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Study of the Extensive Geomagnetic Storm with Helio-Spheric Phenomena during the Period of Solar Cycle 24

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Abstract

Geomagnetic storms are impactful space weather occurrences because they may disrupt power grids, communication systems, and spacecraft operations. The MC sheath, the leading (or front section) area of an MC, the trailing part of an MC, and collective sheath and MC regions can cause an extensive geomagnetic storm. This paper uses descriptive analysis to identify them with helio-spheric phenomena using the Disturbance Storm Time Index (Dst). Depending on the availability of data during the period of solar cycle 24, we include the four extensive geomagnetic storms allied with various solar parameters/interplanetary magnetic field components that were potentially geo-effective and occurred on "St. Patrick's Day" (17 March 2015), (23 June 2015), (20 Dec 2015), and (26 Aug 2018).

Keywords: Geomagnetic Storms (GMs) • Coronal Mass Ejection (CMEs) • Solar Flares (SFs) • Magnetic Clouds (MCs) • Interplanetary parameters

Introduction

The geomagnetic storm is a worldwide disturbance in Earth's magnetic field usually occurred due to abnormal conditions in the Interplanetary Magnetic Field (IMF) and solar wind plasma emissions caused by various solar phenomenon which occur within the atmosphere of the Sun (including solar flares, coronal mass ejections, high speed solar wind, and solar energetic particles are all forms of solar activity). It proposed that geomagnetic, activity is related to variability of interplanetary plasma/field parameters, e.g., Solar Wind Velocity (SWV), Solar Wind Plasma Pressure (SWPP), Solar Wind Plasma Temperature (SWPT), solar wind proton density (SWPD) and Interplanetary Magnetic Field (IMF) B and Bz [1]. The first geo-magnetic storm (Dst_{min}<-73 nT) accompanying with a Coronal Mass Ejection (CMEs) and a driven shock in solar cycle 24 occurred on 6 April 2010, which was allied with a CME occurrence on 3 April 2010. The primary extensive geomagnetic storm in solar cycle 24 occurred during 05–06 August 2011 (Dst_{min}=-107 nT), and the second and third extensive geomagnetic storms occurred during 26-27 September 2011 (Dst_{min}=-101 nT and 24-25 October 2011 (Dst_{min}=-132 nT), respectively (e.g., Wood). There were five extensive geomagnetic storms recorded in 2012 alone, but only two extensive geomagnetic storms were recorded in 2013: one (Dst_{min}=-132 nT) on 17 March 2013 and the other one on 1 June (Dst_{min}=-119 nT). During the rising phase of solar cycle 24, the most intense storm happened during (07-08) March 2012 with Dst_{min} reached (-143 nT). The first extensive geomagnetic storm of solar cycle 24 did not occur until the declining phase on 17 March 2015. It is often seen that the Interplanetary Magnetic Field's (IMF's) southern component significantly leads to the formation of geomagnetic storms. A large southward IMF can be allied with diverse categories of solar wind structures:

- An Interplanetary (IP) shock wave (sheath).
- A Magnetic Cloud (MC) or an IP Coronal Mass Ejection (ICME).
- A helio-spheric current sheet sector boundary crossing.
- A combination of these interplanetary structures.

Among these, MCs are the extreme geo-effective since they generally hold a large, long-lasting southward IMFBz [2]. Nearby 90%of MC events are allied by geomagnetic storms. AMC event consist of the MC itself, usually an upstream shock wave with a sheath (region between the shock and the MC) [3]. Maximum solar cycle 23 significant storms (88 of them) are allied by an ICME or a MC. The MC sheath, the leading (*i.e.*, front section) region of an MC, the trailing part of an MC, and both sheath and MC regions can all cause a geomagnetic storm. It is reported that there is indeed a strong correlation between the severity of a geomagnetic storm and the minimum value of the z component of the IMF (Bzmin) inside an MC (Dst_{min}) [4], we consider the z GSE component. Therefore, measurements of Bzmin in the solar wind can be used

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to predict Dst_{min} [5]. Numerous studies have reported that these storm time variations also known as geomagnetic storm deals the various characteristics of geomagnetic storms and their connection with solar source activities and interplanetary magnetic fields. These variations directly affect us and shows adverse effect in satellites, communication system and power losses. In this paper the explanatory study has been performed to analyze these extensive geomagnetic storms recorded by numerous geomagnetic observatories identified with the help of Disturbance storm time index (Dst). We investigated several solar parameters/interplanetary magnetic field components which were potentially geo-effective and occurred during the solar activity period of solar cycle 24 [6].

Literature Review

Several scientists have tried to establish a relation between properties of solar active regions, associated solar features, their interplanetary manifestations, and their interplanetary and geomagnetic effects. Solar cycle 23 began in August 1996 and ended in December 2008 with its maximum around 2002. Following the minimum of cycle 23, solar cycle 24 began in December 2008 and ended in December 2019 reaching its maximum around mid of 2014. Cycle 24 is found to be weaker than the previous cycle in terms of disturbances that appeared on the solar surface and in the heliosphere [7]. However, several studies have confirmed that the CME rate in solar cycle 24 did not decrease as strongly as the sunspot number from the maximum of cycle 23 to the next maximum.

Some of them have reported that the properties of the earth directed CMEs, such as the internal structure of the magnetic field, may determine whether or not a geomagnetic storm subsequently occurs [8]. This suggests that the magnetic field serves as a link between flares, CMEs, and geomagnetic storms in the geomagnetic field of the magnetosphere. Have analysed active regions to explore the relationship between magnetic configurations of active regions and geomagnetic storms. Each active region was found to be associated with multiple full-halo Coronal Mass Ejections (CMEs). This study demonstrates that, although full-halo CMEs may originate from the same active region they don't need to have similar get effectiveness, depending on the magnetic configurations involved in the corresponding flare activities. The flares, CMEs, and geomagnetic storms are closely related magnetically, as already suggested by many other scientists. The effect CMEs, solar flares associated with radio burst on the geomagnetic field of magnetosphere have also been studied by some other scientists [9]. They have concluded that earth directed CMEs and solar flares associated with type II and type IV radio Burst are geoeffective. The main cause of intense geomagnetic storms is believed to be the large IMF structure which has an intense and long duration southward magnetic field component, Bz. They interact with the earth's magnetic field and facilitate the transport of energy into the earth's atmosphere through the reconnection process. Earth directed CMEs are likely to impact the magnetosphere to cause geomagnetic storms in the magnetosphere [10]. Found an increased rate of CMEs from higher latitudes since 2003 (middle of solar cycle 23) due to the weakening of polar photo-spheric magnetic field which allowed the eruptions from higher latitudes. A similar finding is also reported in Mishra et al. However, some studies suggested that an apparent increase in the CME rate in cycle 24 is due to some artifacts such as cadence and over counting of narrow and faint ejections in different automated and manual CMEs catalogs [11]. Furthermore, a recent study shows that the reduced total pressure in the heliosphere allows CMEs in cycle 24 to appear as halos at a shorter distance from the Sun and also at a lower speed than that in cycle 23. The study reveals that the increased rate of halo CMEs in cycle 24 is not due to eruption characteristics itself, but it is the effect of the weakened state of the heliosphere. Intense geomagnetic storms are found to be mainly caused by CMEs [12].

Methodology

In the present study, we have analyzed only extensive geomagnetic storms Dst ≤-150 nT and are observed during the period of solar cycle 24. If the magnitude of storm (Dst value) recurs for several consecutive days/hours, then the last day/hour is taken as the storm’s day. A set of four extensive large geomagnetic storms Dst ≤-150 nT are presented. We have analyzed extensive geomagnetic storms with different solar and interplanetary disturbances. The hourly values of geomagnetic index have been obtained by solar geophysical data (Prompt Comprehensive report) of U.S. department of commerce, NOAA and omni web data. The Coronal Mass Ejection (CMEs) data have been obtained by SOHO LASCO CME CATALOG, This CME catalog is generated and maintained at the CDAW data center by NASA and the catholic university of America in cooperation with the naval research laboratory SOHO is a project of international cooperation between ESA and NASA." The magnetic cloud and interplanetary shocks data have been obtained by database of Helio-spheric shock waves maintained at university of Helsinki the data base currently including the shocks from ACE, Wind STERO, Helios, Ulysses and Cluster space craft [13].

Results and Discussion

Extensive geomagnetic storms are frequently accompanied by CMEs or IP shocks in the solar wind that is caused by the collision of fast and slow plasma streams. A CME causes a solar wind disruption that is preceded by a shock wave. Interplanetary space missions that have encountered these disturbances have observed higher solar wind concentrations, speeds, and magnetic field amplitudes. Geomagnetic storms are created when these extraterrestrial disturbances hit Earth [14]. The frequency of CME driven storms normally varies with the solar activity cycle; however, it may be momentarily lower at the solar maximum. An increasing percentage of events are affected by CME-associated flows as the storm gets bigger. The extensive geomagnetic storms associated with interplanetary magnetic field are shown in Figures 1-4.

Extensive Geomagnetic storm occurred on “St. Patrick’s Day” (17 March 2015).

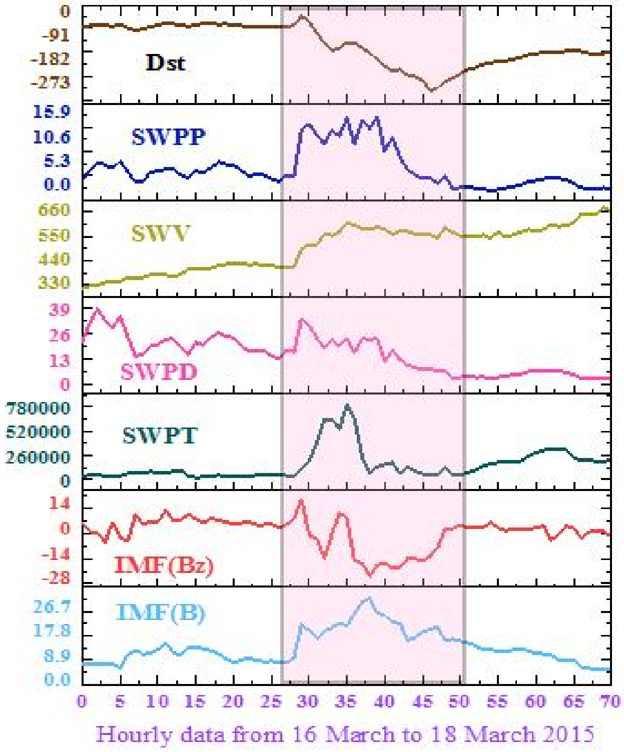

Figure 1. From top to bottom, the panels show the variations of Solar Wind Plasma Pressure (SWPP), Solar Wind Velocity (SWV), solar wind proton density (SWPD), Solar Wind Plasma Temperature (SWPTT), the south-north component of inter planetary magnetic field (IMFBz) and Interplanetary Magnetic Field (IMFB) with Dst (nT).

Extensive geomagnetic storm occurred on (23 June 2015).

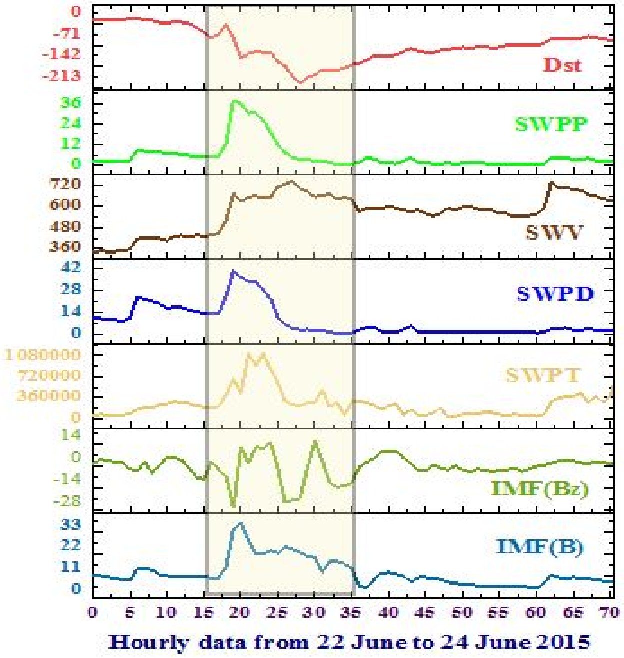

Figure 2. From top to bottom, the panels show the variations of Solar Wind Plasma Pressure (SWPP), Solar Wind Velocity (SWV), Solar Wind Proton Density (SWPD), Solar Wind Plasma Temperature (SWPTT), and the south-north component of Inter Planetary Magnetic Field (IMFBz) and Interplanetary Magnetic Field (IMFB) with Dst (nT).

Extensive geomagnetic storm occurred on (20 Dec 2015).

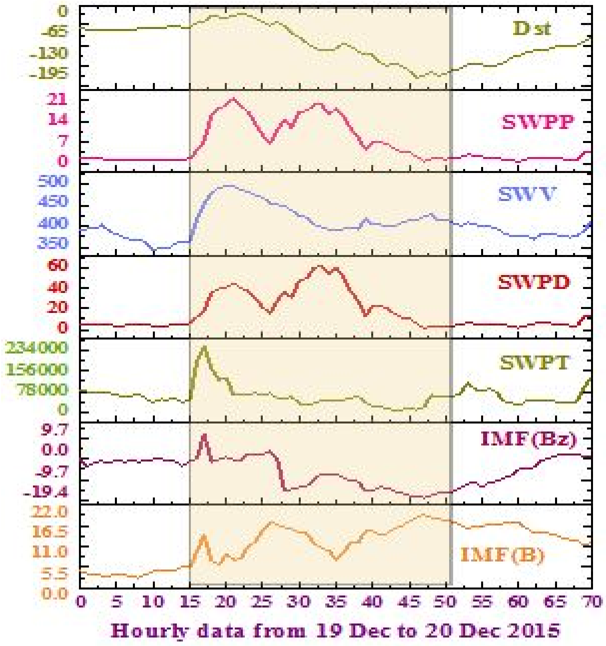

Figure 3. From top to bottom, the panels show the variations of Solar Wind Plasma Pressure (SWPP), Solar Wind Velocity (SWV), Solar Wind Proton Density (SWPD), Solar Wind Plasma Temperature (SWPTT), and the south-north component of Inter Planetary Magnetic Field (IMFBz) and Interplanatry Magnetic Field (IMFB) with Dst (nT).

Extensive geomagnetic storm occurred on (26 Aug 2018).

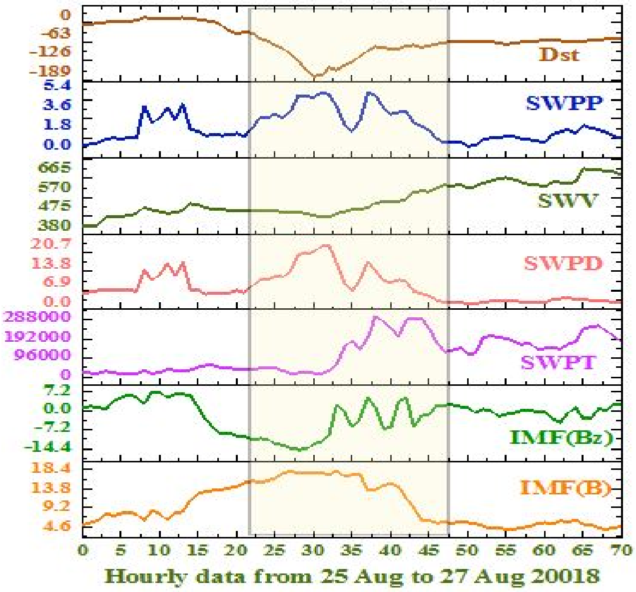

Figure 4. From top to bottom, the panels show the variations of Solar Wind Plasma Pressure (SWPP), Solar Wind Velocity (SWV), Solar Wind Proton Density (SWPD), and Solar Wind Plasma Temperature (SWPTT), the south-north component of Inter Planetary Magnetic Field (IMFBz) and Interplanetary Magnetic Field (IMFB) with Dst (nT).

Extensive geomagnetic storm occurred on “St. Patrick’s Day” (17 March 2015)

The first extensive geomagnetic storm (Dst <–150 nT) of solar cycle 24 occurred on of solar cycle 24 occurred on “St. Patrick’s Day” (17 March 2015). Notably, it was a two-step storm. The source of the storm can be traced back to the solar event on 15 March 2015. At ~2:10 UT on that day, SOHO/LASCO C3 recorded a partial halo Coronal Mass Ejection (CME). The initial propagation speed of this CME is estimated to be (719 Km/s) and acceleration (-9 ms^{-2}) which was associated with M-class solar flare. It is also associated with disturbances in the interplanetary magnetic field, disturbances in the southward component of the interplanetary magnetic field, disturbances in solar wind plasma density, disturbances in solar wind plasma velocity, disturbances in solar wind plasma pressure, with an initial value (4.4 nT), peak value of disturbance in IMF (30.7 nT), the initial value of disturbance in IMFBz (-1.2 nT), the peak value of disturbance in IMFBz (-26.1 nT), the initial value of disturbance solar wind proton density (12 N/cm^3), the peak value of disturbance in solar wind proton density (40.7 N/cm^3), the initial value of disturbance in solar wind plasma velocity (402 km/s), the peak value of disturbance in solar wind plasma velocity (683 km/s), the initial value of disturbance in solar wind plasma pressure (3.6 nPa), the peak value of disturbance in solar wind plasma pressure (14.3 npa) and the initial value of solar wind plasma temperature (39569 K), peak value of solar wind plasma temperature (807336K). An Interplanetary (IP) shock, likely driven by a type 1 Magnetic Cloud (MC), arrived at the Wind spacecraft at 04:00 UT on 17 March and caused a sudden storm commencement [15].

Extensive geomagnetic storm occurred on (23 June 2015)

The second extensive geomagnetic storms with (Dst ≤ -150) occurred on (23 June 2015). The source of the storm can be traced back to the solar event on 21 June 2015. At ~2:36 UT on that day, SOHO/LASCO C3 recorded a halo Coronal Mass Ejection (CME) with speed (1366 Km/s) and acceleration (21.2 ms^{-2}) which was associated with M-class solar flare. It is also associated with disturbances in the interplanetary magnetic field, disturbances in the southward component of the interplanetary magnetic field, disturbances in solar wind plasma density, disturbances in solar wind plasma velocity, disturbances in solar wind plasma pressure, with an initial value (8.7 nT), peak value of disturbance in IMF (37.7 nT), the initial value of disturbance in IMFBz (-5.1 nT), the peak value of disturbance in IMFBz (-29 nT), the initial value of disturbance solar wind proton density (8.7 N/cm^3), the peak value of disturbance in solar wind proton density (40.4 N/cm^3), the initial value of disturbance in solar wind plasma velocity (336 km/s), the peak value of disturbance in solar wind plasma velocity (742 km/s), the initial value of disturbance in solar wind plasma pressure (3.6 nPa), the peak value of disturbance in solar wind plasma pressure (36.8 npa) and the initial value of solar wind plasma temperature (70908 K), peak value of solar wind plasma temperature (812290K). An Interplanetary (IP) shock, likely driven by a type 2 Magnetic Cloud (MC), arrived at the Wind spacecraft at 18:38 UT on 22 June and caused a sudden storm commencement [17,18].

Extensive geomagnetic storm occurred on (20 Dec 2015)

The third extensive geomagnetic storms with (Dst ≤ -150) occurred on (20 Dec 2015). The source of the storm can be traced back to the solar event on 16 Dec 2015. At ~14:24 UT on that day, SOHO/LASCO C3 recorded a halo Coronal Mass Ejection (CME) with speed (525 Km/s) and acceleration (4.2 ms^{-2}) which was associated with B-class solar flare. It is also associated with disturbances in the interplanetary magnetic field, disturbances in the southward component of the interplanetary magnetic field, disturbances in solar wind plasma density, disturbances in solar wind plasma velocity, disturbances in solar wind plasma pressure, with an initial value (7.6 nT), peak value of disturbance in IMF (19.5 nT), the initial value of disturbance in IMFBz (-6.9 nT), the peak value of disturbance in IMFBz (-18.1 nT), the initial value of disturbance solar wind proton density (14 N/cm^3), the peak value of disturbance in solar wind proton density (56 N/cm^3), the initial value of disturbance in solar wind plasma velocity (392 km/s), the peak value of disturbance in solar wind plasma velocity (468 km/s), the initial value of disturbance in solar wind plasma pressure (3.6 nPa), the peak value of disturbance in solar wind plasma pressure (18.7 npa) and the initial value of solar wind plasma temperature (31295 K), peak value of solar wind plasma temperature (206798K) [19]. An Iinterplanetary (IP) shock, likely driven by a Magnetic Cloud (MC), arrived at the Wind spacecraft at 15:38 UT on 19 Dec and caused a sudden storm commencement [20].

Extensive geomagnetic storm occurred on (26 Aug 2018)

The last extensive geomagnetic storms with (Dst ≤ -150) occurred on (26 Aug 2018). The source of the storm can be traced back to the solar event on 26 Aug 2018. At ~21:36 UT on that day, SOHO/LASCO C3 recorded a partial halo Coronal Mass Ejection (CME) with speed (167 Km/s) and acceleration (-0.2 ms^{-2}) which was associated with B-class solar flare. It is also associated with disturbances in the interplanetary magnetic field, disturbances in the southward component of the interplanetary magnetic field, disturbances in solar wind plasma density, disturbances in solar wind plasma velocity, disturbances in solar wind plasma pressure, with an initial value (6.2 nT), peak value of disturbance in IMF (19.1 nT), the initial value of disturbance in IMFBz (-3.9 nT), the peak value of disturbance in IMFBz (-12.9 nT), the initial value of disturbance solar wind proton density (6.2 N/cm^3), the peak value of disturbance in solar wind proton density (23.2 N/cm^3), the initial value of disturbance in solar wind plasma velocity (401 km/s), the peak value of disturbance in solar wind plasma velocity (519 km/s), the initial value of disturbance in solar wind plasma pressure (0.8 nPa), the peak value of disturbance in solar wind plasma pressure (4.5 npa) and the initial value of solar wind plasma temperature (21481 K), peak value of solar wind plasma temperature (205987K). An Interplanetary (IP) shock, likely driven by a type 2 Magnetic Cloud (MC) arrived on 26 Aug and caused a sudden storm commencement.

Conclusions

In this paper, we have presented the effect of extensive geomagnetic storms on the variation associated with various solar parameters and Interplanetary Magnetic Field Components (IMFB and Bz) which were potentially geo-effective that occurred on "St. Patrick's Day" (17 March 2015), (23 June 2015), (20 Dec 2015) and (26 Aug 2018) depending upon the availability of data during period of solar cycle 24.

We summarize the main results of the paper as follows:

- The first two comprehensive analysis of the effects of the St Patrick's day geomagnetic storm (17–19 March 2015) and (25–27 Aug 2018) storms with Dst=–223 nT and –204 nT were most strong space weather event of solar cycle 24. Stronger and longer duration signal amplitude anomalies occurred due to the March storm as compared to the June storm.
- The first extensive geomagnetic storm (Dst <–150 nT) of solar cycle 24 occurred on of solar cycle 24 occurred on "St. Patrick's Day" (17 March 2015). Notably, it was a two-step storm. The source of the storm can be traced back to the solar event on 15 March 2015. At ~2:10 UT on that day, SOHO/LASCO C3 recorded a partial halo Coronal Mass Ejection (CME). The initial propagation speed of this CME is estimated to be (719 Km/s) and acceleration (-9 ms^{-2}) which was associated with M-class solar flare. It is also associated with an Interplanetary (IP) shock, likely driven by a type 1 Magnetic Cloud (MC), arrived at the Wind spacecraft at 04:00 UT on 17 March and caused a sudden storm commencement.
- The second extensive geomagnetic storms with (Dst ≤ -150) occurred on (23 June 2015). The source of the storm can be traced back to the solar event on 21 June 2015. At ~2:36 UT on that day, SOHO/LASCO C3 recorded a halo Coronal Mass Ejection (CME) with speed (1366 Km/s) and acceleration (21.2 ms-2) which was associated with M-class solar flare. It is also associated with an interplanetary (IP) shock, likely driven by a type 2 Magnetic Cloud (MC), arrived at the Wind spacecraft at 18:38 UT on 22 June and caused a sudden storm commencement.
- The last two comprehensive analysis of the effects of the extensive geomagnetic storm (19–20 Dec 2015) and (22–25 June 2018) storms with (Dst=–198 nT and –189 nT) were most intense space weather event of solar cycle 24.
- The third extensive geomagnetic storms with (Dst ≤ -150) occurred on (20 Dec 2015). The source of the storm can be traced back to the solar event on 16 Dec 2015. At ~14:24 UT on that day, SOHO/LASCO C3 recorded a halo Coronal Mass Ejection (CME) with speed (525 Km/s) and acceleration (4.2 ms^{-2}) which was associated with B-class solar flare. It is also associated with disturbances in the interplanetary magnetic field, disturbances in the southward component of the interplanetary magnetic field, disturbances in solar wind plasma density, disturbances in solar wind plasma velocity, disturbances in solar wind plasma pressure. It is also associated with an Interplanetary (IP) shock, likely driven by a Magnetic Cloud (MC), arrived at the Wind spacecraft at 15:38 UT on 19 Dec and caused a sudden storm commencement.
- The last extensive geomagnetic storms occurred on 26 Aug 2018. The source of the storm can be traced back to the solar event on 26 Aug 2018. At ~21:36 UT on that day, SOHO/LASCO C3 recorded a partial halo coronal mass ejection (CME) with speed (167 Km/s) and acceleration (-0.2 ms-2) which was associated with B-class solar flare. It is also associated with an Interplanetary (IP) shock; likely driven by a type 2 Magnetic Cloud (MC) arrived on 26 Aug and caused a sudden storm commencement.

We also found that choosing the correct Dst$_{min}$ estimating formula for predicting the intensity of MC associated geomagnetic storms is crucial for space weather predictions, because solar wind speed, solar wind plasma pressure, solar wind proton density, interplanetary magnetic field IMFB as well as Bz, plays an important role in the prediction of geomagnetic activity.

Another important scientific goal is to understand how energy, momentum, and mass are transferred from the Sun to Earth under various solar disturbances under various planetary configurations.

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