Variation of intense geomagnetic storms at high latitudes During Solar Cycle 24

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ABSTRACT: It is important to understand the complicated current system in magnetosphere and ionosphere during the storm. Because the solar wind has huge amount of charged particle, so those charged particle interact to Earth magnetic field affect life on the Earth. Moreover that it is clear from the observations of geomagnetic storm events that the occurrence of Geomagnetic Storms is highly correlated with the southward turning of Bz, the z component of IMF. The magnitude of turning of Bz into southward direction from northward direction depends highly upon the severity of the storm.

The magnetosphere sub storm plays a crucial role in the solar wind energy dissipation into the ionosphere. We report on the intensity of the high-latitude ionospheric irregularities during one of the largest storms of the current solar cycle. The database of more than 2500 ground-based Global Positioning System (GPS) receivers was used to estimate the irregularities occurrence and dynamics over the auroral region of the Northern Hemisphere.

Keywords. Ionosphere irregularities; Geomagnetic storm; Auroral latitudes, Geocentric Solar Magnetospheric (GSM)

1 Introduction

A geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. Occurrence of the ionospheric irregularities is difficult to forecast and to model, because of the temporal and spatial variability of the ionosphere and solar activity. The linkage of the high-latitude ionospheric irregularities, which produced the radio signal scintillation, to the GPS measurements is of special importance for several research activities. One of these concerns the study of the physical processes in the polar region, needed to understand the fundamental aspects of the coupling between the solar wind and the Earth’s magnetosphere and ionosphere. The other focuses on the space-related technical applications, as the presence of the ionospheric irregularities can impact variety of trans-ionospheric radio communication and even distort the performance of the global navigation systems (e.g., Smith et al. 2008). So, study of morphology and spatio-temporal dynamics of the ionospheric irregularities, their dependences on geophysical factors for proper specification by an empirical model is actual for both fundamental and applied tasks. This study focused on the testing of potential drivers for the GPS-based empirical modeling of the ionospheric irregularities' occurrence and intensity in the polar and auroral latitudes. Geomagnetic storms of solar cycle 24 are reviewed in this study. Among all the storm events occurred during the solar cycle only those storms whose DST value are less than (≤ -100nT) are considered which represented an intense Geomagnetic storms. It is found that the effect of solar and geomagnetic storm disturbances is strongest at the low latitude and weakest at the high latitude during the geomagnetic storm time.

1.1 The Geomagnetic Storm of March 7-11 2008

![Graphs showing IMF (Bz), solar wind speed, interplanetary electric field (IEF)Ey, and Dst-index on March 7-11 2008.]

Figure 1.1: The Geomagnetic storm of March 7-11 2008
On March 9th 2008 the effect of Geomagnetic storm event, the inter-planetary magnetic field (IMF) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel and disturbance storm time (DST) index bottom panel for five Consecutive days is plotted from March 7/2008 to March 11/2008. The initial phase of the storm day started from March 7 and 8, their DST index value -36 nT (weak storm) at 04:00 UT followed by moderate storm (-57 nT) at 05:00 UT. But the main phase of the storm occurred on March 9/2008 which was another type of moderate storm (-86 nT) at 06:00 UT. The DST-index value increased and the recovery storm started on March 10 and 11, their corresponding DST-index value -83 nT at 07:00 UT and -70 nT at 08:00 UT and the storm type was moderate storm for both. From the above Fig.(1.1) the interplanetary magnetic field (IMF) negative (southward) and the interplanetary electric field (IEF) north ward shows the decreasing of the ring current. As indicated in Fig. (1.1), on top panel shows the IMF (Bz) during storm time is continuously changing its polarity from north to south and vice-versa at the same time the DST index value on bottom panel reveals it is a moderate geomagnetic storm. Similarly the interplanetary electric field, lower middle also indicating a fluctuating signature. At the same time the solar wind on upper middle Panels is small as compared to storms driven by CMEs. These all signature reveals the source of the geomagnetic storm is a CIR. Also the Fig.(1.1) indicates the solar wind speed increasing positively and cause for the compression of magneto-sphere because of the magnetopause pushed inward.

1.2 The Geomagnetic Storm of July 20-24 2009
The interplanetary magnetic field (IMF) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel and disturbance storm time (DST) index bottom panel for five consecutive days plotted from July 20/2009 to July 24/2009 shown in the figure 1.2. The IMF (Bz) was initially southward and then reversed to northward direction and oscillates again from north to south directions which means that the graph is fluctuated. The initial phase of the storm day started from July 20 and 21, their DST-index value = -53 nT (moderate storm) at 05:00 UT and -80 nT (moderate storm) at 06:00 UT respectively. But the main phase of the storm occurred on July 22/2009 their value was -83 nT at 07:00 UT which is the maximum DST index value and the storm was moderate storm to be observed. The DST index value increase and the recovery phase storm started on July 23 and 24 their corresponding DST-index value -69 nT at 08:00 UT and -75 nT at 09:00 UT respectively. From Fig.(1.2) there is a good interaction between interplanetary magnetic field (IMF (Bz)) and Interplanetary electric field (IEF) because when the IMF northward (positive) the IEF was south ward (negative), So the solar wind particles have a much easier time entering to our magnetosphere and affect the Earth magnetic field. This means that the IMF (Bz) often herald widespread auroras by solar wind. In addition to this the graph shows there was turn fluctuated, this means there was low geomagnetic storm events and difficult to measured and the source of the geomagnetic storm event was the CIR due to low solar activity. As observed from Fig. (1.2) the solar wind speed increased positively, so the compression of magnetosphere occurred.
1.3 The Geomagnetic Storm of August 2-6 2010

On August 4th 2010 the effect of Geomagnetic storm expressed, when the interplanetary magnetic field (IMF) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel and disturbance storm time (DST) index bottom panel for five Consecutive days plotted from August 2/2010 to August 6/2010. The initial phase of the storm day started from August 2 and 3, their DST-index value -72 nT at 24:00 UT and -69 nT at 01:00 UT, the type of storm for initial phase categorized as moderate storm. The storm was initiated in August 4/2010 and its minimum DST value is recorded about -74 nT which reveals the storm is moderate storm. The DST-index value increased and the recovery storm started on August 5 and 6 their corresponding DST-index value -65 nT at 03:00 UT and -64 nT at 04:00 UT respectively and a moderate storm type was observed. The IMF (Bz) on to panel of Fig. (1.3) shows oscillation from north to south and vice-versa which is one indicator of CIR driven storm. The SWS and IEF on upper middle and lower middle panels respectively are also showing similar behavior. That is the IEF changing its polarity. The Dst value on the lower panel shows a longer recovery period which is a signature of the CIR driven geomagnetic storm. As observed from Fig. (1.3) the IMF (Bz) negative (south ward) and IEF north ward (positive), causes decreasing of the ring current. But the solar wind speeds positively increased, so the compression of magnetosphere occurred.

1.4 The Geomagnetic Storm of October 23-27 2011

The effect of Geomagnetic storm event on October 25th 2011 expressed as, the interplanetary magnetic field (IMF) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel, and disturbance storm time (DST) index bottom panel for five consecutive days plotted from October 23/2011 to October 27/2011. An intense magnetic storm event of October 25th, 2011 is illustrated in Fig. (1.4). This storm had a minimum DST excursion of -147 nT. The IMF
Figure 1.4: The Geomagnetic storm of October 23-27 2011

(Bz) and Dst index for the duration of October, 2011. The sudden storm commencement occurred at 24:00 UT. The DST amplitude started decreasing (main phase onset) from 01:00 UT and reached its minimum amplitude of -147 nT at 02:00 UT. It was accompanied with a steep drop and polarity reversal in z component of IMF, Bz. It turns to southward and attain a maximum negative value of -64 nT at 08:00 UT afterwards there was a steep rise noticed and it turns to northwards. In the main phase of storm the IEF has reached its maximum value obtained at the same hour when the IMF (Bz) is turned south and the DST has obtained its least value. After the IMF (Bz) is turned North the DST index gently increases to its normal time in 24 hours time. It is clear from the observations of geomagnetic storm events that the occurrence of geomagnetic storms is highly correlated with the southward turning of Bz, the z component of IMF. The magnitude of turning of Bz into southward direction from northward highly depends upon the severity of the storm.

1.5 The Geomagnetic Storm of March 7-11 2012

Figure 1.5: The Geomagnetic storm of March 7-11, 2012
The effect of Geomagnetic storm on March 9th 2012 also explained with the value of interplanetary magnetic field (IMF) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel and disturbance storm time (DST) index bottom panel for five consecutive days plotted from March 7/2012 to March 11/2012. The initial phase of the storm day started from March 7 and 8 with a DST-index value of -78 nT at 08:00 UT and -114 nT at 07:00 UT respectively. But the main phase of the storm occurred on March 9 their value was -131 nT at 09:00 UT which means the minimum DST-index value and the maximum Geomagnetic storm shown and the storm categorized as an intense storm. The DST-index value increase the recovery storm started on November 10 and 11 their corresponding DST-index value -110 nT at 10:00 UT and -111 nT at 11:00 UT the storm type was an intense storm for both. And also the IMF (Bz), top panel of Fig. (1.5) shows southward on day 7 and continuously started to oscillate between south and north directions. This stays up to three days. This type of storm is classified as CIR driven storm. The interplanetary electric field also shows fluctuations in an oscillatory manner. From Fig.(1.5), there is a good interaction between interplanetary magnetic field (IMF (Bz)) and Interplanetary electric field (IEF) because when the IMF southward (negative) the IEF was positive (northward) which means that they moves in opposite direction, due to this the charged particle easily enter to the magnetosphere and is good opportunity to reduce the Earth magnetic field.

**1.6 The Geomagnetic Storm of March 15-19 2013**

The effect of Geomagnetic storm on March 17th 2013 described with the graph of IMF top panel, SWS upper middle panel, IEF lower middle panel and DST index bottom panel plotted for five consecutive days from March 15/2013 to March 19/2013. The initial phase of the storm day started from March 15 and 16 and their DST-index value -99 nT at 19:00 UT and -116 nT at 20:00 UT respectively.

But the main phase of the storm occurred on March 17 their value was -132 nT at 21:00 UT which means the minimum DST-index value and the maximum Geomagnetic storm shown and the storm type was an intense storm event. The DST-index value decrease and the recovery phase storm started on March 18 and 19 their corresponding DST-index value -131 nT at 22:00 UT and -116 nT at 23:00 UT respectively. The Source of Geomagnetic storm on March 17th 2013 was the occurrence of CME on March 15th 2013 as reported by NASA’s Advanced Composition Explorer. As the graph indicates there is a good interaction between IMF (Bz) and IEF because when the IMF southward and the IEF was northward, the magnetic reconnection occurred and solar 50 wind particle easier to much on the magnetosphere and reduced the earth magnetic field. In addition to these as the graph show there was no turn fluctuated, this means there was large geomagnetic storm events and to be measured. The source of the geomagnetic storm event was the CME due to high solar activity because as Fig. (1.6), shown the DST-index value less than (< -100nT), indicates it is good enough to produce shock at the upper boundary of the magnetosphere.
1.7 The Geomagnetic Storm of February 17-21 2014

To describe the storm of February 19th 2014, the interplanetary magnetic field IMF (Bz) top panel, solar wind speed (SWS) upper middle panel, interplanetary electric field (IEF) lower middle panel and the disturbance storm time (DST) index value bottom panel have been plotted for five consecutive days during February 17/2014 to February 21/2014 and its main phase was 19th which was shown in Fig. (1.6). From the variation of the DST index value the three storm, the initial occurred on 07:00 UT its value -95 nT (moderate) storm and the main phase occurred later two hours (09:00 UT) the value was -116 nT which was the maximum value Record and high geomagnetic storm occurred and which is called an intense storm event. After one hour later its value decreased and the recovery phase happened from 10:00 UT to 11:00 UT their value was -94 nT and -83 nT, the storm type was moderate. The significant enhancement of DST index from February 17-21 on 2014 was the indication of CME interacts to the solar wind and caused for the Geomagnetic storm to be happened. The IMF (Bz) in repeatedly reverses from south to north and vice-versa several times implies that several storms were occurred during the storm event time. This is also rejected in the DST index value. As the graph indicates there was a good interaction between IMF (Bz) and Interplanetary electric field (IEF) because when the IMF south ward the IEF north ward, and the magnetic reconnection occurred and solar wind particle easier to much on the magnetosphere and reduced the earth magnetic field. This means that the IMF (Bz) southward turn highly depends on the severity of geomagnetic storm. In addition to these as the graph show there was no turn fluctuated, this means there was large geomagnetic storm events and to be measured. Due to this the cause of the geomagnetic storm event was the CME due to high solar activity.

1.7 The Geomagnetic Storm of 17 March 2015 (The St. Patrick’s day geomagnetic storm)

The severe geomagnetic storm occurred on 17 March 2015 and caused the dramatic response in the ionosphere–plasmasphere–magnetosphere system.
Fig 1.7 Variations of the interplanetary and geomagnetic parameters during 15–20 March 2015 storm: the IMF Bz, Bx, and By components (Geocentric Solar Magnetospheric (GSM)), density, velocity, and dynamic pressure of the solar wind, and Sym-H index.

Red line indicates the SSC time.

Figure (1.7) shows the variations of interplanetary and geomagnetic parameters during 15–20 March 2015. The sudden storm commencement (SSC) was registered at ~0445 UT and then there was a quick drop of the SYM-H index to the value of ~226 nT, observed at ~2300 UT, with a couple of local minima of ~93 and ~164 nT at ~0940 and ~1740 UT respectively (Fig.1.1). The planetary index of the geomagnetic activity Kp reached the maximum value of 8 after ~12 UT on 17 March 2015, qualifying it as a severe geomagnetic storm. During the main phase of the storm (17 March), the interplanetary magnetic field (IMF) orientation displayed a highly complex behavior. Three IMF components (top panels of Fig. 1.7) switched several times from positive to negative values and vice versa. Right after the shock arrival, the northward IMF Bz component reached the value of about 25 nT. At ~0530 UT the IMF Bz turned southward and reached the first minimal value of ~18 nT at 0615 UT. Then the IMF Bz sharply turned northward and varied significantly between north and south during ~8 h. After ~1340 UT the Bz turned southward again and remained south till the end of this day. From ~06 till 11 UT, there are observed dominating positive Bx and negative By with peak values of 16.5 and ~16.8 nT for Bx and By, respectively. During 11–15 UT with the new southward turning of Bz, the opposite situation with Bx/By domination occurred—Bx became negative with the minimal values of ~14 nT while By component became positive with the peak of 30 nT. After 15 UT, IMF By turned sharply to negative values, reaching ~8 nT, and then again to the positive ones with the new peak of 20 nT around 18 UT. Kamide and Kusano (2015) reported that this severe geomagnetic storm (G4 level) was a result from the superposition of two successive, moderate storms, driven by two successive, southward IMF structures. The intense geomagnetic storm on 17–18 March 2015 leads to the auroral particle precipitation and an enhancement of the substorm activity. During this storm, aurora was observed as far south as 55–60° MLAT in the USA, Europe, and Japan (e.g., Nishitani et al. 2015; Kamide and Kusano 2015; GUVI TIMED JHU/APL website 2015). This storm results in significant consequences on satellite operations, radio waves propagation, and GNSS related services and applications. As reported by the WAAS Test Team (Wanner 2015) during the 17 March 2015 storm, the degradation of positioning performance was registered.

1.8 G3 (STRONG) Geomagnetic storms observed on 08 May 2016

G3 (Strong) geomagnetic storm conditions were observed beginning at 08/0559 UTC and G3 storms are expected to persist until 08/0900 UTC. A surprisingly strong geomagnetic storm hit Earth this morning. This is likely the earlier than expected arrival of a coronal hole solar wind stream. The NOAA SWPC reported strong G3 geomagnetic storm conditions and the Wing-Kp as well as Potsdam reported moderate G2 geomagnetic storm conditions. Today's header image comes from the talented Brian Drourr Photography who captured this amazing shot from Algonquin Provincial Park, Canada.

The Bz component of the interplanetary magnetic field went down to -13 nT for a couple of hours after midnight UTC and this combined with the fast solar wind speed (500km/s) caused a significant geomagnetic response that sparked aurora which could be seen from many locations in the northern United States.

More geomagnetic storming up to the minor G1 geomagnetic storm level remains possible in the hours ahead as the solar wind speed remains elevated around 600km/s and the direction of the IMF (Bz) is mostly southward, dipping as low as -10nT.

1.9 Geomagnetic storms observed on May 23, 2017 (CME impact sparks G3 - Strong geomagnetic storm)

In the early days of 2017 September, an exceptionally energetic solar active region AR12673 aroused great interest in the solar physics community. It produced four X class flares, more than 20 CMEs and an intense geomagnetic storm, for which the peak value of the Dst index reached up to -142nT at 2017 September 8 02:00 UT. In this work, we check the interplanetary and solar source of this intense
Geomagnetic storm. We find that this geomagnetic storm was mainly caused by a shock-ICME complex structure, which was formed by a shock driven by the 2017 September 6 CME propagating into a previous ICME which was the interplanetary counterpart of the 2017 September 4 CME. To better understand the role of this structure, we conduct the quantitative analysis about the enhancement of ICME's geoeffectiveness induced by the shock compression. The analysis shows that the shock compression enhanced the intensity of this geomagnetic storm by a factor of two. Without shock compression, there would be only a moderate geomagnetic storm with a peak Dst value of -79 nT. In addition, the analysis of the proton flux signature inside the shock-ICME complex structure shows that this structure also enhanced the solar energetic particles (SEPs) intensity by a factor of ~5. These findings illustrate that the shock-ICME complex structure is a very important factor in solar physics study and space weather forecast.

A coronal mass ejection (CME) produced during the early UTC hours of May 23, 2017 hit Earth's magnetic field at 15:36 UTC on May 27, more than 24 hours after it was expected. Although the solar wind speed is relatively slow, the embedded magnetic field had a prolonged period of southward Bz that managed to spark G3 - Strong geomagnetic storm. G3 - Strong geomagnetic storm (K-index of 7) threshold was reached at 04:19 UTC. Under G3 conditions, the area of impact is primarily pole ward of 50 degrees Geomagnetic Latitude. Power system voltage irregularities are possible and false alarms may be triggered on some protection devices. Spacecraft systems may experience surface charging and increased drag on low Earth-orbit satellites and orientation problems may occur. Intermittent satellite navigation (GPS) problems, including loss-of-lock and increased range error may occur. HF (high frequency) radio may be intermittent, aurora may be seen as low as Pennsylvania to Iowa to Oregon.

The quiet unsettled levels are expected after 12:00 UTC on May 28 through May 29 as CME effects diminish. Generally, quiet conditions are expected on May 30 with the return of a nominal solar wind regime.

Discussion

Ionospheric variability during the magnetic storms of February 17-21, 2014 one intense storms was observed in the month of February 19, 2014. Hourly foF2 variation from 17 to 21 are plotted along with AE, Kp and Dst index in Fig.1. The intense storm of February 17 started with SSC at 09:00 UT. With maximum negative excursion of Dst ~ -112 nT is noted and the storm lasted until February 19 which was followed by the recovery phase on February 21. AE value is reaches 520 nT when Dst has more negative. With the main
A CME exploded from the vicinity of sunspot 1164 during the late hours of March 7, 2011. It leapt away from the Sun traveling ~2200 km/s, making it the fastest CME since September 2005. On March 9, active region 1166 erupted in an X1.5 flare. A R3-level radio blackout was reported. The related CME caused a G2 geomagnetic storm two days later. 21 M-class flares were registered this month.

On August 5, 2011, the combined cloud of three consecutive CMEs produced brilliant auroras, reported as far south as Oklahoma and Alabama. The geomagnetic storm reached a G4 (severe) level, enough to make power outages. It was one of the strongest geomagnetic storms in years. In the southern hemisphere, auroras could have been seen as far north as South Africa, Southern Chile and Southern Australia. The CMEs were hurled by three M-class flares erupted in active sunspot 1261: M1.4 on August 2, M6.0 on August 3 and M9.3 on August 4.

Sunspot 1283 erupted with an M5.3-class solar flare on September 6 at 01:50 UT. A R2 (moderate) blackout radio alert was issued. The burst was Earth-directed. Just 21 hours later, an X2.1-class flare – some four times stronger than the earlier flare – erupted from the same sunspot region. NOAA detected a R3 (strong) radio blackout and a S1 (minor) solar radiation storm. The combined CMEs of these bursts arrived the Earth on September 9, provoking a G3 (strong) geomagnetic storm.

The ionospheric storm response depends on the interplanetary drivers of the geomagnetic storms. In non-CME cases (e.g., storms driven by CIRs/HSSs) the energy dissipation in the upper atmosphere tends to increase the ionospheric ionization especially in the afternoon sector. The ionospheric effects that accompany the CME driven storms are satisfactorily captured by current ionospheric prediction models, operational and phenomenological. Substantial improvements in our prediction ability will be driven by the better description of the ionospheric response to storm events driven by CIRs/HSSs.

The effect of Geomagnetic storm that observed in my result discussed above:

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<th>STORM TYPE</th>
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<td>Moderate</td>
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<tr>
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<td>Moderate</td>
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Conclusion

The above study shows the Variation of Geomagnetic storm for solar cycle 24. The present analysis also shows there was large Geomagnetic storms and the source of the storm was CME but from 2007 to 2010 the Geomagnetic storm was low and the corresponding cause of the storm event was CIR, where as from 2011 until 2014 the Geomagnetic storm event was large and the source of storm was the CME due to high solar activity. The strong geomagnetic storms observed in 2015 show that the dynamics of the high-latitude ionospheric irregularities and the ROTI intensity strongly depend on both the auroral electrojet and the auroral hemispheric power indices. The geomagnetic storm event for 2017 was the CME due to the high solar activity.

The graph indicated for 2012 is fluctuated so it is source is CIR rather than CME. In short 9.09 percent of the analysis show Extreme event, 36.36 percent of the analysis show moderate event and the other 54.54 percent was an intense storm event. Extended periods of southward IMF (Bz) leads to the main phase of the magnetic storm and is responsible for magnetic reconnection. On the other hand, northward IMF (Bz) has only minimal day side reconnection. The increase day side reconnection increases the penetration of the solar wind into the magnetosphere, increases convection and ring current injection. The storms caused by CIR storms are usually associated with high speed streams and their DST values are greater than (> -100nT), where as the storm caused by CME associated with high speed and DST value less than (< -100nT), the magnetic field show high storm event and disturb the Earth magnetic field which means that more negative value of DST index value cause reducing the Earth magnetic field and affect their purpose. CME’s faster than ~ 500 Km/s eventually drive shock waves which normally strike the Earth’s magnetosphere in 24 to 36 hours after the event onset on Sun. The solar wind energy deposited into the magnetosphere during geomagnetic storms will eventually be dissipated into the ionosphere and thermosphere.

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