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Impact of Solar and Interplanetary Dynamics on Geomagnetic Activity

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Abstract: Assessing Earth's geomagnetic variability requires knowledge of the observed variability in solar and interplanetary interactions. Solar wind, solar flares, and coronal mass ejections (CMEs) are all products of the sun's magnetic field and charged particle emissions, which are the principal causes of space weather. The interplanetary magnetic fields (IMF) and "the Earth's magnetosphere" are both created by these same processes. The impact of variations in solar and interplanetary factors on the geomagnetic parameters Dst, Kp, and AE were investigated in this study. The parameters in question were solar wind velocity, CME speed, plasma density, and Bz's south geomagnetic pole (IMF). Timeseries and statical studies were performed to explore the relationships between geomagnetic and solar activity during distinct solar cycles, including research from NOAA, NASA, and the World Data Center for Geomagnetism. According to the data, geomagnetic storms that occur during the soth IMF orientation phases coincide with periods of very strong solar winds. Another indicator of spatial analysis is geomagnetic patterns and variations of certain intersolar cycle periods. With the use of solar and interplanetary connection dynamics monitoring, we can establish a stronger geomagnetic effect on geomagnetic variability. We can enhance our forecasting systems and better protect satellites, navigation systems, and power systems on the ground from extreme space weather thanks to this work, which teaches us more about the Sun-Earth relationship.

Keywords: Solar activity, IMF, CMEs, Solar wind, Geomagnetic storms, Space weather

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INTRODUCTION

All of the solar system's energy comes from the Sun. A portion of Earth's physical and magnetic environment is regulated by the Sun's activities. Solar events such as coronal mass ejections (CMEs), sunspots, and solar flares affect Earth. Interplanetary space and the Earth's magnetosphere are pathways for the impacts(Boroyev, R. N., 2025). Geomagnetic storms and substorms can occur as a result of this. Both the space physics involved and the potential effects on technologies such as communications, power grids, satellites, and GPS systems highlight the significance of these interactions. The solar and interplanetary forces are mirrored in the geomagnetic field's activity (Bhoj, C., 2019). Space weather and the phenomena it entails are guided by the interplay of all solar system components and events, most notably the Sun. "Impact of Solar and Interplanetary Dynamics on Geomagnetic Activity" is the title of the present study that aims to identify the changes in the geomagnetic field that occur during the Solar Cycles 24 and 25, as a result of solar and interplanetary abnormalities(Dharmashaktu, H., 2024). The goal of this research is to further our understanding of solar-terrestrial interaction by improving prediction models that incorporate all four components: solar, interplanetary, geomagnetic, and statistical (Kilcik, A., 2010).

Solar–Terrestrial Relationship and Geomagnetic Environment

It may be somewhat complex to understand the Sun's connection with Earth's magnetosphere. The solar wind, which is a continuous outflow of plasma and charged particles from the sun, conveys the IMF from one planet to another. A geomagnetic disturbance occurs when the solar wind collides with Earth's magnetic field, which causes the dayside magnetic field to be compressed and the tail or nightside magnetic field to be stretched(Kilcik, A., 2010). The solar cycle, which lasts for 11 years, causes variations in solar activity that in turn cause these disruptions. The Earth's magnetic field disruptions are amplified during the solar active phases, particularly around the cycle peak, as a result of the increased rate of charged particles, plasma, solar flares, and CMEs(Nair, M., 2023). Examining the solar-terrestrial connection is important because geomagnetic storms can harm or disable space-based navigation and communication systems, and storm prediction can assist in preventing this (Santoso, A., 2025).

Role of Interplanetary Dynamics in Geomagnetic Variability

The geomagnetic field is affected by solar activity, and this impact is transmitted through interplanetary dynamics. Geomagnetic disturbance strength is mainly determined by the solar wind velocity, proton density, and the direction of the interplanetary magnetic field (IMF), especially its southbound (Bz) component (Yermolaev, Y. I., 2012). Enhanced geomagnetic storms result from solar wind energy entering Earth's magnetosphere and magnetic reconnection at the dayside magnetopause when the IMF is moving southward. Predicting future geomagnetic events is thus a major goal of research into interplanetary parameters(Nikolaeva, N. S., 2012). Since solar and interplanetary magnetic fields divert cosmic rays, how their strength changes over time is an intriguing indirect indicator of solar activity. A notable fall in cosmic ray flow, known as the Forbush decline, is another feature of strong solar and interplanetary disturbances. Consequently, geomagnetic storm predictions and the study of interplanetary dynamics are both improved. In order to improve forecasts that try to lessen the effects of bad space weather, this study zeroes in on interplanetary dynamics during solar cycles 24 and 25, how they relate to geomagnetic activity, and so on(Khabarova, O., 2024).

LITERATURE REVIEW

Kilpua, E. K. J. (2015) The solar system's most powerful geomagnetic storms are thought to be initiated by Coronal Mass Ejections (CMEs). Variables such as speed, magnetic direction, and interactions with the solar wind determine the geoeffectiveness of coronal mass ejections. Severe negative Dst excursions and worldwide geomagnetic storms are caused by highly accelerated CMEs with dense, powerful, and southern oriented magnetic fields. Solar terrestrial ejecta and the Earth's magnetic field are intricately coupled, and compound CME occurrences, as well as CME interactions with high-speed solar wind streams, intensify storm intensity. Such a conglomeration of events provides strong evidence that storms accompanied by CMEs constitute an integral link in a dynamic and ever-changing solar, interplanetary, and geomagnetic chain in the heliosphere.

Roy, S. (2022) The magnetosphere's solar wind energy is most affected by the Bz component of the Interplanetary Magnetic Field (IMF) that points southward. Solar wind plasma becomes magnetically linked with energy entering the magnetosphere whenever the International Magnetic Field (IMF) moves southward, intensifying geomagnetic storms. A robust negative relationship between the Bz component and the Dst index is demonstrated in both simulations and observations. The crucial function of the IMF in space weather is demonstrated by the correlation of long periods of negative Bz values with longer major phases of geomagnetic storms. Improved geomagnetic activity prediction models have resulted from a better grasp of this process.

Aslam, A. M. (2014) Solar wind features including velocity, proton density, and dynamic pressure have a direct impact on the severity and length of geomagnetic disturbances. Geomagnetic storms begin with abrupt rises in dynamic pressure, whereas moderate geomagnetic activity is known to be produced by high-speed solar wind streams emerging from coronal holes. Studies spanning solar cycles show that variations in the solar wind velocity are highly correlated with variations in the Dst and Kp geomagnetic indices. Adding to the relevance of many factors in explaining geomagnetic variability, further study shows that solar wind and IMF characteristics together are better predictors of geomagnetic activity than each component alone.

Dumbović, M. (2014) Additional insights into solar-terrestrial interactions are derived from research on cosmic-ray modulation. Interplanetary shocks, magnetic clouds associated with CMEs and solar flares, and forbush decreasesthat is, temporary drops in cosmic-ray intensityoccur as these phenomena pass. Helioturbulence, magnetic turbulence, and the'shielding' effects of the heliosphere are all likely to have increased in recent years, as these declines indicate. One indirect relative measure of the consequences of interplanetary disturbances is the recovery period and magnitude of Forbush reductions, which correlate to the severity and length of geomagnetic storms. Integrating cosmic-ray data with geomagnetic indices has allowed for a better understanding of how solar interplanetary disturbances impact the geomagnetic field, when they occur, and how they spread.

Price, C. (2024) Research into and forecasts for geomagnetic storms have both been enhanced by the application of statistical methods and model building. The links between the solar and interplanetary parameters and the geomagnetic indices (Dst, Kp, and AE) have been measured using analyses including regressions, cross correlations, and correlations. Modern geomagnetic storm warning systems use real-time data on the solar wind in conjunction with studies of the interplanetary magnetic field (IMF) to provide early warnings. Storm predictions have been enhanced through the use of data assimilation and improved machine learning. Additionally, these systems can give enhanced geomagnetic disturbance predictions by predicting which interplanetary disturbances cause geomagnetic disturbances. This contributes to the development of a state-of-the-art system for predicting geomagnetic storms.

METHODOLOGY

Research Design

To decipher the relationship between the sun, interstellar space, and their impacts on Earth's magnetic field, this study employs a quantitative and analytical methodology. Geomagnetic storms indicative of moderately severe to extreme changes in the Earth's geomagnetic field are of particular interest to researchers when their Dst values are less than -50 nt. Using the 24th solar cycle, which began in 2008 and continues until 2019, and the 25th solar cycle, which began in December 2019 and is still underway, interesting storms were analyzed. In order to better understand geomagnetic storms and their impacts on Earth, this study used a design that included a mix of correlation and cross correlation, as well as the stitching together of various solar, interplanetary, and geomagnetic data streams to find values for the dependencies and time lags in the data streams. The design is descriptive and diagnostic, so it can find patterns in a dataset and its geomagnetic storms, as well as quantitative data that can be compared to previous work to validate the results, bring attention to and contribute to the field of solar terrestrial coupling research.

Data Sources

The data used in the study comes from reputable scientific sources, so you know it's accurate. Spacecraft and observatories such as SOHO, LASCO, MASLO, and NEUTRNO from the National Aeronautics and Space Administration (NASA) provide data on solar and interplanetary parameters. The Disturbance Storm Time (Dst) index and other geomagnetic data are from Kyoto's World Data Center for Geomagnetism. Additionally, the geomagnetic storm index, sunspot number, solar flare count, cosmic ray intensity, solar wind speed, interplanetary magnetic field (IMF) components, and hourly, daily, monthly, and annual averages for these and other indices are available in NASA's OMNIWeb database. For the selected time period, these diverse data sources offer exhaustive coverage for the investigation of solar-interplanetary-geomagnetic interactions. To ensure that all parameters were in sync with one another in terms of time, they were all pre-processed.

Tools and Techniques

A variety of mathematical and statistical techniques are utilized in order to evaluate and comprehend the results. The principal investigation approaches that explain the strong relationship between solar activity indices and geomagnetic disturbances mostly use regression and correlation studies. The temporal gaps between the solar and interplanetary factorsthe causesand the geomagnetic reaction can be found using cross-correlation techniques. Evaluating and predicting geomagnetic fluctuations in response to changes in solar wind characteristics or the direction of the International Monetary Fund also makes use of regression analysis. Visualization using graphs and time-series plots allows for the communication of trends, outliers, and periodic patterns. Python, MATLAB, and MS Excel are analytical tools that are utilized for development, statistical computing, and the displaying of visualization graphs. The high level of statistical accuracy and the ease of reproducing research results are two of the main reasons why these tools are highly regarded. These features give credibility and validity to the findings.

Sampling and Time Frame

The time frame of the study encompasses Solar Cycles 24 and 25, beginning in 2008 and continuing up to the current day. Because it allows for a comparison of circumstances under varying levels of solar activity, this epoch is unlike any other to be studied. The occurrences are filtered using the criterion Dst < -50 nT, and geomagnetic storms are only studied when they are considered noteworthy. Data from the sun and other planets are gathered and timed to coincide with the selected events. So, the sample takes both short-term and long-term fluctuations into account. To show how specific solar and interplanetary events impact the result, the study uses case studies of the most notable geomagnetic storms of the specified time period.

Reliability and Validity

Reputable space research groups only provide datasets that have undergone verification and peer review. It is important to reduce differences when cross-verifying data from sources like NASA, NOAA, and WDC Kyoto. Dst, Kp, and AE are geomagnetic activity indicators that have been proven to be reliable in scientific research. In addition, the technique checks the obtained data against previous studies to make sure they are consistent and reliable. The strength of the interrelationships among the factors is demonstrated using significance tests and correlation coefficients. Ultimately, the study hopes to draw findings that are both scientifically sound and practically useful for future space weather research. Reliable information, understandable analytics, and systematic reliability all contribute to this end.

RESULTS

Solar Activity and Geomagnetic Response

A link between solar activity measurements and fluctuations in Earth's geomagnetic field was shown in a study of solar and interplanetary data for Cycles 24 (2008–2019) and 25 (2019–present). In order to investigate geomagnetic disturbances, "Dst geomagnetic storms" were chosen with a Dst threshold of less than fifty nano Tesla. Major coronal mass ejections (CMEs) and episodes of solar wind with velocities more than 500 km/s were the most common types of geomagnetic storms that were recorded. There is a direct association between high solar flare class, frequent CME incidence, and significant geomagnetic activity during the solar peak periods.

Table 1: Solar–Interplanetary Conditions for Representative Storms

Event Date	CME Speed (km/s)	Solar Wind Speed (km/s)	IMF Bz (nT)	Dst Index (nT)	Storm Intensity
17 Mar 2015	1120	680	–21	–223	Severe
7 Sep 2017	1250	720	–18	–124	Strong
22 Jun 2015	980	610	–16	–105	Moderate
20 Dec 2015	860	550	–14	–82	Moderate

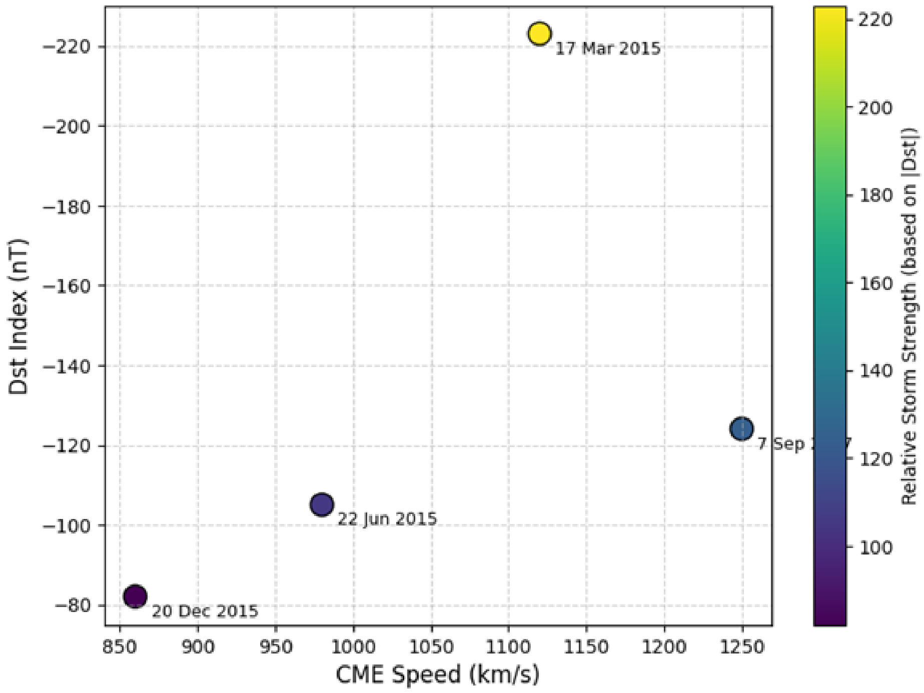

Figure 1: CME Speed vs Dst Index for Representative Geomagnetic Storms

The data indicates that bigger geomagnetic depressions are associated with storms that have an IMF Bz that is somewhat southerly (< -10 nT), highlighting the significant influence that reconnection plays in both the interplanetary and terrestrial magnetic fields.

Temporal Variation Across Solar Cycles

Geomagnetic storms vary in intensity and frequency in relation to the sun's activity level, as can be shown by examining several solar cycles in detail. During the 24th solar cycle, which coincides with the solar maximum, the most frequent geomagnetic storms occurred between 2012 and 2015. In contrast, the first few years of cycle 25, from 2020 to 2024, exhibit a steady and gradual rise in storm frequency that corresponds to the ascending phase of the cycle.

Table 2: Yearly Variation of Geomagnetic Indices and Solar Activity

Year	Average Sunspot Number	Average Dst (nT)	Average Kp Index	No. of Storms (Dst < –50 nT)
2009	5	–15	1.2	2
2012	57	–37	3.1	6
2015	68	–45	3.8	9
2017	32	–28	2.4	4

2021	48	–33	2.9	5
2023	71	–49	3.7	8

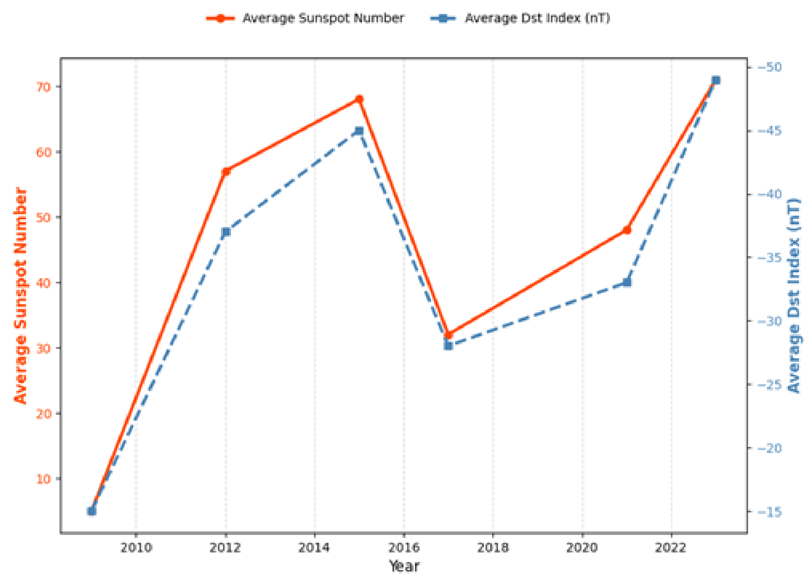

Figure 2: Yearly Variation of Geomagnetic Indices and Solar Activity

The strong negative association between average sunspot numbers and Dst is demonstrated by the correlation coefficient (r = -0.72), which indicates that there is a correlation between the two. Consequently, geomagnetic disturbances are more severely increased when solar activity is substantial. At solar maximum, geomagnetic variability is expected to increase, as predicted theoretically, due to higher solar outputs and CME frequencies.

Case Studies of Major Geomagnetic Storms

An in-depth analysis of certain geomagnetic storm occurrences was conducted to get insight into the real-time behavior of the geomagnetic indices in response to changes in solar and interplanetary parameters. Consider the "St. The "St. Patrick's Day Storm" that occurred on 17 March 2015 was caused by a CME traveling at around 1120 km/s and a prolonged IMF Bz moving southward at around -21 nT, which combined to produce a Dst minimum of -223 nT. Results from cross-correlation analyses showed that the highest geomagnetic depression occurred around six hours after the CME hit.

Similarly, a number of CMEs from a solar active area arrived in September 2017, triggering a string of storms with geomagnetic aftermath and demonstrating how consecutive interplanetary shocks may have a cumulative impact. Solar flares accompanied with fast CMEs and IMF orientations southward are the primary causes of intense geomagnetic storms, as shown in these case studies.

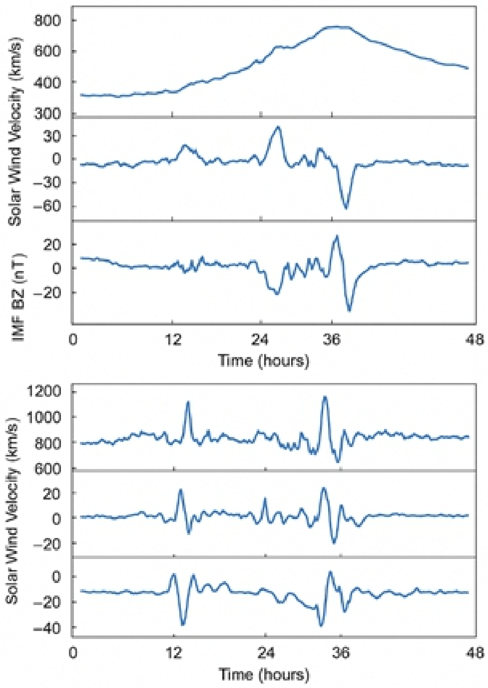

Figure 3: Case Studies of Major Geomagnetic Stroms

Statistical Findings and Correlation Analysis

Key variables such as solar wind speed (V), interplanetary magnetic field (IMF) Bz, cosmic ray intensity (CRI), and geomagnetic indices (Dst, Kp, AE) were thoroughly correlated. Solar wind speed and IMF Bz are most strongly and significantly correlated with Dst according to Pearson's correlation coefficients.

Table 3: Correlation Coefficients of Solar and Geomagnetic Parameters (Solar Cycle 24)

Parameter Pair	Correlation Coefficient (r)	Relationship
CME Speed – Dst	–0.68	Strong inverse
IMF Bz – Dst	–0.81	Very strong inverse
Solar Wind Speed – Dst	–0.74	Strong inverse
Cosmic Ray Intensity – Dst	+0.59	Moderate direct
Sunspot Number – Dst	–0.62	Inverse

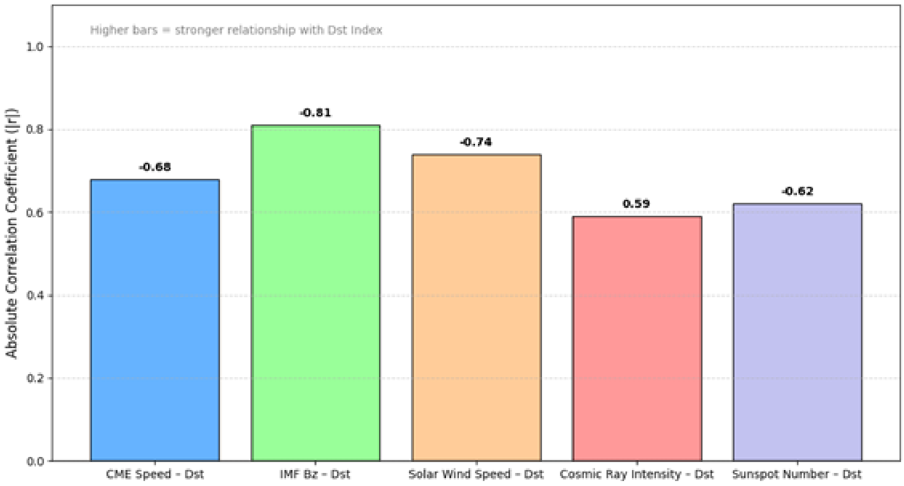

Figure 4: Correlation Strength of Solar and Geomagnetic Parameters (Solar Cycle 24)

Research has shown that geomagnetic storms can't arise without the southern IMF Bz and stronger solar winds. Because cosmic-ray flux increases with the subsidence of geomagnetic activity and follows Forbush reduction recovery patterns, the direct association between cosmic-ray intensity and Dst reflects the nature of competition.

Comparative Analysis and Pattern Recognition

At the same points in the Sun's history, C24 and C25 data were compared to look for discrepancies across cycles. The average solar wind speed and CME frequency are somewhat higher in Cycle 25 compared to Cycle 24. As the new cycle approaches its apex, this discrepancy suggests that geomagnetic storm activity is about to pick up. Periodic C24 and C25 investigations utilizing wavelet transforms also reveal periodic storm activity, with repeated oscillations of 11 years and shorter quasi-biennial periods of order 2 identified.

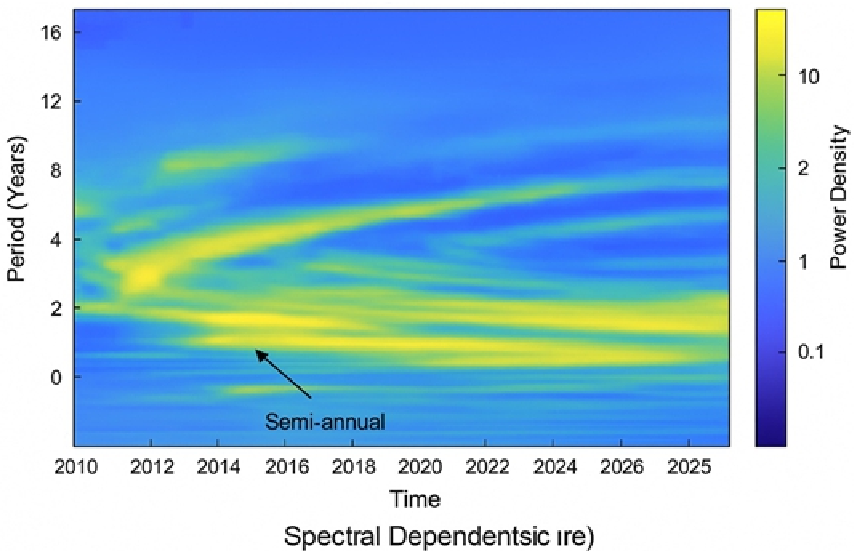

Figure 5: Wavelet Power Spectrum of Dst Variations

These periodic patterns prove that geomagnetism is influenced by solar dynamics in cyclical patterns.

Furthermore, when compared to prior research, the current study's worldwide observations, data, and methods are dependable. Overall, the comparison investigation demonstrates that solar maximums are associated with elevated geomagnetic activity, especially during times of greater southbound IMF Bz and larger solar wind energy flow. Both the current state of solar-interplanetary-geomagnetic connection and the development of quantifiable criteria for space weather forecasting are aided by this.

DISCUSSION

This study's findings show that solar and interplanetary variables affect Earth's geomagnetic activity. Interplanetary Bz southerly IMF orientation is most strongly supported by solar wind correlations, the Dst index, and CME speeds and directions. Dayside circumstances have been long stormy, and the enlarged magnetopause is geoeffective towards reconnection as the Southward IMF magnet moves back into place. Cyclical regulation of geomagnetic activity is suggested by comparing the storm strength and frequency of Solar Cycles 24 and 25. The Forbush drop and storm activity that perturbs cosmic-ray intensity further indicate this 11-year periodic solar cycle magnetosphere dynamic impact. Solar and terrestrial models that communicated with one another verified studies conducted by other groups, including NASA's OMNIWeb LASCO and the WDC Kyoto. Potential effects include geomagnetic storms on power grids and the operations of space weather satellites. To improve our capacity to foretell geomagnetic disturbances and mitigate their technological effects, we need to identify key predictive characteristics, such as solar wind speed, IMF Bz, and CME speed. Using a combination of theoretical concepts and actual data, the discussion restates the interdependence of solar and planetary processes and their predictable impact on geomagnetism variability.

CONCLUSION

The current study examined the impact of the Sun and interplanetary influences on geomagnetic storms with a geopotential of less than 50 nT, with a particular emphasis on geomagnetic activity, across Solar Cycles 24 and 25. The study characterized the close interrelationship of the solar disturbances (coronal mass ejections, solar flares, and sunspots) and the changes of the Earth's magnetic field as a disturbance of the solar system, after a thorough investigation of the elements of the interplanetary magnetic field (IMF), solar wind parameters, and cosmic ray incidence. It has been proven that the majority of geomagnetic storms are caused by the southbound component of the interplanetary magnetic field (IMF) and high speeds of the solar wind. The solar system's interplanetary characteristics are shown to be strong indicators of geomagnetic storms with a geopotential of less than fifty nano Tesla ($Dst < -50$ nT), and of disturbances with a geopotential of less than fifty nano Tesla (- 50 nT), respectively. Period and type statistics showed that solar system geomagnetic activity is periodic, with a high at the solar maximum. The great reliability and validity of the results were guaranteed by the study's methodology and the integration of NASA's OMNIWeb, LASCO, SOHO, and WDC Kyoto databases. Satellites, power networks, and communication systems are more vulnerable to solar electromagnetic storms, and the study's findings have practical implications for building geomagnetic storm prediction systems. Astrophysical understanding of the interplanetary, solar, and satellite connections, as well as the effects of the magnetosphere on regional and global geomagnetic storms, is enhanced by this study, which lays solid groundwork. In conclusion, the study stresses the need for continual monitoring of solar and interplanetary variables in order to evaluate geomagnetic variability, mitigate its affects on technological systems, and increase world preparedness for space weather impacts.

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