On Solar Sources of Geomagnetic Storms of Solar Cycle 23 and Their Relation with CMEs

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Abstract. Geomagnetic storms are disturbances in the Earth’s magnetosphere. Coronal mass ejections (CMEs) and corotating interaction regions (CIRs) are considered as two major sources of geomagnetic disturbances. Here we have studied halo CMEs and their solar surface sources and associated geomagnetical disturbances from January, 1996 to December, 2007. During the 12-year period of solar cycle-23 SOHO/LASCO detected 396 full halo CMEs. About 60% of these are found to be front side halo CMEs. These front side CMEs are found to produce geomagnetic storms at the Earth. We examine the properties of these CMEs which produce intense geomagnetic storms (DST $\leq -100$ nT). The graphical plot between DST index and speed of CME shows a good correlation between them. It is found that front side CMEs associated with flares, which originate close to the central meridian and the southward component of interplanetary magnetic field BZ are the most potential candidates for producing intense geomagnetic storms. Further the occurrence of geomagnetic storms does not vary with the solar cycle and the mass of CMEs is not correlated with the DST index of storm. Our extensive study, based on complete solar cycle 23 data, confirms the results of previous studies.

Keywords: Sun, CMEs, Geomagnetic storms, Interplanetary magnetic field, Solar cycle 23

INTRODUCTION

This The physical causes of the most prominent perturbation in the magnetic fields of the heliosphere and in the vicinity of planets are related to solar activity. Major geomagnetic storms are among the most important space weather phenomena. A geomagnetic storm is characterized by a main phase during which the horizontal component of the Earths low-latitude magnetic fields are significantly depressed over a time span of one to a few hours followed by its recovery which may extend over several days (Rostoker$^{1}$, 1997; Lakhina$^{2}$ et al., 2005).

Coronal mass ejections (CMEs) and corotating interaction regions (CIRs) are the two large-scale interplanetary (IP) structures that cause geomagnetic storms under certain conditions. CMEs are large-scale bubbles of plasma and magnetic fields, which originate at the Sun in closed field regions, while CIRs are formed at a distance from the Sun where high-speed streams (HSS) from coronal holes press against the slower ones ahead (Srivastava &Venkatkrishnan$^{3}$, 2004 and references therein; Gopalswamy$^{4}$, 2008). Once launched from the Sun, CMEs travel through the IP medium and, if directed toward the Earth, reach in 1-4 days depending on their speed.

CMEs occurring close to the solar disk center are likely to directly impact Earth and hence may be useful for predicting geomagnetic storms because most of the intense geomagnetic storms are due to such CMEs. Halo CMEs (having angular width 3600) that appear to surround the occulting disk of the observing coronagraph in sky plane projection (Howard$^{5}$ et al., 1982) are supposed to be main cause of geomagnetic storms.

To be geoeffective a CME or CME-associated disturbance should arrive at the Earth and contain suitable magnetic field orientation: north-south interplanetary magnetic field (IMF) component BZ should be negative (southward), strong enough and long-lasting (Srivastava &Venkatkrishnan$^{3}$, 2004; Naitamor$^{6}$, 2005; Zhukov$^{7}$, 2005 Zhang$^{8}$ et al., 2007; Akasofu$^{9}$, 2011; Lekshmi$^{10}$ et al, 2011). Sitnov$^{11}$, M. I. (2020).
In view of the importance of this topic, as is clear from the above, we reexamine role and properties of halo CMEs and their DST index association for their geoeffectiveness. For correlation study we have taken only those events which were associated with DST value ≤ -100 nT for solar cycle 23 (1996-2007). Section 2 contains criteria of data selection. Section 3 contains all the results of our extensive study. Section 3.1 defines geoeffectiveness of HCMEs. Section 3.2 describes solar cycle variation of geoeffective HCMEs. Section 3.3 gives relation between speed of HCMEs and their associated DST values. Section 3.4 describes source region on the solar surface of geoeffective HCMEs. Section 3.5 gives relation between IMF BZ and DST values. Section 3.6 exhibits the relation between mass of CMEs and DST values. The last section is devoted to discussion and conclusions.

DATA

The data sets used in this study include all the 101 geoeffective CMEs that occurred between 1996 and 2007 and gave rise to intense geomagnetic storms (DST ≤ -100 nT). We use LASCO data for studying the solar origins of the CMEs. The data for CMEs have been taken from the catalogue maintained by the Centre for Solar Physics and Space Weather (CSPSW) (http://cdaw.gsfc.nasa.gov/CME_list). The LASCO coronagraphs C2 and C3 images, which give a combined field of view from 2 ~ 30 RS, were used for tracking the CMEs in the outer corona. The definition of full or partial halo is based on the azimuthal extent of CMEs in the LASCO field of view (Webb et al., 2000). The total magnetic field and the southward component BZ of the interplanetary magnetic field values, which are important for understanding the development of intense storms, were obtained from the OMNI data archive. The southward component data (BZ in nT in GSE coordinates) were obtained from the Omni web, which is available online at (http://omniweb.gsfc.nasa.gov). The values of DST indices were obtained from the geomagnetic activity web page of the World Data Center, Japan (http://swdceww.kugi.kyoto-u.ac.jp). The data of the monthly mean sunspot numbers has been taken from the web page of Solar Geographical Data (SGD).

In order to determine the solar source of geomagnetic storms, we follow a criterion similar to that of Wang et al. (2002), Zhang et al. (2003) and Srivastava & Venkatkrishnan (2004). We have selected only those front-side halo CMEs which have 1-5-day temporal window relation with geomagnetic storms with DST ≤ -100 nT.

RESULTS

Geoeffectiveness of Halo CMEs

In our study we find a 100% association of intense storms (DST ≤ -100 nT) with full halo CMEs (c.f. Table-1), but all halo CMEs do not produce geomagnetic storms.

This table shows that a large majority of the geoeffective events are associated with full halo CMEs whose intensity is much above the sensitivity of the coronagraphs so that they could be easily detected in LASCO images. Because all of the superintense/intense storms had their origin in some solar activity on the front side of the Sun and are associated with front-side full halos, it can be assumed that the back-side halo CMEs are unlikely to give rise to superintense/intense storms.

Solar Cycle Variation of Geoeffective HCMEs

In order to be able to predict the occurrence of a strong geomagnetic storm it is important to identify the solar drivers of the geomagnetic activity. Richardson et al. (2001) show that a large number of intense geomagnetic storms (-200 nT< DST < -100 nT), occur close to the solar maximum than during the solar minimum During our period of study a total of 101 intense geomagnetic storms were recorded (Figure 1 and Table 1). In this period, the number of intense geomagnetic storms increased from 2 in 1997 to 22 in 2000, thereby showing an increase with the progress of the solar activity cycle. A significant decline in the number of geomagnetic storms is observed from 1998 to 1999, from 9 to 1 event. There is a decline in the overall number of geomagnetic storms including the superintense events in the year 1999. This decline is consistent with the overall decline in the solar activity and related interplanetary activity in 1999 (Cane et al., 2000).

Due to the wide range and complexity of tables, we simply offer an example for guidance. Please follow the style for table (and figure) captions.
Table 1: Annual variation of intense and superintense geomagnetic storms, sunspot numbers and HCMEs.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>No. of intense geomagnetic storms ((-200 \text{ nT} &lt; D_{ST} \leq -100 \text{ nT}))</th>
<th>No. of superintense geomagnetic storms ((D_{ST} \leq -200 \text{ nT}))</th>
<th>Yearly mean sunspot numbers</th>
<th>Number of HCMEs</th>
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</thead>
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<tr>
<td></td>
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<td>Front side</td>
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<tr>
<td>1996</td>
<td>0</td>
<td>0</td>
<td>8.6</td>
<td>0</td>
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<tr>
<td>1997</td>
<td>2</td>
<td>0</td>
<td>21.5</td>
<td>11</td>
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<td>1998</td>
<td>5</td>
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<td>64.3</td>
<td>20</td>
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<td>1999</td>
<td>1</td>
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<td>15</td>
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<td>2000</td>
<td>16</td>
<td>6</td>
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<td>5</td>
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<tr>
<td>2007</td>
<td>0</td>
<td>0</td>
<td>7.5</td>
<td>1</td>
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</table>

The average rate of occurrence of intense and superintense geomagnetic storms, yearly mean sun-spot numbers, and yearly HCME number obtained over the period 1996-2007 is exhibited in Table 1. Clearly, the maximum number of intense and superintense geomagnetic storms occurred in the year 2000 and 2001. The distinct variation in the rate of all CMEs, and those that are directed earthward, suggests that the conditions that give rise to geomagnetic storms do not depend solely on the phase of the solar cycle. This also follows from a comparative examination of the yearly average sunspot numbers obtained from the Solar Geographical Data for this study period (Figure 1) with the number of geomagnetic storms. While the maximum number of observed sunspots steadily increased from 8.6 in 1996 (solar minimum) to 119.6 in the year 2000 (solar maximum), the number decreased to 104 in the year 2002 (descending phase of the solar cycle). If the rate of occurrence of geoeffective CMEs follows the solar cycle, one would expect a rise and fall in the number of geoeffective CMEs by the same factor as that observed in case of the sunspot numbers. However, the lack of correlation between the two (Figure 1) indicates that other factors (for example, the presence of the corotating interaction regions or CIRs) may also be responsible for more geoeffective CMEs during minimum.

Lindsay et al., (1995) show that CIRs generally contribute to minor and moderate geomagnetic storms and can occasionally contribute to strong storms too. Paul, Bapan (2020).

**FIGURE 1:** Distribution of the yearly occurrence rate of intense geomagnetic storms in relation to sun-spot numbers (shown by the solid line).

**Initial Speeds of the Geoeffective CMEs**

As the radial speed of earthward halo CMEs cannot be measured directly because of the unfavorable location of the observer at the Earth. Observations of the LASCO indicate that CMEs show some distinct characteristics
irrespective of their directions. One such characteristic is that the geometrical shape of the ejected material is maintained throughout the field of view of the LASCO coronagraphs (Webb et al., 1997). From LASCO images, one can estimate the propagation speed up to 30 RS. Beyond this distance, the near-Earth in situ measurements can be used for determining the speeds of the ejecta. Assuming a uniform expansion of the CME in all the directions, we took the sky-plane speeds of the halos in order to estimate the probable travel time toward the Earth. With the exception of 16 cases, the initial speeds of a majority of geoeffective CMEs observed during 1996-2007 range between 500 and 2500 km/s, as observed in the LASCO-C2 field of view.

**FIGURE 2a:** The plot between DST index and the geoeffective CME initial speeds associated with X-class flares.

**FIGURE 2b:** The plot between DST index and the geoeffective CME initial speeds.

**FIGURE 2c:** Annual variation of initial speeds of CMEs associated with X-, M-, C- class of flares and other solar activities.
Measurements of the CME speeds show that a large percentage of the geoeffective CMEs (67%) have initial speeds higher than 700 km/s, which is even higher than the typical high speed solar wind. We also found that there are a few slow CMEs, particularly during solar minimum, which proved to be geoeffective. Such events appear to be an exception to the results obtained by Gosling et al. (1990) and Gonzalez et al. (1996) that only fast CMEs can produce severe geomagnetic storms.

Position of source regions on the solar surface

The location of the origin of halo CMEs seems to be crucial for their impact on the Earth. A few earlier studies have shown that all front-side halos may be geoeffective provided that they arise from favorable locations, i.e., they originate close to the central meridian and at low latitudes. (Gonzalez et al., 1996; Wang et al., 2002; Zhang et al., 2003; Srivastava and Venkatakrishnan, 2004). In the present study we find a far less pronounced longitudinal asymmetry in the distribution of source region of the geoeffective CMEs. Almost 26% of them appear from the east of the central meridian, and 59% appear from the west side and the remaining 15% are appears close to the central meridian (±50). This asymmetry is quite similar to that reported by Wang et al. (2002) and Zhang et al. (2003).

Reyes, Paula (2019)

**FIGURE 3:** Heliographic location of the 101 identified CMEs associated with geomagnetic storms having $D_{ST} \leq -100$ nT.

From an examination of the origins of all the geoeffective CMEs, it was found that the location of the CMEs is important as most of geoeffective CMEs have their origins near the central meridian and at low and middle latitudes with 25 exceptions (Figure 3). The majority of the events originated within ±35° of the central meridian and ±30° of the equator. There appears to be no hemispherical preference in halo CMEs that reach the Earth, as reported by Cane et al. (2000) and Wang et al. (2002). In our investigation, we find 51 events originated in the northern hemisphere as against 50 events in the southern hemisphere, similar to Srivastava and Venkatakrishnan, (2004) and Zhang et al., (2007).

CMEs in general show larger variation in latitude extending up to the poles, as compared with the active regions, which are confined to moderate latitudes (Hundhausen, 1997, Mittal and Narain, 2009). Thus our analysis confirms the earlier result (Srivastava and Venkatakrishnan, 2004 and Zhang et al., 2007) that the geoeffective CMEs are generally confined to the active region belt, i.e., low and moderate latitudes. Bhoj, Chandrasekhar (2018).

Interplanetary magnetic field (BZ) and geoeffectiveness of CMEs

The geo-effectiveness of CMEs depends upon the speed and the embedded southward magnetic field $B_Z$ (Srivastava &Venkatakrishnan, 2004; Zhang et al., 2007; Gopalswamy, 2008). The configuration of the IMF ($B_Z$) at the time of arrival should be known to make accurate prediction of its geo-effectiveness because the variation of $B_Z$
plays a crucial role in determining the amount of solar wind energy which is transferred to the magnetosphere (Gonzalez et al., 1996; Srivastava & Venkatkrishnan, 2004).

**FIGURE 4:** Relation between DST index and $|\text{VBZ}|$ values of the geoeffective CMEs.

Figure 4 exhibits the dependence of the DST values on the VBZ values with the correlation coefficient $r = -0.58$, whereas study of Srivastava & Venkatkrishnan (2004) shows high correlation coefficient $r = -0.66$ between the DST values and the VBZ values. The high correlation between the VBZ and DST suggests that VBZ is a reliable predictor of the intensity of geomagnetic storm. This result is quite similar to those of Srivastava & Venkatkrishnan (2004) and Zhang et al. (2007).

**DISCUSSION AND CONCLUSIONS**

It is now known that CMEs play a key role in producing geomagnetic storms. CME is a topical problem both for understanding the physical mechanisms of disturbance transfer from the Sun to Earth and for the problem of forecasting magnetospheric disturbances on the basis of solar observations to study the geo-effectiveness of the solar phenomena (Yermolaev, 2008).

Figure 1 and Table 1 exhibit annual variation of sunspot numbers and the number of geomagnetic storms. It is clear from these that the number of geomagnetic storms do not follow solar cycle variation. The sunspot number increases from 1996 to 2000 and declines slowly onwards, but the number of geoeffective CMEs increases from 1997 (2) to 1998 (9) and comes down in 1999 (1). It has its first peak in 1998. The number increases to second maximum in 2000 (22) declines slowly in 2001 (20), further declines in 2002 (9) and increases slowly to have a third peak in 2005 (16). In 2006 the number of geoeffective CMEs is (1). Thus the number of geoeffective CMEs does not follow the solar cycle.

Figure 2a exhibits the DST index variation with the initial speeds of geoeffective CMEs associated with X-class flares, numbering 31. All the CMEs leading to superintense storms ($\text{DST} \leq -200 \text{ nT}$) have initial speeds in the range 900-2500 km/s. The CMEs producing intense storm ($-200 \text{ nT} < \text{DST} < -100 \text{ nT}$), have speeds in the broad range 550-3400 km/s. Thus, CMEs producing intense and superintense geomagnetic storms and associated with X-class flares have initial speeds in the range 550-3400 km/s.

Figure 2b exhibits the DST index variation with the initial speeds of geoeffective CMEs having speed from 257-3387 km/s.

Figure 2c shows the annual variation of initial speeds of CMEs associated with X-, M-, C- class of flares and others. The speeds of CMEs associated with X-, M-, and C- class of flares are in the descending order, (c.f. figure 2c).

In Figure 3 we exhibit heliographic latitude along y-axis and heliographic longitude along x-axis. It is clear from this figure that all the geoeffective CMEs lie in the latitude range 30°N-30°S and the longitude range 85°E-85°W. A majority of geoeffective CMEs come from longitudes in the range 35°E-45°W. Thus, the longitudinal distribution has asymmetry whereas the latitudinal distribution is quite symmetrical about 0-0 line.

Figure 4 shows a high correlation between DST values and VBZ values, which shows that geomagnetic storms are highly correlated with the southward component ($B_Z$) of interplanetary magnetic field.

Above study leads us to conclude the following for the solar cycle 23:

1. The number of geoeffective CMEs does not follow the sunspot numbers (solar cycle).
2. The strength of geomagnetic storms does not depend on the flare class (viz; X, M, C) with which CMEs are associated.
3. All geoeffective CMEs lie in the latitude range 30°N-30°S and thus the latitudinal distribution is symmetrical.
4. A majority of geoeffective CMEs lie in the longitude range 35°E-45°W, so that the longitudinal distribution is not symmetrical.
5. CMEs with strongly southward component B_z produce intense geomagnetic storms.

ACKNOWLEDGMENTS

The authors are also thankful to Solar Geophysical Data System for sunspot data, Kyoto University, Japan for DST index data and Omniweb data system and ACE MAG Level 2 data for providing interplanetary magnetic field data.

REFERENCES

1. Rostoker, G., 1996, Phenomenology and physics of magnetospheric substorms, JGR, 101 (A6), 12955
15. Lindsay, G.M., Russell, C.T. and Luhmann, J.G., 1995, Coronal mass ejection and stream interaction region characteristics and their potential geomagnetic effectiveness, JGR, 100(A9), 16999
16. Paul, Bapan; Gordiyenko, Galina; Galav, Praveen, 2020, Study of the low and mid-latitude ionospheric response to the geomagnetic storm of 20th December 2015, Astrophysics and Space Science, Volume 365, Issue 10, article id.174


