 8 presents the histogram of the $D_{st\min}$ of LLGMS of the above groups. The median values of $D_{st\min}$ for the six groups are $-157$, $-155$, $-115$, $-181$, $-113$, and $-116$ nT, respectively. The multiple CME groups possessed relatively large median $D_{st\min}$ values with a median value of $-157$ nT for group 1 (all multiple CME cases) and $-181$ nT for group 4 (multiple CME with >3 CMEs). Group 3 (CIR cases) and group 5 (cases with HSS involved) exhibited modest median intensity with a median $D_{st\min}$ of $-115$ nT and $-133$ nT, respectively. In the multiple CME group 4, the CME interaction may play an important role in enhancing the intensity of the LLGMS events. Figure 9a shows the relationship between the LLGMS intensity and the degree of interaction ($ni$) (see definition in section 3). It is found that the correlation coefficient ($r$) between the intensity and $ni$ is 0.67.

4.3. Preconditioning in LLGMS Events

[21] The relationship of the intensity of magnetic storms to solar wind parameters can be examined using the Burton equation [Burton et al., 1975]. Burton’s equation has been tested and improved by numerous authors [e.g., Clua de Gonzalez and Gonzalez, 1998; Fenrich and Luhmann, 1998; O’Brien and McPherron, 2000; Wang et al., 2003]. It is given by O’Brien and McPherron in a slightly different form:

$$\frac{dD_{st\ast}}{dt} = Q(t) - \frac{D_{st\ast}(t)}{\tau},$$

where the energy injection term

$$Q = \begin{cases} a(VB_s - E_c) & VB_s > E_c \\ 0 & VB_s < E_c \end{cases}$$

Figure 5. A LLGMS associated with a single CME event: corresponding solar wind data, IMF, and the $D_{st}$ index from 2 April 2000 to 11 April 2000. The associated CME is a fast halo with an actual speed of 1139 km/s.
Figure 6. A LLGMS associated with a HSS event: corresponding solar wind data, IMF, and the $D_{st}$ index from 4 October 2002 to 13 October 2002. There was a coronal hole a few days earlier near the disk center at 2200 UT in the 5 October 2002 EIT image (not shown).
Figure 7. Histograms of durations for the six groups of LLGMS events. These six groups are (a) all multiple CME cases; (b) all single CME cases; (c) all CIR cases with no related CME; (d) multiple CME cases with >3 CMEs; (e) all cases with HSS involved; (f) cases with no HSS and ≤ 2 CMEs.
Figure 8. Histograms of $Dst$ minimums (absolute value) for the six groups of LLGMS events. These six groups are (a) all multiple CME cases; (b) all single CME cases; (c) all CIR cases with no related CME; (d) Multiple CME cases with > 3 CMEs; (e) all cases with HSS involved; (f) cases with no CME interaction.
considered the influence of O’Brien and McPherron’s improved model has also
ring currents, and
ing the changes of both the quiet time magnetopause and the
a constant of proportionality, and
changes and does not take into account any preexisting condition in
errors.
are optimized by minimizing the root-mean-square (RMS)
(see review by Gonzales et al. [1994]). However, Burton’s formula and its variations [e.g., O’Brien and McPherron, 2000; Wang et al., 2003] depend only on the solar wind coupling value \( V_{SW} \) and does not take into account any preexisting condition in the magnetosphere, so they might not be applicable for the multistep \( Dst \) development of LLGMS events when preconditioning occurs due to the presence of successive storms. In order to investigate whether Burton’s formula and its variations are applicable for the \( Dst \) development of LLGMS, we studied the relationship between \( B_z \), \( V_{SW} \), and \( Dst_{min} \). We divided the LLGMS events as individual ring current intensifications, i.e., individual \( Dst \) dips in the main and recovery phases. We identify the \( Dst \) dips according to the following conditions: (1) \( Dst_{min} \) must be less than \(-50 \text{ nT}\); (2) two consecutive dips must be separated by more than 3 hours; (3) the magnitude of the decrease of \( Dst_{min} \) in a dip must be less than \(-30 \text{ nT}\) or \( Dst_{min} \) remains the same level (see Figure 3a as an example) for more than 6 hours. We use the first criterion to exclude weak storms, which are mostly caused by HSS events. The second criterion excludes cases in which apparent decreases in \( Dst \) were caused by substorm effects such as the so-called current wedge, not a true increase in the storm time ring current [Kamide et al., 1998]. The third criterion is employed to help distinguish a well-defined dip.

Figure 9. Relationships and correlation coefficients for
(a) LLGMS duration and the number of associated CMEs (\( nc \)); (b) LLGMS intensity and the degree of interaction (\( ni \)).

\( V \) is the solar wind flow speed, \( V_{SW} \) is the solar wind dawn-dusk electric field, the proportional constant \( a \) is \(-4.4 \text{ nT/h(mV/m)}^{-1} \) and the electric field threshold \( E_c \) is \( 0.49 \text{ mV/m} \). The pressure-corrected index \( Dst^p = Dst - b \sqrt{p} + c \), from which the contribution of the magnetopause current to \( Dst \) has been removed, \( p \) is the solar wind dynamic pressure, \( b \) is a constant of proportionality, and \( c \) is a constant representing the changes of both the quiet time magnetopause and the ring currents, and \( \tau \) is the decay time of the ring current, associated with loss processes in the inner magnetosphere. O’Brien and McPherron’s improved model has also considered the influence of \( V_{SW} \) on \( \tau \) as follows: \( \tau = 2.40 \exp [(9.74/4.69 + VB_s)] \) with \( V_{SW} \) in \text{mV/m}. More recently, Wang et al. [2003] suggested that the O’Brien and McPherron’s model can be further improved by \( Q = a(VB_s - E_c)p(p_0)\gamma \), where the index \( \gamma \) and the constant \( p_0 \) are optimized by minimizing the root-mean-square (RMS) errors.

The empirical \( Dst \) model combined with the statistically derived decay time have had remarkable success in predicting the strength of geomagnetic storms (see review by Gonzalez et al. [1994]).

5. Summary and Discussion

We investigated 37 LLGMS events from 1998 to 2002. We find three causes of LLGMS events: (1) multiple CMEs (64.9%, 24 of 37); (2) single CME (21.6%, 7 of 37); (3) HSS in CIRs (13.5%, 5 of 37). The first two causes of LLGMS events involved possible HSS events, causing complex interaction regions in the interplanetary medium. In the multiple CME cases, the associated IP driver is a merged interaction region involving IP shock, complex ejecta, and HSS. The LLGMS events involving multiple CME have medium long duration and high intensity due to successive CMEs and various interactions. The single CME cases generally involve a fast halo CME associated with a very strong interplanetary shock, which produces super intensity (>280 nT) storm. In the CIR cases, the LLGMS events have modest intensity (~100 nT) but the longest duration due to extended periods of the highly fluctuating \( B_z \) within HSS.

If an LLGMS is associated with interacting CMEs, there is a good correlation between the number of CMEs involved in an LLGMS and the LLGMS duration with
Figure 10. Relationships of $D_{st_{min}}$ with $B_s$ and $V B_s$. From top to bottom, panels are the results for all dips in LLGME events, dips in main phases, and dips in recovery phases, respectively.
correlation coefficient $r = 0.78$. Interaction between successive CMEs plays an important role in enhancing the intensity of the LLGMS events. The intensity of LLGMS is well correlated with the degree of interaction (i.e., the number of CMEs interacting with HSS or with themselves in the associated interaction region) with $r = 0.67$. Of the 37 LLGMS events we studied, there were 20 (54.1%) events involving possible CME interaction. The largest LLGMS during 1998–2002 is the 31 March 2001 event with $D_{st,\text{min}} \sim -387$ nT, which involved four successive CMEs interacting with one another. Note that there are cases of interacting CMEs which do not trigger LLGMS due to unfavorable northward IMF conditions. Our analysis does not include these cases because we are interested in the solar origin of the existing LLGMS.

As we expected, there is a good correlation between $D_{st,\text{min}}$, $B_s$, and $V_B$. The correlation of $D_{st,\text{min}}$ with $B_s$ is slightly better than with $B_s$ with $r = 0.80$ and 0.84, respectively, for all dips and main phase dips. However, in the recovery phases, the correlation relation is relatively poor, with coefficients of 0.59 and 0.60 between $D_{st,\text{min}}$ and $V_B$, respectively.

Our results suggest that the preconditioning may have little effect on multiple $Dst$ development in the main phase of LLGMS, while it does affect the recovery phase. The reason is that the recovery phase involves both the ring current decay of prior storms and intensification of later storms in an LLGMS event. After the $Dst$ negative peak, the cumulative effects of prior storms on plasma sheet characteristics will alter the response of the magnetosphere to subsequent solar wind drivers, as suggested by Kozyra et al. [1998, 2002]. However, how the plasma sheet responds to the solar wind driver and how it is affected by the pre-existing storms are still not well understood. Further detailed investigation on the preconditioning is needed.

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