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Analysis of the Occurrence of the First Most Intense Geomagnetic Storm (G4) to Hit the Earth in Solar Cycle 25; A Multiple-Step Geomagnetic Storm

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Abstract

A study of the occurrence of the first intense Geomagnetic storm (G4) to hit the Earth since the start of the Solar Cycle 25 is carried out. This study analyzed the Geomagnetic Storm that occurred between the 28th of October and the 7th of November 2021. The values of the Disturbance storm time (Dst) index of the storm reach -115 nT (G4) which occurred on the 4th of November at 1300UT. The storm is the first intense magnetic storm that occurred in the solar cycle 25. It is also a multiple-step storm with moderate two-step storm occurrence which occurred on the 5th and 6th of November at 1500UT and 0600UT respectively towards the recovery phase after the intense storm. The interplanetary magnetic field (IMF)Bz (nT) during these storm events decreases. Our analysis shows that the rise in solar wind speed, temperature and the enhancement of pressure plays a significant role in the occurrence of the first intense Geomagnetic storm of Solar Cycle 25.

Keywords: Intense Geomagnetic Storm; Disturbance Storm Time Index; Interplanetary Magnetic Field; Solar Wind Speed.

I. Introduction

The sun being the most important body in the solar system has a regular pattern of change called the solar cycle which usually lasts for approximately 11 years after which the magnetic poles flip. The solar cycle is classified into solar maximum and solar minimum. Solar activities such as solar flares, high-speed solar wind, coronal mass ejections (CMEs) and its associated geomagnetic storm can affect the Earth. Geomagnetic storms are intense disturbances in the Earth's magnetosphere [1]. They are mainly caused by solar wind or Coronal Mass Ejection. CME are huge bubbles of magnetized plasma ejected from the sun [2]. During geomagnetic storm occurrence, energy and momentum are deposited into the Earth's magnetosphere which in turn energizes the terrestrial atmosphere through Joule heating and particle precipitation [3]. Reference [4] noted that during geomagnetic storms, the number of particles in the ring current increases and as a result causes a southward depression of the earth's magnetic field. Reference [5], noted that during geomagnetic storm events, electron density is significantly enhanced, particularly in the aurora zone, which leads to a large increase in radio wave absorption. According to [6], the phases of the occurrence of a geomagnetic storm are classified into three phases namely, the initial phase, the main phase and the recovery phase. The initial phase IP or Sudden Storm Commencement (SSC) marks the gradual commencement of the storm. The main phase is the time from which Dst declines southward i.e. $-50\,nT \leq Dst \leq -350\,nT$ and beyond while the recovery phase is when the Dst plot returns to quiet time or its pre-storm values. The activity of the ring current as a major form of magnetic disturbance is observed by different indices among which is the Disturbance Storm Time (Dst) index [7] which is the most common and efficient indication of magnetospheric disturbances, particularly for geomagnetic storms [8].

Reference [8] noted that the velocity V and the magnetic field are the most important parameters in the production of perturbations of the geomagnetic field. In recent times, several research [7], [9], [10], [11] and [12] have been carried out on geomagnetic storms in the previous solar cycles. However, many discrepancies still exist in the behaviours of solar wind parameters. Also, no study has been carried out on the first intense storm of solar cycle 25 which occurred in November 2022. Therefore, this paper seeks to study the effect of this storm and the behaviours of its associated solar wind parameters on the terrestrial atmosphere.

II. Method and Data Selection Criteria

The hourly Dst data used in this research was obtained from World Data Centre (WDC) for geomagnetism Kyoto, 2021-12-08. Using simple Python code and libraries, the hourly IAGA format data was reduced to mean hourly data for easy analysis using (1) for all values ranging from 300-320 days (27th October- 16th November 2021).

$$X = \frac{\sum_{i=0}^{60} x_i}{n} \quad (1)$$

Where X is the mean of each solar wind parameter, x_i the value of each 1 minute resolution solar wind parameters and n, the total number of each solar wind parameter.

The Dst index is expressed in Nano-Tesla (nT). In other to study the effect of this solar storm in the terrestrial atmosphere, we compared the solar wind parameters e.g. solar wind speed, Plasma Temperature, Interplanetary Magnetic Field (IMF) etc. with Dst variation.

III. RESULTS

Fig. 1 has three panels (a), (b) and (c). Panel A shows the Dst variation, panel (b) represents the IMF B_z (nT) and panel (c) shows the solar wind speed (km/h). The Dst index fluctuates until 1300UT on November 4th when it gradually depressed to attain the first $Dst_{min} = -110\,nT$. The Dst sharply increased and immediately depressed to Dst min = -115nT indicating the storm main phase. While the Dst turns southward below $-40\,nT, B_z$ depresses as observed in panel (b). At $0400\,UT$ on November 6th, The Dst decreased to $-46nT$ and thereafter begin to recover. This is a double-step geomagnetic storm.

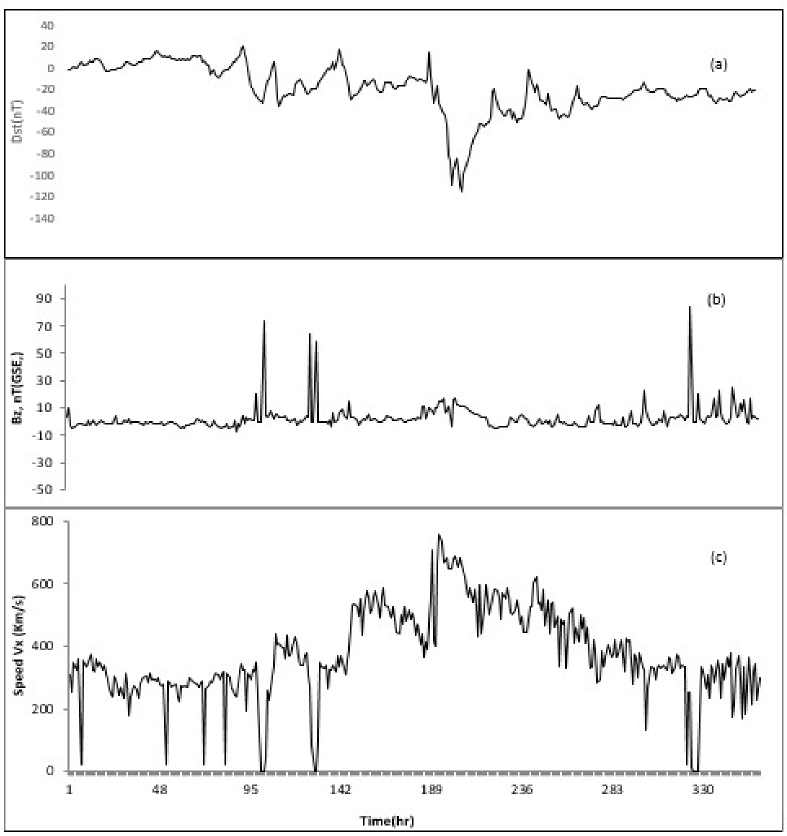

Fig. 1 Panel (a) shows the Dst plot in Nano-Tesla while Panel (b) and (c) shows IMF B_z and Solar wind speed respectively.

The solar wind speed, on 4th November, increased from $421k\ m/s - 756\ km/s$ before the commencement of the first storm and then decreases to 556km/s during the storm's main phase.

Fig. 2 contains three panels; (a) (b) and (c). Panel (a) shows the Dst variation, Panel (b) shows the variation of plasma temperature and Panel (c) shows the dynamic flow pressure.

The Plasma temperature and the dynamic flow pressure were observed to increase distinctively before the commencement of the storm. At 0700UT, November 3rd, the temperature increased steadily from $59494.9\ K - 87595.2\ K$. The temperature sharply decreased to $549673.6\ K$ and immediately, it increased to $622844.68\ K$ and thereafter decreased steadily. Within the interval $2200\ UT$ November 4th – $1500\ UT$ November 5th the temperature was nearly steady and at $1800\ UT$, November 5th the temperature began to increase from $3004\ K$ and attained a temperature $T = 141027.35\ K$ and thereafter decreased with fluctuation.

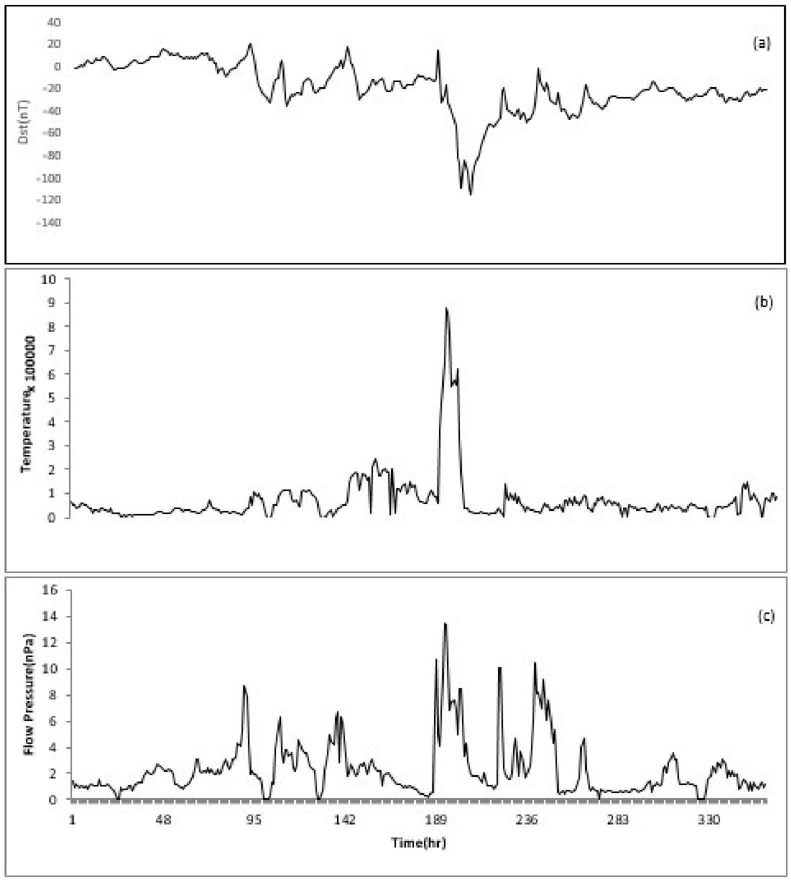

Fig. 2 Panel (a) shows the Dst variation in nano-Tesla, Panel (b) shows the variation of plasma temperature (K) and Panel (c) shows the dynamic flow pressure.

IV. DISCUSSION

The storm began at 0100UT on the 4th of November 2021 with a corresponding Dst index $of\ -32\ nT$. At $1300\ UT$, the commencement of the storm main phase began when the Dst variation declines to $-115\ nT$ at $1300\ UT$ indicating the presence of a strong storm. The southward turning of the Dst signals the depression of the H-component caused by the intensification of the ring current. Most of the Dst variation is caused by the solar wind [13]. The solar wind carrying plasma varies in speed, temperature and dynamic flow pressure etc. According to [14], intense geomagnetic storms occur only when the solar wind velocity is greater than 350 km/s. This can be observed in Fig. 1, panel (c). The solar wind speed just before the occurrence of the storm increased from $421\ km/s$ to $756\ km/s$ (supersonic speed). This abrupt rise in the speed of the solar wind is evidence of an interplanetary shock or disturbance.

Previous studies [15], [16] and [11] and references therein have shown that the magnitude of geomagnetic storms is strongly dependent on the southward deviation of the interplanetary magnetic field B_z. This southward deviation of B_z is a good indication of an impending geomagnetic storm. While the IMF B_z is pointing southward, it causes a very intense fall in the Dst value [17] and therefore has a strong impact on the cause of geomagnetic storm [9]. Fast solar winds carrying hot electrons and protons are usually accompanied by high temperatures as they emanate from the sun's corona. The solar wind temperature increased steadily before the commencement of the storm from $86688.07\ K - 875952.22\ K$. This extremely high temperature helps the ionized plasma to overcome the gravitation attraction of the sun [18]. The flow pressure is also seen to increase from $4.94 - 13.15\ nPa$ during this period. This sudden outburst of the solar wind dynamic pressure aggravated the rising in the value of plasma temperature [17].

V. Conclusion

The activities of solar wind on the solar surface and its intensity on the earth's magnetosphere have been studied. The magnitude of the geomagnetic storm within this period was observed. By comparing the Dst variation with other interplanetary parameters, it was observed that during a magnetic storm, The interplanetary magnetic field B_z deviates southward as a consequence of the increase in the number of particles contained in the ring current. The plasma temperature was also seen to increase abruptly during the storm's main phase. The behaviours of the other solar wind parameters as already discussed also show a similar relationship with a good number of related works on GMs in the recent solar cycle.

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