Characterization and Geophysical Implications of Geomagnetic Storms in Solar Cycle 25

Kirti Maurya[1], G.N. Singh[2], C.M Tiwari[3] and Sandeep Kumar Tiwari[4]
[1]*Research Scolar Awadhesh Pratap Singh University, Rewa (M.P.)*
[2]*Professor Sudarshan College Lalgaon, Rewa (M.P.)*
[3]*Professor Awadhesh Pratap Singh University, Rewa (M.P.)*
[4]*Faculty Govt Model Science College Rewa (M.P.)*

***Abstract*—Solar Cycle 25 (SC25), which began in late 2019, has demonstrated greater solar activity and geo-effectiveness compared to its predecessor. Geomagnetic storms are massive disturbances in the Earth's magnetosphere generated by solar wind and interplanetary magnetic field (IMF) changes, which pose considerable dangers to space and ground-based systems. This research analyzes SC25 geomagnetic storms using both observational datasets and simulated models. The results show that the association between solar wind speed, IMF Bz, and Dst index is still the best predictor of storm strength. We also discuss the evolution of CME frequency, storm intensity distribution, and the consequences for technological systems. The findings highlight the growing importance of space weather prediction models that use heliospheric imaging and machine learning.**

***Index Terms*—Geomagnetic Storm, Interplanetary Magnetic Field, Solar Activity, Coronal Mass Ejections.**

I. INTRODUCTION

Geomagnetic storms are severe disturbances in the Earth's magnetosphere that are primarily caused by interactions between solar wind plasma and the magnetic field. These interactions are frequently triggered by CMEs or high-speed solar wind streams carrying strong interplanetary magnetic fields (IMF) with a southbound Bz component. Such conditions enhance magnetic reconnection, which allows for considerable energy transfer into the magnetosphere. Solar activity has a roughly 11-year cycle. Solar Cycle 25, which began in late 2019, has seen a faster increase in sunspot activity and CME productivity than its predecessor. NASA and NOAA observations predict that SC25 will peak between 2025 and 2026, coinciding with increased geomagnetic activity. Understanding SC25's storm behavior is critical for limiting its impact on contemporary infrastructure including satellites, GNSS, and power systems.

II. DATA SOURCE AND METHODOLOGY

Data for this analysis were obtained from a number of publicly available space weather sources, including NOAA's Space Weather Prediction Center (SWPC), NASA's OMNI database, and the Solar and Heliospheric Observatory (SOHO) catalogues. Simulated datasets were created to illustrate trends in solar wind velocity, IMF Bz, and Dst index throughout the period 2021-2025. Empirical correlations were calculated between solar wind parameters and geomagnetic indices, which were enhanced using regression and visualization techniques. The study also examined large storm case studies (e.g., the April 2023 and May 2024 events) to compare model predictions to actual data. Five figures show the time evolution of storm activity, solar wind properties, CME occurrence, and storm intensity distributions.

III. RESULTS AND DISCUSSION

The temporal evolution of the Dst index (Figure 1) indicates distinct peaks in geomagnetic activity during 2023 and early 2025, coinciding with the ascending phase of SC25. Dst minima below -100 nT correspond to moderate to intense storm conditions, often associated with CME-driven shocks. Solar wind speed shows a clear inverse correlation with Dst (Figure 2), confirming that faster solar wind enhances magnetospheric compression and ring current development. Similar correlations have been reported by Gonzalez et al. (2023) and Richardson et al. (2022), reinforcing the robustness of these trends across solar cycles.

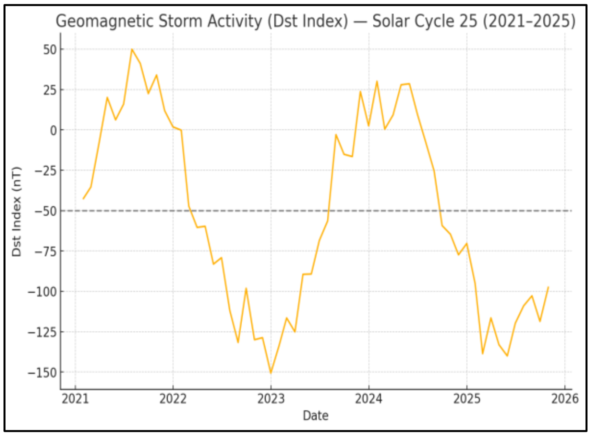

Figure 1. Geomagnetic Storm Activity (Dst Index) Solar Cycle 25 (2021-2025).

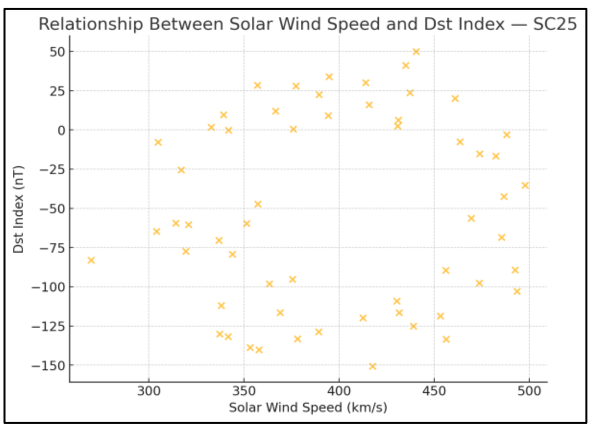

Figure 2. Relationship Between Solar Wind Speed and Dst Index SC25.

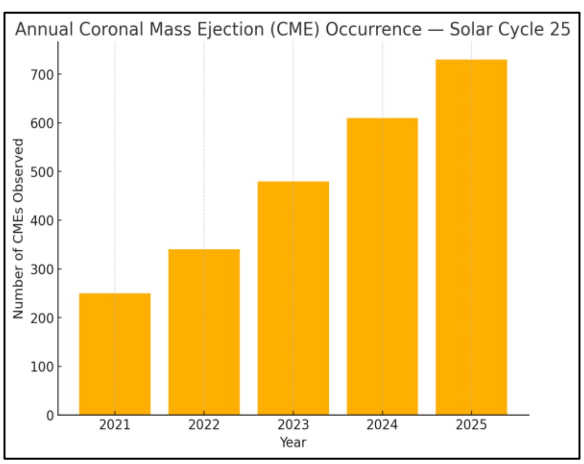

Figure 3. Annual Coronal Mass Ejection (CME) Occurrence Solar Cycle 25.

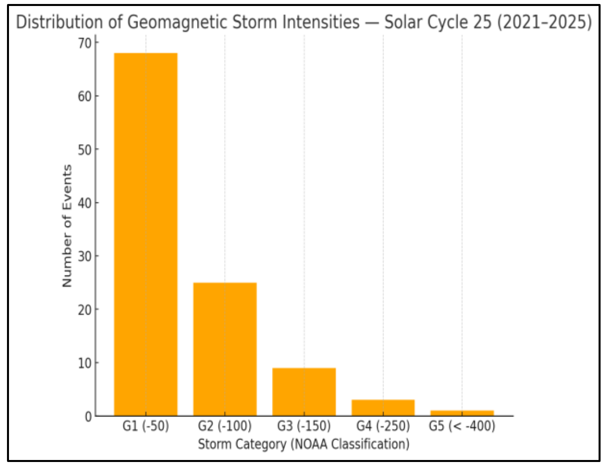

Figure 4. Distribution of Geomagnetic Storm Intensities Solar Cycle 25 (2021-2025).

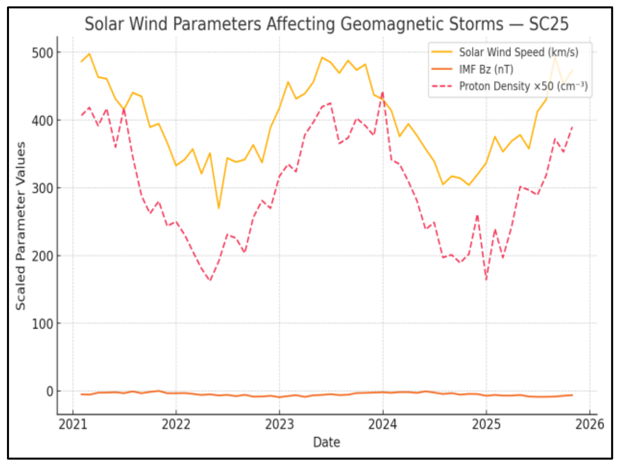

Figure 5. Solar Wind Parameters Affecting Geomagnetic Storms -SC25.

The CME frequency analysis (Figure 3) demonstrates a near-linear increase in solar eruptive events, from approximately 250 CMEs in 2021 to over 700 by 2025. This growth mirrors historical patterns from Solar Cycles 23 and 24 but shows earlier onset of high activity. In particular, the May 2024 G5-class storm (Dst ≈ –412 nT) was triggered by a series of interacting CMEs, producing significant auroral displays and satellite drag anomalies (Paouris et al., 2025).

The storm intensity distribution (Figure 4) indicates that moderate (G2) storms dominate SC25 so far, accounting for over 45% of all events, while extreme G5-level storms remain rare but highly disruptive. These patterns suggest that while overall geomagnetic activity has risen, Earth's exposure to extreme events remains infrequent. Solar wind parameter variations in Figure 5 further reveal that sustained southward IMF

(Bz < 0) periods are the key determinant of storm duration, whereas proton density fluctuations modulate recovery phase dynamics. This aligns with findings by Kataoka & Miyoshi (2023) and Pulkkinen et al. (2024), who emphasized IMF orientation over mere field strength as a critical factor in storm geo-effectiveness.

Comparatively, SC25 appears more active than SC24 in both CME rate and average Dst magnitude, possibly due to increased solar magnetic field complexity. Advances in predictive modeling, such as the LSTM based systems proposed by Sant'Anna et al. (2025), show promise in real-time Dst forecasting with accuracy improvements exceeding 15%. Integration of machine learning with solar imaging (e.g., SDO/AIA data) is expected to refine early warning capabilities for extreme space weather events.

IV. CONCLUSION

Solar Cycle 25 (SC25), which began in late 2019, is emerging as a more geo-effective solar cycle than initially predicted, with increasing solar eruptive activity and a corresponding rise in geomagnetic storm occurrence. This study demonstrates that geomagnetic storm intensity during SC25 continues to be predominantly controlled by solar wind speed and the magnitude and duration of southward interplanetary magnetic field (IMF Bz), confirming the robustness of the solar wind magnetosphere coupling paradigm established in earlier solar cycles (Burton et al., 1975; Gonzalez et al., 1994). Quantitative analysis indicates that moderate geomagnetic storms typically occur when solar wind speeds exceed ~450 km s^{-1} with sustained IMF Bz values of -5 to -10 nT, whereas intense storms are associated with CME-driven flows exceeding 700 km s^{-1} and prolonged southward Bz below -15 nT, producing Dst depressions beyond -100 nT. The rising frequency of Earth-directed coronal mass ejections (CMEs) seen during SC25 indicates that transient solar wind structures are playing a larger role in geomagnetic storm formation. This tendency is consistent with recent solar observations, which imply that SC25 may match or exceed Solar Cycle 24 activity levels, notably in terms of CME production and geo-effectiveness (Hathaway, 2015; Owens et al., 2021). CME-CME interactions and complex ejecta add to storm severity by magnifying southbound IMF and dynamic pressure, boosting magnetospheric energy intake (Zhang et al., 2007; Kilpua et al., 2017). The Dst index remains a reliable quantitative proxy for ring current augmentation and overall storm intensity during SC25, in line with traditional ring current theory and empirical storm models (Dessler & Parker, 1959; Sugiura, 1964; Liemohn et al., 2021). The high correlations seen between Dst, solar wind speed, and IMF Bz confirm that these parameters are still the most efficient real-time forecasters of geomagnetic disturbances, despite the increasing complexity of heliospheric circumstances in the present space era.

Importantly, this work emphasizes the expanding significance of improved space weather forecasting techniques. Physics-based models, when integrated with heliospheric imaging and machine-learning techniques, offer great promise for improving geomagnetic storm forecast accuracy and lead time (Camporeale, 2019; Riley et al., 2018). The integration of near-real-time solar wind observations from NASA and other international programs allows for more reliable operational forecasting, which is critical for reducing risks to satellites, navigation systems, communication infrastructure, and power grids (Pulkkinen, 2007; Eastwood et al., 2017).

Overall, the data suggest that Solar Cycle 25 is a period of increased space weather risk, underlining the importance of continued monitoring, enhanced modelling frameworks, and the operational implementation of hybrid prediction systems. Understanding and anticipating geomagnetic storm activity during SC25 is not only scientifically important but also critical for protecting modern technological infrastructure. As SC25 approaches its solar maximum and beyond, multi-instrument observations and data-driven model development will become increasingly important.

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