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The Relationship of Geomagnetic Storm Intensity with The Solar Interplanetary Environment: An Analysis of Two Major Events in 2023

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Abstract: *This research examines the relationship between the strength of geomagnetic storms and the solar interplanetary environment. By analyzing solar wind parameters, interplanetary magnetic fields, and their interactions with Earth's magnetosphere, we aim to understand the factors contributing to geomagnetic storm strength. Using data from space-based observatories, we identify important solar wind (SW) variables, including solar wind speed (Vsw), dynamic pressure (Psw), input energy (IEsw), and the interplanetary magnetic field (IMF) Bz component, and investigate their relationship with geomagnetic storm intensity. Geomagnetic disturbances are measured in our study using the symmetrical part of the horizontal component of the geomagnetic field (SYM/H), and they are classified as moderate geomagnetic storms (SYM/H = -60 nT) and intense geomagnetic storms (SYM/H = -120 nT). We then compared these disturbances to the SW variables (Bz, Vsw, Psw, IEsw). Our results indicate that Bz, Vsw, and Psw influence the strength of geomagnetic storms. The results show a significant increase in range values from moderate storms (Bz = -5 nT, Vsw = 5 kms^{-1}, Psw remained constant) to intense storms (Bz = -22 nT, Vsw = 120 kms-1, Psw = 28 nPa). In contrast, solar wind input energy (IEsw) is found to have weak response to geomagnetic storm intensity index, with no significant change observed in its range values. This research provides insights into the timing of geomagnetic storms in relation to SW parameters.*

Keywords: Geomagnetic storm strength, solar wind, intense geomagnetic storm, moderate geomagnetic storm

1. INTRODUCTION

Large-scale disruptions known as geomagnetic storms cause a considerable number of ions and electrons to be injected into the inner magnetosphere from the magnetotail. This causes global magnetic disturbances by amplifying the ring current [1]. SW plasma emissions and the interplanetary magnetic field (IMF) are the primary contributors to geomagnetic storms [2][36]. The intensity and impact of these storms are closely linked to solar wind parameters. SW parameters, such as the interplanetary magnetic field (IMF) components (B_x, B_y, B_z), solar wind speed (*Vsw*), and dynamic pressure (*Psw*), play crucial roles in determining the severity of geomagnetic storms [3]. These SW characteristics are involved in magnetospheric processes that allow energy, momentum, and mass to reach the magnetosphere. Figure 1 depicts the essential part of the magnetospheric process. As a result, it is essential to investigate the main solar wind factors that affect magnetic storm formation. The incidence of a geomagnetic storm correlates with magnetic reconnection. Some researchers discovered the strong southward B_z conditions with large magnetic reconnection [4]. At the same time, David et al. (2022) discovered that strong geomagnetic storms occur more frequently during mild southward B_z [5]. A few studies have demonstrated the SW dynamic pressure and speed in driving the intensified magnetospheric process, which corresponds to a major geomagnetic storm [6][7]. Watari et al. revealed that SW speed affects geomagnetic storm severity, with an electric field correlated with storm strength [8].

According to Telloni et al. (2020), extreme geomagnetic events (Dst < −100 nT) occur with the most intense SW energy (E> 10) and fastest (V = 800 kms^{-1}), making it the most geoeffective driver [9]. Several studies suggested that SW characteristics (speed, pressure, density) have a statistically significant influence on geomagnetic storms, with SW speed generating the most important contribution [10][11].

In this study, we investigated the relationship between SW parameters and the intensity of geomagnetic storms at the solar maximum of the 25th solar cycle. To do this, the high-resolution geomagnetic indices (SYM/H) index of varying strength, along with significant SW characteristics, will be assessed. This research has made significant improvements to space weather forecasting, which is useful for ground and space application technology development.

2. METHODOLOGY

This study examines the strength of geomagnetic storms using SW variables at the solar maximum of solar cycle 25. It evaluates the moderate and intense geomagnetic storms of February and December 2023 by examining variations in selected solar wind parameters. The SYM/H index quantifies the variation of the magnetosphere's intensification of the ring current in the equatorial zone, which causes geomagnetic storms [15].

Simultaneously, the classification of the geomagnetic storm index (SYM/H) is presented in Table 1. The SW parameters chosen are the IMF magnetic field magnitude (*Bz*), SW speed (*Vsw*), SW dynamic pressure (*Psw*) and SW input energy (*IEsw*). The dynamic SW pressure is measured according to Equation (1) and the SW input energy is calculated using Equation (2).
The dynamic pressure (*Psw*) can be expressed according to (Kasran et al. 2015) [16].

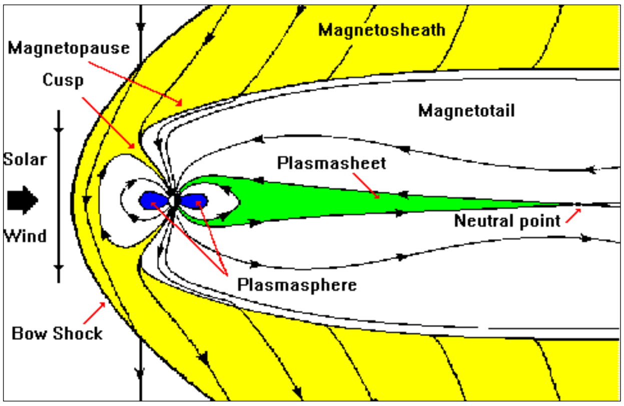

Fig. 1. The inflow of SW plasma into the essential part of the magnetosphere [12][13][14].

$$PSW = 1.6726e - 6NV2\ (nPa) \qquad (1)$$

where e represents the exponential, N was solar wind proton density [cm-3], and V is solar wind speed [kms-1].

The SW input energy, epsilon (ε), is determined using the original Akasofu parameter, as mentioned by Akasofu (1981) and Kasran et al. (2015) [17][16].

$$\varepsilon = \frac{4\pi}{\mu_0} V B^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2\ (\text{ergs}^{-1}) \qquad (2)$$

where V is the speed of the solar wind [kms^{-1}], B is the magnitude of the IMF [nT], and Io denotes a seven Earth radius. The polar angle of the IMF vector (θ), projected onto the Y-Z plane, as tan-1 abs (B_y/B_z) for $B_z > 0$ and 180° -tan^{-1} abs (B_y/B_z) for $B_z < 0$. The selected SW variables are considered in this analysis as they are defined as primary sources in the magnetospheric process, leading to geomagnetic storms [18]. The SW parameters and geomagnetic indices have been extracted from the OMNI data set available on OMNIWeb at https://omniweb.gsfc.nasa.gov/form/omni_min.html. The 1-minute data resolution of solar wind parameters penetrating the magnetosphere is used in this analysis.

3. RESULT AND DISCUSSION

Various SW factors significantly impact the intensity of geomagnetic storms. The following analysis shows how the strength of a geomagnetic storm depends on SW variables.

Table 1. SYM/H Index Classification [19][37].

Geomagnetic storm	SYM/H index (nT)
Super	SYM/H ≥ -250
Intense	-100 > SYM/H ≥ -250
Moderate	-50 > SYM/H ≥ -100
Weak	-30 > SYM/H ≥-50

3.1 Moderate geomagnetic storm index on SW parameters (*Bz, Vsw, Psw, IEsw*)

The weak geomagnetic storm (SYM/H = -60 nT) is observed on the SYM/H plot in mid-February 21th, 2023, as shown in Figure 2. Significant solar wind variables (*Bz, Vsw, Psw, IEsw*) plotted alongside the SYM/H index show an increase in *Vsw* from 359 to 410 kms^{-1}, while the SW pressure remains around (*Psw*= 2 nPa). This indicates that the SW energy is approximately (*IEsw* =2 to 14 x 10^{14} ergs). The variability in *Vsw, Psw,* and *IEsw* responds to changes in the southward *Bz*-component (*Bz* = -6 to -11 nT), as illustrated in Figure 2. This physical mechanism in the solar interplanetary environment responds to a weak geomagnetic storm with a short delay of ~2 hours. This observation is supported by studies from Yermolaev et al. (2010) and Maggiolo et al. (2018) [20][21]. The dotted line in Figure 1 shows the depending of selected SW variables (*Bz, Vsw, Psw, and IEsw*) on the occurrence of a weak geomagnetic storm (*SYM/H* = -60 nT).

3.2 Intense Geomagnetic storm on SW variables (*Bz, Vsw, Psw, IEsw)*

The SW variables (*Bz, Vsw, Psw, IEsw*) exhibit significant variability during intense geomagnetic storms (SYM/H = -120 nT), as illustrated by the dotted line in Figure 3. High SW speeds (*Vsw* = 400 to 520 kms^{-1}) are accompanied by rapid increases in the southward Bz-component (*Bz* = 0 to -22 nT) and SW pressure encounters high variation (*Psw* = 1 to 28 nPa). Consequently, SW energy (*IEsw* = 2 to 10 x 10^{19} ergs) increases within the magnetosphere. The magnetospheric processes involved exhibit inherent time scales, causing a delay of 2 hours before the onset of the intense geomagnetic storm on mid-December 1st, 2023. It is noteworthy that variations in *Bz, Vsw, Psw,* and *IEsw* within an enhanced range contribute to the delayed onset of the intense storm, as indicated by the dotted region in the SW and SYM/H index plot.
The analysis above has shown that *Bz, Vsw, Psw, and IEsw* demonstrate significant changes in range values

from weak geomagnetic storms to intense geomagnetic storms.

For a weak storm (*SYM/H*= -60), the parameters were *Bz* = -5 nT, *Psw* remained constant, *Vsw* = 51 kms^{-1}, and *IEsw* = 12 ergs. In contrast, for an intense storm, the parameters were *Bz* = -22 nT, *Psw* = 28 nPa, *Vsw* = 120 kms-*1*, and *IEsw* = 8 ergs. Except for *IEsw,* there were no ascending changes in range values from the weak storm index to the intense storm index. This analysis has shown that solar wind energy may weakly influence the relationship with storm index intensity. Nakamura (2006) stated that the response of SW energy in triggering magnetic storms is generally not instantaneous [22]. Pulkkinen et al. (2010) found a small correlation between SW energy and geomagnetic storm strength, owing to the temporal delay associated with the beginning of geomagnetic storms [23].

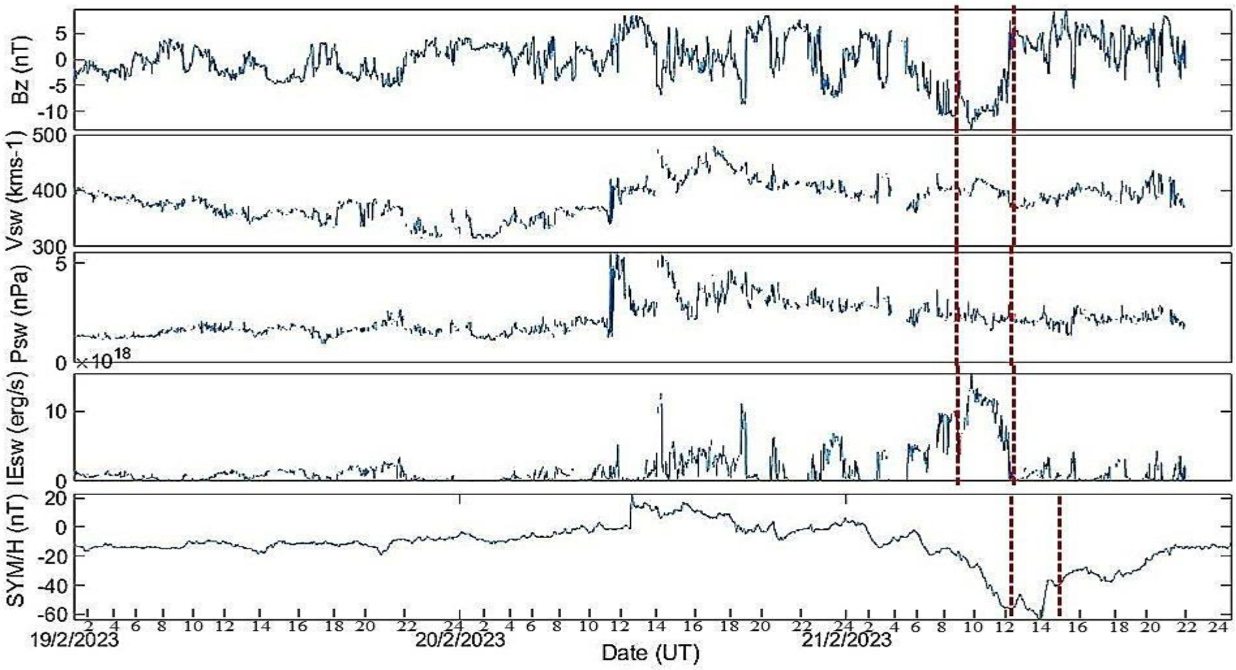

Fig. 2. Variations in SW variables (*Bz, Vsw, Psw, IEsw*) related to the delayed commencement of a weak geomagnetic storm (*SYM/H* = -60 nT) in mid-February 21th, 2023 (indicated by a dotted line).

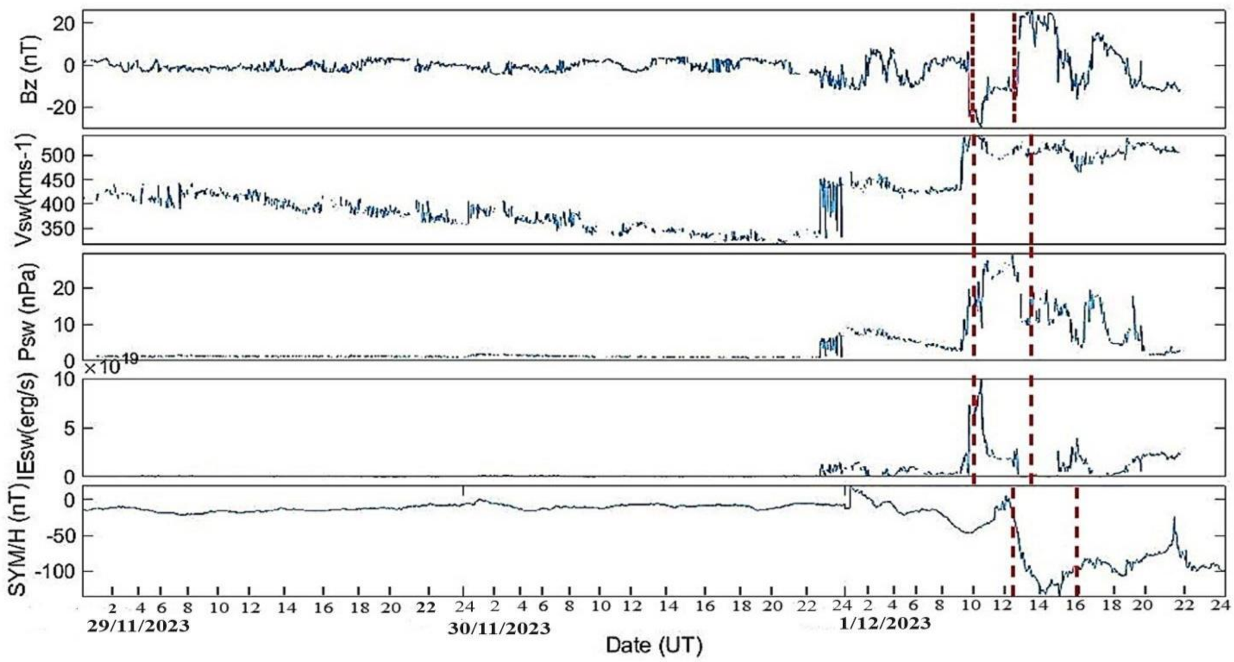

Fig. 3. Variations in SW variables (*Bz, Vsw, Psw, IEsw*) associated with the delayed commencement of an intense geomagnetic storm (*SYM/H* = -120 nT) in mid-December 1st, 2023 (indicated by a dotted line)

This present analysis has exhibited a significant relationship between SW variables (*Bz, Vsw, Psw*) and the intensity of the storm index. This finding is reinforced by research by Singh et al. (2017) and Zhang and Moldwin (2015), who indicated that the peak intensity of storms is closely connected with the *Bz*-component, SW speed, and SW pressure, emphasizing the importance of these parameters in geomagnetic storms [24][25]. The delay of weak and intense geomagnetic storms, as seen in the above analysis, is explained by the prolonged reaction of SW disturbances into the inner magnetosphere. This influences the formation and intensification of the ring current, which is responsible for the occurrence of geomagnetic storms [26][27]. The analysis of the dependence of SW variables (*Bz, Vsw, Psw, IEsw)* on the severity of the geomagnetic storm index revealed that each of them plays an important part in the magnetospheric processes that cause geomagnetic storms The geomagnetic storm index reacts to these processes by injecting plasma sheet particles into the magnetotail, which is triggered by increased solar wind dynamic. pressure [28][29]. Delcourt et al. 2005 found that SW dynamic pressure compresses the frontside of the magnetosphere, energizing plasma injection and inducing electric fields [30]. At the same time, strong SW speeds propel particle density into the inner magnetosphere, significantly impacting the conditions of the Earth's magnetosphere.

Several studies have revealed that the velocity of the SW is a major factor determining particle density and electron dynamics in the inner magnetosphere [31][32]. The interaction between conveyed momentum, mass, and energy of particles with the magnetosphere contributes to the magnetic reconnection process, which is shown by the southward *Bz* component. [33]. The turning of the IMF *Bz*-component to a southward direction at the magnetopause (dayside) and the magnetotail (nightside) causes magnetic reconnection, leading to strong magnetospheric processes [34]. Yamada et al. (2010) explained where the large amounts of energy and plasma distributed into the inner magnetosphere are boosted by significant magnetic reconnection, potentially leading to major geomagnetic storms [35].

4. CONCLUSION

According to this study, the strength of geomagnetic storms is determined by SW variables (*Bz, Vsw, and Psw*). This is apparent in the analysis plots of SW variables, which indicate a greater variance in range values in combination with intense geomagnetic storms, such as those observed in mid-December 2023, compared to weak geomagnetic storms, such as those observed in mid-February 2023. SW input energy (*IEsw*) appears to have a weak response to geomagnetic storm strength, as no notable change in its range values was found between weak and intense storm occurrences. Additionally, the study highlights a delay in the magnetic reconnection process, which results in a delayed formation of both weak and intense storms.

The delay of weak and intense geomagnetic storms is described by the long-running reaction of SW disturbances into the inner magnetosphere and its impact on the formation and intensification of the ring current. The association between geomagnetic storm strength and SW variables is related to solar wind- wind-wind-magnetosphere coupling. High SW speeds transfer energy, mass, and momentum through plasma, while strong SW dynamic pressure enhances plasma injection under strong southward *Bz* conditions, leading to more powerful geomagnetic storms. This study has significance to developing forecasts of geomagnetic storm timing and strength by scientifically investigating magnetosphere dynamics using observed SW and interplanetary magnetic field conditions. Additionally, it serves to enhance space and ground technological applications.

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