Study of geomagnetic storms with Dst < -100 nT during 1999 – 2002

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Ninety geomagnetic storms (GMSs) of intense nature, i.e. with Dst < -100 nT have been noticed using solar geophysical and interplanetary data during solar cycle 23. Out of which, 36 GMSs of intense (-200 nT ≤ Dst < -100 nT) nature and 10 of super intense (Dst < -200 nT) nature have occurred during the maximum phase, i.e. from 1999 to 2002, of solar cycle 23. The variation in time delay between the commencement and peak time of GMS is observed to be 5.5 to 42.5 h for different storms. The strength of GMS does not reveal any dependence with the duration of the storm as well as with the number of CMEs involved in the occurrence of storm. The high speed solar wind plasma, may be in the form of CMEs or else, is more likely to cause the intense and super intense GMSs. The solar features, i.e. X-ray solar flares (SFs), active prominences and disappearing filaments (APDFs), coronal mass ejections (CMEs), etc. responsible for causing GMSs have been studied. The geo-effective CMEs show longitudinal as well as hemispherical bias. Geo-effective CMEs causing intense and super intense GMSs are mostly confined between ±30° latitude and ±40° longitude. The correlation coefficients of 0.71 and 0.66, respectively of Bz and Vsw.Bz with Dst index indicates that Bz and Vsw.Bz may be considered as key contributors in determining the strength of GMSs.

Keywords: Coronal mass ejection (CME), Solar flare (SF), Active prominences and disappearing filament (APDF), Interplanetary magnetic field (IMF), Geomagnetic storm (GMS)

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1 Introduction

The geospheric environment is highly affected by the Sun and its features such as solar flares (SFs), active prominences and disappearing filaments (APDFs), coronal holes, coronal mass ejections (CMEs), etc. Research over last three decades identifies CMEs as the energetic events in the heliosphere1. CMEs are now understood as large scale magnetised plasma structures originating from closed magnetic field regions on the Sun - active regions, filament regions, active region complexes and trans-equatorial interconnecting regions2. CMEs from the Sun drive solar wind (SW) disturbances in terms of magnetic field, speed and density, which in turn cause geomagnetic disturbances at Earth3. The intensity of GMS is primarily decided by CME’s speed and strength of magnetic field it contains2, whereas, according to Manoharan4, primary factors determining the geo-effectiveness are: the direction of propagation of CMEs, its speed, size, density and further, orientation and strength of the magnetic field at the near Earth space. Intense GMSs are found to be mainly caused by CMEs3. CMEs are associated with a number of solar phenomena like radio bursts, SFs, prominence eruptions (PEs), solar energetic particles (SEPs), etc. The frequency of CMEs varies with sunspot cycle. CMEs are often associated with SFs and PEs, somehow, they may also occur in the absence of either of these processes5.

In the present paper, the intense and super intense GMSs during the period 1999-2002, based on disturbance storm time (Dst) index, have been identified. The intense GMSs have been designated by -100 nT > Dst ≥ -200 nT, whereas, super intense GMSs by Dst < -200 nT following Gonzalez et al.6 and Srivastava & Venkatakrishnan, which is different from Loewe & Prols3.

In the present investigation, the SFs of X-Ray importance, APDFs and CMEs associated with the intense and super intense GMSs have been studied. The CMEs with an apparent width of 360° are taken as ‘halo’, whereas the CMEs with width ≤ 359° (ref. 3) and 120° are taken as ‘partial halo’
An attempt has been made to identify the solar features and the solar and interplanetary parameters (IPs) that contribute to the occurrence of intense and super intense GMSs, and further to investigate the solar wind–geo-magnetospheric coupling problems during the maximum phase of solar cycle 23.

2 Data and its analysis

Forty six GMSs having intense and super intense nature have been observed during the period 1999-2002. Out of which, 45 GMSs have been investigated for which the data is available online. The values of Dst indices are taken from World Data Center, Japan (http://swdcwww.kugi.kyoto-u.ac.jp). Solar geophysical data and SOHO/LASCO CME Catalogue (http://cdaw.gsfc.nasa.gov/CME_list) are used to study storm sudden commencement (SSC) as well as association of SFs, APDFs and CMEs with GMSs. Location of halo CMEs responsible for causing intense GMSs have been cross-verified by http://cdaw.gsfc.nasa.gov/publications/gopal2007.halo_dst.table.pdf. A criterion similar to Kumar & Yadav is followed to determine the solar sources of GMSs. OMNIWEB data is used to obtain the values of SW while ACE data helped in providing the IMF values.

3 Results and Discussion

3.1 Solar activity and GMSs

The solar activity is analysed on the basis of sunspot numbers (SSNs) present over Solar disk during the solar cycle 23. The largest value of the sunspot acquired in a year has been plotted yearly in Fig. 1. Solar cycle 23 rises slowly in the beginning, depicting smooth maxima between 1999 and 2002, moreover, acquiring the maximum value of sunspots, i.e. 246 in the year 2000, which is the largest number in 23rd cycle and then declines.

During the 11-year period of 23rd solar cycle, 90 GMSs have been observed with Dst < -100 nT. Out of which, 51% have occurred during maximum phase, i.e. from 1999 to 2002. The number of intense GMSs observed during the period of investigation is 36, whereas, super intense GMSs are found to be 10, which is shown in Fig. 2. Hence, large number of high strength GMSs are observed during maximum phase of solar cycle as compared to the rising and declining phases.

3.2 Geomagnetic indices

The onset of GMSs can be estimated from the decrease in Dst value. There is a time delay between the onset of GMS and Dst minimum value. The variation in delay time is from a minimum of 5.5 h to a maximum of 42.5 h in the present study. The wide variation in time delay is understandable because it depends on the occurrence of southern magnetic field. Since the southward field may be contained in the front or rear sections of interplanetary CMEs (ICMEs), one expects a large variation in delay time.

In more than half of the events, i.e. 60% of present investigation, southward component of interplanetary magnetic field (Bz) follows the shock front in less than 15 hours.
3.3 Association with solar features

As the CMEs take 1 to 5 day’s time in reaching the Earth distance\textsuperscript{10,12}, so the 5-day interval prior to the onset of GMSs has been considered. A statistical investigation of the intense GMSs has revealed that 92% events seem to be associated with CMEs, which are of halo or partial halo nature. Further, 26% events are associated with single CME and 66% are associated with multiple CMEs. Also, 63% of the intense events are associated with full halo CMEs, whereas, 29% are associated with partial halo CMEs. When these 92% events are further investigated for other solar features, it is found that 25% are associated with APDFs, whereas, 93% are also associated with X-ray SFs as well. However, only 44% flares are of major importance, i.e. they belong to M and X classes.

Since, the speed in some of the cases, where a CME is preceded by a fast moving CME and angular width of CMEs increases during its propagation, one cannot ignore that some exceptional cases may be associated with narrow CMEs, which is also an observation by Zhang \textit{et al.}\textsuperscript{3} and Manoharan\textsuperscript{4}. Therefore, rest of the 8% events may be associated with narrow CMEs having slowly increasing angular width and sometimes getting accelerated during its path or it could be due to SFs or may be due to corotating interaction regions (CIRs), which is a rare possibility\textsuperscript{10}. Somehow, it cannot be overlooked.

All the super intense events are associated with halo CMEs. Only 22% have single CME dependence, whereas, 78% have multiple CMEs association, which are completely halo or combination of halo and partial halo CMEs. On further investigation for other solar features, 10% events are found associated with APDFs, whereas, 100% association is observed with X-ray SFs in addition to CMEs. Out of these X-ray SFs, 70% are of major importance.

This clearly shows that majority of the intense and super intense GMSs are caused by halo or partial halo CMEs. For intense events, the importance of the SF does not reveal any association with the nature of GMS, somehow, for super intense events, it might be possible that major class flares along with the CMEs provide strength to the GMS and hence, the Dst falls to very low values.

3.4 Location of geo-effective CMEs on solar disk

In the present investigation, 41% of the geo-effective CMEs responsible for intense and super intense GMSs are found to appear from the East of the central meridian while 59% appear from the west side. Thus, the distribution is asymmetrical as also observed by Wang \textit{et al.}\textsuperscript{13} and Zhang \textit{et al.}\textsuperscript{3} and is contrary to the observations by Cane \textit{et al.}\textsuperscript{14} and Srivastava & Venkatarakshan\textsuperscript{7}. Hence, the longitudinal distribution of geo-effective CMEs has a clear western bias. Further, 85% of the total CMEs observed have originated within ± 40° of the equator. Therefore, geo-effective halos causing intense and super intense GMSs are generally the disk events, i.e. longitudes mainly confined between ±45° and not the limb events where the longitude is confined between 45° and 90° (ref. 10).

There also appears hemispherical bias in geo-effective CMEs which are investigated in contrast to the observations of Srivastava & Venkatarakshan\textsuperscript{7}. About 56% events are reported in northern hemisphere, whereas, 44% events occurred in southern hemisphere. All the events are observed within ± 30° of the central meridian suggesting that geo-effective CMEs are generally confined close to the equator and they occur at low and moderate latitudes, as it is apparent from Fig. 3. Eight events are not shown in Fig. 3 due to unidentification of location of CMEs on solar disk.

3.5 Initial speed of associated CMEs

The linear speed derived from the height-time plot is considered as the initial speed of CME (refs 3, 4). The minimum and maximum speeds observed for intense GMSs are 271 and 1810 km s\textsuperscript{-1}, respectively with an average of 888 km s\textsuperscript{-1} while for super intense GMSs, the minimum and maximum speeds are 453 and 2411 km s\textsuperscript{-1}, respectively with an average of

![Fig. 3—Location of geo-effective CMEs on solar disk](image-url)
1186 km s\(^{-1}\). This shows that 44\% of the CMEs responsible for intense GMSs and 50\% for super intense GMSs have speed more than the average speed which is depicted by the velocity distribution of CMEs for intense and super intense events plotted in Figs 4 and 5, respectively. This indicates that such type of GMSs is likely to be caused by high speed solar wind streams (HSSWSs) may be in the form of CMEs. It is also clear from the present study that except one event of 5 November 2001, all the other events of the super intense GMSs and 69\% of the intense GMSs are high speed events with speed more than 700 km s\(^{-1}\), whereas, the maximum speed of the solar wind just prior to the arrival of the CME in most of the cases is observed to be less than 700 km s\(^{-1}\).

As shown in Table 1, the weak dependence between V\textsubscript{cme} and the D\textsubscript{st} indicates that the initial speed of CME might not be used as the parameter for predicting geomagnetic activity, which is also observed by Zhang et al\(^3\). It is observed that some slow CMEs can also cause intense GMS like that of 3 November 2000 with V\textsubscript{cme} = 291 km s\(^{-1}\) and super intense GMS, e.g. the CME of 1 November 2001 with V\textsubscript{cme} = 453 km s\(^{-1}\). Therefore, the criteria of initial speed of CME (whether CME is slow or fast) alone, may not be applied to predict the nature of GMS, which is in contradiction to the findings of Cane et al\(^{14}\) and Srivastava & Venkatakrishnan\(^7\). However, some other parameters like angular width of CME, location of CME on solar disk, etc. alongside the initial speed of CME might be useful in predicting the strength of GMS.

### 3.6 Travel time of associated CMEs

Travel time is the time taken by CME from the solar disk to arrive at near Earth distance. Different authors have defined this travel time in different ways\(^3,7,13\). In the present analysis, the travel time of CME at 1 AU distance is considered as the difference between the time of occurrence of CME at solar disk and the initiation/onset of GMSs at the Earth (TTI). The minimum travel time of 23.5 h and a maximum of 117.5 h are observed for intense cases, whereas, the minimum and maximum values for super intense events are 28 and 84.5 h, respectively. An exceptional case of very small travel time of just 16 h is observed on 18 April 2002, however, the pretty high velocity of 1240 km s\(^{-1}\) of halo CME associated with the GMS justifies its association with the storm.

The travel time of CME from its occurrence at the solar disk up to the moment when storm is at its peak (TTP) against initial velocity of CME is also studied and it reveals better dependence with anti-correlation coefficient of -0.6 (depicted in Fig. 6) as compared to TTI where anti-correlation coefficient of -0.54 is obtained against initial velocity of CME. Four contradictory findings are also observed where the TTI or TTP are high along with the high velocity of CME

<table>
<thead>
<tr>
<th>SP/IP</th>
<th>Geomagnetic index</th>
<th>Corr coeff</th>
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<tbody>
<tr>
<td>V\textsubscript{cme}</td>
<td>Dst</td>
<td>-0.20</td>
</tr>
<tr>
<td>Bz</td>
<td>Dst</td>
<td>0.71</td>
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<tr>
<td>V\textsubscript{sw}.Bz</td>
<td>Dst</td>
<td>0.66</td>
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<tr>
<td>V\textsubscript{sw}.B</td>
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<tr>
<td>B</td>
<td>Dst</td>
<td>-0.58</td>
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<tr>
<td>V\textsubscript{sw}</td>
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CME or vice versa. These exceptional cases can be taken care of by the fact that CMEs initiated with high velocity decelerates while those initiated with low velocity accelerates during their propagation.

3.7 Solar wind velocity and $D_{st}$

One obvious parameter from the solar wind data is the speed of shock wave, which can be used to calculate the maximum travel time of these features from the Sun to the near Earth space at the onset of GMS. The minimum and maximum value of SW velocity is observed to be 333 and 540 km s$^{-1}$, respectively for intense GMSs, whereas, for super intense GMSs, the minimum and maximum values are 369 and 866 km s$^{-1}$, respectively.

As shown in Table 1, the $V_{sw}$ and $D_{st}$ show a better anti-correlation and thus leading very clearly to the dependence of $D_{st}$ on $V_{sw}$ so as to conclude that SW plasma of high speed causes the GMSs of high intensity. Thus, $V_{sw}$ seems to be an important parameter in determining the nature of GMSs.

3.8 Duration of GMSs

The duration of the storm is found to be different in different cases. Some storms end up in few hours, like that of 23 May 2002, which ended up in just 13 h, while some gets prolonged to few days, like the one of 21 October 1999, which extended upto 67 h. In a peculiar case of intense GMS of 2 October 2002, the storm extended upto 3 days with the minimum $D_{st}$ value of $-116$ nT and is not found associated with any halo or partial halo CMEs. A flare of very low class, i.e. C1.5 is observed during that time. Another typical case of intense GMS is observed on 29 November 2000, where, the storm ended up in less than a day (22 h) while minimum $D_{st}$ value is found to be $-119$ nT and six halo and three partial halo CMEs are observed in 5 days window. Thus, there seems no relation between the GMS’s duration and its strength or the number of CMEs involved in its occurrence.

3.9 Association with interplanetary parameters

The main cause of intense GMSs is believed to be large IMF structures, which have an intense, long duration and southward magnetic field component (Bz) (refs 6,15). They interact with the Earth’s magnetic field and facilitate the transport of energy into the Earth’s atmosphere through the reconnection process. In order to understand the response of the magnetosphere to IP conditions, interplanetary magnetic field (IMF) strength ($B$) and $B_z$ are investigated. It is observed from Table 1 that the correlation coefficient between $B_z$ with $D_{st}$ is quite significant, indicating the parameter $B_z$ to be the reliable indicator for the initiation of intense GMSs.

As stated earlier, $V_{sw}$ and IMF component $B_z$ show significant correlation with $D_{st}$ index. Thus, the coupling between the Sun-Earth parameters seems essential so as to forecast the magnitude of an impending GMS. The product of magnitude of $V_{sw}$ with the magnitude of IMF parameters show the energy transform from SW to magnetosphere. As observed from Table 1, $V_{sw}.B_z$ shows a much better correlation coefficient with $D_{st}$ than that of $V_{sw}.B$ with $D_{st}$. Hence, $B_z$ and $V_{sw}.B_z$ may be considered as key contributors in determining the strength of GMSs.

4 Conclusions

Based on the present investigations, the following conclusions can be derived:

1. More than half (51%) of the high strength GMSs are observed during maximum phase of solar cycle 23 as compared to the rising and declining phases.
2. The variation in time delay is from 5.5 to 42.5 h between the commencement and peak time of GMSs, which is likely to be due to the difference in timings in the striking and reconnection of southward component of IMF with Earth’s magnetosphere for different storms.
3. The strength of GMS does not reveal any dependence with the duration of the storm. No relationship is observed between the nature of the GMSs and the number of CMEs involved in the occurrence of storm.
4 The high speed solar wind plasma, may be in the form of CMEs or else, is more likely to cause the intense and super intense GMSs.

5 Majority (69%) of the intense GMSs are associated with full halo CMEs, whereas, all the super intense GMSs are found to be associated with full halo CMEs.

6 The initial speed of CME at Sun cannot be taken as a parameter in deciding the nature of GMSs.

7 The geo-effective CMEs show longitudinal as well as hemispherical bias. Most of the events occurred in northern hemisphere and on the west side of central meridian.

8 Geo-effective CMEs causing intense and super intense GMSs are mostly confined between ±30° latitude and ±40° longitude.

9 Majority of the geo-effective CMEs are associated with X-Ray solar flares. The importance of flare does not reveal any significance with the nature of storm for intense events. However, 70% of the super intense events show major flare class dependence indicating that these flares along with CMEs make the GMSs more intense.

10 Bz and Vsw.Bz may be considered as key contributors in determining the strength of GMSs.

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