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RESEARCH

Effect of Solar Parameters on Geomagnetic Storm Formation in the Ascending Phase of the 25th Solar Cycle

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Abstract

In this paper, starting from solar storms, which are the main cause of geomagnetic storms, the effects of the speed (v) and density (Np) of solar plasma coming to the Earth on geomagnetic storms are investigated. During the ascending phase of the 25th solar cycle (2021 – 2022), various geomagnetic storms from G1 to G4 were examined. Multiple linear regression models are created to examine the effects of solar parameters that cause changes in geomagnetic storm processes. The effects of the speed and charge density of solar wind, coronal mass ejections (CMEs), corotating interaction regions (CIRs), and CME-CME interactions on the Dst index, which reflects disturbances in the Earth's magnetic field and the scale of geomagnetic storms, are statistically analyzed. It is determined that a one-unit change in speed in 82 geomagnetic storms in the statistical models created a decrease in Dst of approximately −0.25 nT. In contrast, it is determined that a unit increase in particle density also reduces the effect and duration of a geomagnetic storm. However, if there is an increase in density during the main phase of the storm, then the storm level increases. We believe that our results will significantly contribute to predicting the formation of geomagnetic storms and their possible effects on space weather.

1. Introduction

Space weather is the process created by solar events in the Earth's near-space environment. Sunspots, coronal mass ejections (CMEs) thrown from the solar corona into the interplanetary space environment, and particle precipitation called solar wind cause magnetic disturbances in the Earth's magnetic field called geomagnetic storms (Gonzalez, Tsurutani, and Clua de Gonzalez 1999). The periods when geomagnetic storms are most common are the maximum phases of the 11-year solar cycle, which is a measure of the number of sunspots (Singh and Bhargawa 2019). Between 2021 and 2022, when the 25th solar cycle reaches its maximum, many sunspots and particle flows will maintain space weather under control by creating geomagnetic storms in the magnetosphere, ranging from G1 to G5. This situation not only affects devices such as sattelites but also those used on the surface of the Earth

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and plays a role in shaping life on Earth (Singh, Singh, and Siingh 2014; Singh et al. 2021; Tsurutani and Hajra 2021; Yermolaev et al. 2023).

The main drivers of magnetospheric storms, solar wind, CMEs, and corotating interaction regions (CIRs), which combine fast and slow particle currents to form intense flows, are important elements in understanding geomagnetic storms (Huttunen, Koskinen, and Schwenn 2002; Tsurutani, Gonzalez, and Gonzalez 2006). These events mostly have some common features in initiating storms. First, the interplanetary magnetic field (IMF) is oriented south, causing the magnetic strength of the Earth's magnetic field to decrease on the daytime side and subsequent magnetic reconnection (Dungey 1961; Tsurutani and Meng 1972; Tsurutani et al. 1988). Thus the particles and energy enter the geomagnetic field. This situation causes the initiation of various chain events starting from the Sun, through the geomagnetic field and from there to the atmospheric layers and the ground surface (Singh, Singh, and Siingh 2014). The second common feature is that when the structures of geomagnetic drivers are examined, they are generally at high speeds (> 350 km/s) together with the amount of dense particles (Hundhausen 1993; Tsurutani and Lin 1985; Liu et al. 2014). Although the occurrence of geomagnetic storm processes is known, the interaction and dynamics of the drivers and the geomagnetic field are not fully understood (Crary et al. 2005). This is due to the diverse behaviors of the magnetosphere and how solar wind, which causes these behaviors, strongly affects the magnetosphere (Singh et al. 2021). Gonzalez and Tsurutani (1987) investigated the solar wind–magnetosphere interaction by examining 10 severe geomagnetic storms in the years when the 21st solar cycle was rising toward maximum ($\mathrm{Dst} < -100$ nT) (Gonzalez and Tsurutani 1987; Gonzalez et al. 1989). The increase in solar wind density causes energy accumulation in the magnetosphere. The increase in energy accumulation is the cause of severe geomagnetic storms. During severe storms, compression and expansion occur in the magnetosphere. The compression of the magnetopause causes the Dst index to increase to negative values and then the Dst index to increase to positive values with the expansion of the magnetopause.

In this study, multiple linear regression models were established to determine the effects of solar parameters that cause geomagnetic storms to occur and change storm processes between 2021 and 2022, the ascending period of the 25th solar cycle. Understanding the formation and process of geomagnetic storms provides insight into space weather prediction, the structure and dynamics of the magnetosphere, the study of auroral phenomena, and the understanding of energy transfer mechanisms. Understanding these processes provides insight into how the Earth is protected from space influences and is critical for both scientific research and technological infrastructure. The relationships between the speed (v) and charge density (N_p) in various particle flows coming from the Sun (solar wind, CME, CIR, CME-CME) and between the speed (v) and the charge density (Dst), which indicate the distortion in the Earth's magnetic field and the level of the geomagnetic storm, were statistically explained and discussed.

2. Materials and Method

We obtained geomagnetic storms and their magnitudes from https://www.spaceweatherlive.com/. We used the Kp and G indices, which are the highest values (maximum) of 24 hours. Values between 5 and 9 in the Kp index correspond to storm levels G1 and G5, respectively (Gonzalez, Tsurutani, and Clua de Gonzalez 1999). G5 represents the highest level of geomagnetic storms. A total of 82 geomagnetic storms occurred between 2021 and 2022. Of

these, 66 were determined to be G1-level geomagnetic storms, 12 were G2-level geomagnetic storms, three were G3-level geomagnetic storms, and one was a G4-level geomagnetic storm. The solar events that formed the storms were not of a single type but of different types, such as CME, CIR, and CME-CME. However, only the speed and load density of the events in these various structures were added to the analysis as variables. Thus the days to be analyzed for the 25th solar cycle were determined.

We obtained the solar activity parameter's total speed and load density N_p values hourly from https://wind.nasa.gov and the Dst indices hourly from https://wdc.kugi.kyoto-u.ac.jp/dstdir/Kyoto. The hours of solar parameter and geomagnetic data are matched, and the data are adjusted for regression by determining missing data. Thus, if there were no data for a variable at the same hour, then the other data at that same hour were also eliminated. While obtaining the data, the day before and the day after the storm (quiet days) are also included in the data. If the storm lasted longer than one day (the recovery phase exceeded one day), then the data from another day after the storm ended were added to the analysis. Since some geomagnetic storm days were consecutive, these storms were combined in a single regression model.

A multiple linear regression model was created for each storm. With these statistical models based on the data, a confidence interval of 0.95 (95%) was selected. For this reason, since models with a p-value greater than 0.05 were statistically insignificant, these storm models were removed from the study. A total of 50 statistically significant storms were used in this study, but since some storms occurred on consecutive days, a single regression model was created, resulting in a total of 33 regression models in the study.

In the storm models created, statistically significant models could not be formed in some cases, and there are several reasons for this. Firstly, the interaction between the solar wind and the Earth's magnetic field has a complex nature. This interaction can be affected by various external factors; this situation can make it difficult to establish a linear relationship on some dates. Secondly, the short duration of the storm on some dates may not cause significant changes in the Dst value. In addition, together with the small changes in the storm, noise, deficiencies, and errors in the data may have caused the model not to be formed for some dates. In this study, simple linear regression models in which only one independent variable was significant were not included in the regression evaluation. The reason for this is that we want to see the relationship between the solar wind speed and density and the Dst value together.

Multiple linear regression models are formulated as in the equation

$$Y = \beta_1 X_1 + \beta_2 X_2 + \cdots, \tag{1}$$

where X is the independent variable, and Y is the dependent variable. In the multiple linear regression model, the dependent variable is explained by the independent variables. For this purpose, the effectiveness of the model was determined by examining the R and R-square values (Nasution et al. 2023). β values in Equation (1) are the coefficients of the independent variables and show how much a unit change in the independent variable will cause, on average, the change in the dependent variable. In our study, our independent variables are particle speed and particle density, and our dependent variable is the Dst index, which represents the amount of distortion in the geomagnetic field. The number of quiet days, which included one day before and after the storm, was considered in the study, and a dummy variable was used during storm hours when specifying storm hours in the model. When determining storm hours, the smallest Dst value stated in the literature as the beginning of a

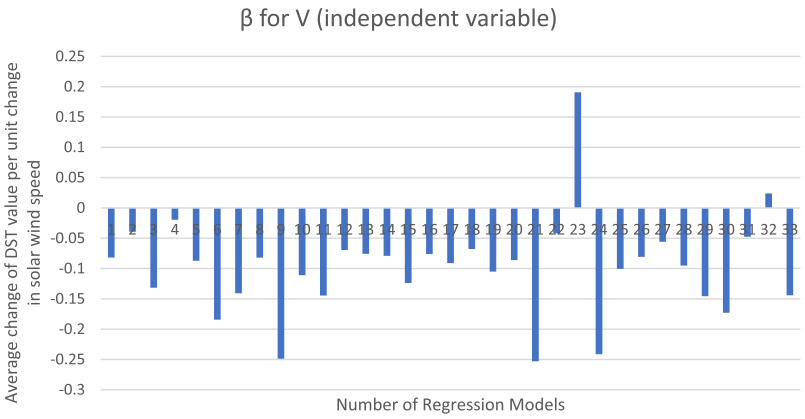


Figure 1 β values of the independent variable v in multiple linear regression models of geomagnetic storms from 2021 – 2022 in the 25th solar cycle.

geomagnetic storm was determined to be −30 nT (Gonzalez, Tsurutani, and Clua de Gonzalez 1999). Since some storms were short-lived, −25 nT was also included in the dummy variable during the stormview.

In this study, β values were calculated via statistical models created to observe the effect of solar parameters on the Earth's magnetic field. R and R-squared values are determined in the Results section to show that the values and models are statistically significant. Each variable is graphed in the Results section, and the results are interpreted.

3. Results

The graph in Figure 1 shows the values of the coefficient β of the particle speed v for each storm in 50 storms and 33 regression models. Approximately 93.94% of the β values of the particle speed v were negative, and 6.06% were positive. According to the statistical model of geomagnetic storms occurring during 2021 – 2022, which represents the ascending phase of the 25th solar cycle, the change in the unit speed of the particles causing a geomagnetic storm reveals that the Dst index is moving toward more negative values. The unit change in speed reduces the maximum Dst value to approximately −0.25 nT in Dst.

Figure 2 shows the values of β, which is the coefficient of particle density N_p, for each storm in 50 storms and 33 regression models. Approximately 78.79% of the β values of N_p, which is the second independent variable in the same models, are positive, whereas 21.21% are negative. In geomagnetic storms during the solar cycle, the Dst index becomes positive in response to a unit change in particle density. The maximum change in the Dst index is approximately 2.78 nT.

The R and R-squared values of each of the regression models are given in Figure 3. For each of the statistical models to be statistically significant, the values in Figure 3 must be close to 1. Except for a few models, the R value of the majority of regression models is approximately 90% on average. When looking at the R-squared values for the models, we see that the values mostly vary approximately 80%.

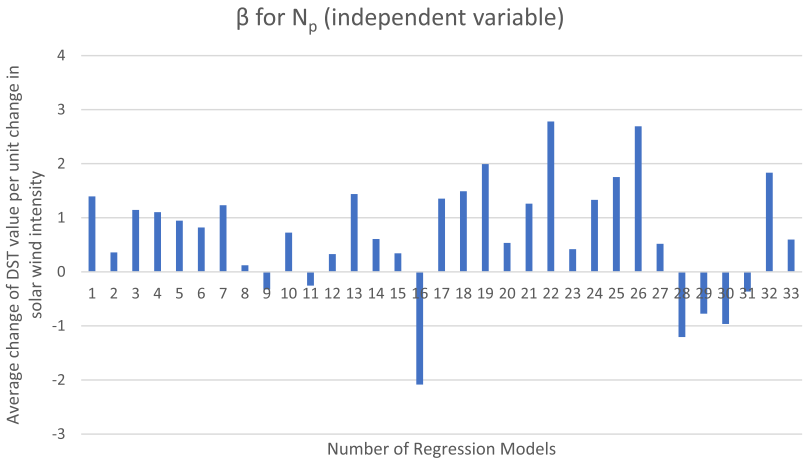


Figure 2 β values of the independent variable N_p in multiple linear regression models of geomagnetic storms from 2021 – 2022 in the 25th solar cycle.

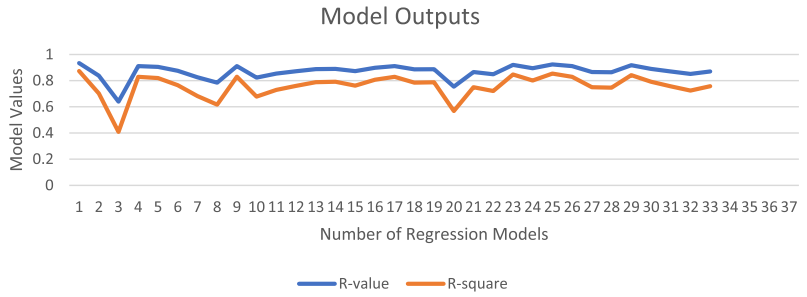


Figure 3 The R values and R-squared values of the regression models (all the models close to 1 are statistically significant).

4. Discussion and Conclusions

In this study, we created statistical models of geomagnetic storms that occurred from 2021 – 2022, the rising period of the 11-year period of the 25th solar cycle. We created regression models with Kyoto and WIND data for the dates determined by space weather as geomagnetic storms.

The β values of v and N_p obtained from all the multiple linear regression models are shown in Figures 1 and 2, respectively, apart from a few exceptions. Our first conclusion in our effort to understand the driving forces of geomagnetic storms in the 25th solar cycle is as follows: In statistical models, with a one-unit increase in the variable v, on average, the Dst value goes to more negative values; that is, the geomagnetic storm power increases more, and the storm duration becomes longer (note that an increase in the independent variable will increase the Dst value, and thus it will take a long time for the high Dst value to return to normal, i.e., the regeneration phase will be prolonged). In brief, the speed of the solar wind, or material ejected from the sun, has a positive effect on the amount of weakening in the Earth's magnetic field and prolongs the duration of the weakening. However, this does not have the same effect on the β values of the independent variable N_p. Our second

conclusion in our study, which emerged as a result of a few exceptions in the models created, is as follows: when the N_p value increases by one unit in storms, the Dst value moves toward positive values. In other words, the solar wind and the intensity of matter ejected from the sun reduce the impact and duration of geomagnetic storms. Thus the storm approaches more quickly toward a calm day or causes a lower storm to emerge.

As shown, there are some exceptional cases in Figures 1 and 2. When these situations are examined, it may not be easy to say exactly what the real reason is. This could be due to the model, data, or other situations that occur during storms. However, since we examined the storms statistically, we can state that these situations are based on the data. When we compared the data from the storms that were statistically significant in the regression, we observed the following situation. In the data we received from Wind, the N_p value was lower during the storm (at -30 and lower Dst values) than before and after the storm, and as a result, the β values of N_p were positive. However, this situation is different for outliers, that is, negative values, in the graph. In these storms, the N_p value either remains constant or increases more than before and after the storm, so the β values of N_p appear to be negative. This shows that an increase in density during a storm actually increases the strength of the geomagnetic storm.

Figure 3 shows that the independent variable v and N_p, which is a solar parameter, significantly explain the change in the dependent variable Dst. The blue line in the chart represents the R values of the models. The figure shows the correlation between the independent and dependent variables, and values close to 1 are found in the majority of the models, which indicates that the change in the distortion of the Earth's magnetic field, which is the dependent variable of the models, depends on the solar parameters on a large scale. The other parameter in the graph is the R-squared value, represented by the orange line. As shown in the graph, almost all 33 regression models of 50 storms (consecutive storms were analyzed as a single regression model) had an R-squared value of approximately 80%. A high R2 represents the extent to which the independent variable (v, N_p) can explain the change in the dependent variable (Dst). The conclusions drawn from the models reveal that, statistically, the models explain the distortion in the magnetic field with high accuracy and that the strength and duration of geomagnetic storms are strongly dependent on solar parameters. However, independent variables have different effects on the formation and continuity of geomagnetic storms, both positively and negatively.

Although the high statistical significance of the results of the models requires us to be positive, it should not be forgotten that this study is limited to the 2021 – 2022 geomagnetic storms in the 25th solar cycle, and even some storms in this two-year period do not match the model. However, the results obtained from basic models of statistics, such as regression models, are known to be correct considering the size of the R and R-squared values when looking at the data and statistics. For that reason, according to the number of storms used in the model, the general pattern of β values, and the percentage rates obtained, it is clear that the study makes statistically significant new and other confirming contributions to the literature on the current solar cycle and the interactions between the Earth and similar magnetic field planets and their stars.

The drivers of storms, which are two important elements of geomagnetic storms, are among the most important space weather conditions, and the dynamics of the magnetic field where they occur are still not fully understood. In particular, there is a lack of physics-based models in the literature. Moreover, the underlying effects and processes, such as how solar matter ejected from the Sun still shakes the planetary magnetic field during a geomagnetic storm, remain unknown (Crary et al. 2005; Singh et al. 2021). For this reason, the results of the data-based models in this study and other studies are expected to lead to future studies.

To establish physical models, statistically significant results must be drawn from the data obtained by satellite and ground-based vehicles in space weather research. Thus the results of statistical analyses could form a basis or a starting point for establishing new models for physical situations that remain mysterious.

By explaining the variation in solar parameters in the Earth's magnetic field in this study a contribution is made to understanding the geomagnetic storm processes. It contributes to understanding the processes and consequences of space weather, which has an impact on everything from satellites in Earth's orbit to ground-based technology and life on the Earth's surface. We aimed to offer a new perspective to create a general model for geomagnetic storms in the later periods of the solar cycle and old solar cycles.

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Data Availability This study's speed and charge density values can be accessed from https://wind.nasa.gov. The DST index data can be accessed from https://wdc.kugi.kyoto-u.ac.jp/dstdir/. Information on using this hourly downloaded data is available on the given sites. Information on the geomagnetic storms and their scales used in this research is available at https://www.spaceweatherlive.com/. Analysis was performed in this research using programs within Yıldız Technical University.

Declarations

Competing interests The authors declare no competing interests.

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