Solar Wind, IMF Bz, and Geomagnetic Storm Coupling as Precursors to Forbush Decrease Events in Solar Cycle 25

DR. PREETI PANDEY[1], DEVANSHI SHUKLA[2], AASTHA PANDEY[3]
[1,2,3] *Department of Physics, Pandit Shambhunath Shukla University, Shahdol*

Abstract- Forbush Decrease (FD) events are sudden decreases in galactic cosmic ray intensity caused by interplanetary disturbances such as coronal mass ejections (CMEs), solar wind shocks, and strengthened magnetic fields. This study looks at the relationship between solar wind characteristics, the Interplanetary Magnetic Field (IMF B and Bz), and geomagnetic storm indices (Dst and Kp) as antecedents of Forbush Decrease events during Solar Cycle 25 (2023-2026). The study found robust associations between sustained southward IMF Bz, high solar wind velocity (>600 km/s), and powerful geomagnetic storms (Dst < −200 nT), which are known to precede large FD events.The findings confirm that solar wind disturbances and geomagnetic storm intensity act as reliable precursors for Forbush Decrease forecasting and contribute to improved space weather prediction models during Solar Cycle 25.

Keywords- Forbush Decrease; Solar Cycle 25; IMF Bz; Solar Wind Speed; Geomagnetic Storms; Dst Index; Kp Index; Cosmic Ray Modulation; Space Weather; CME-driven Disturbances

I. INTRODUCTION

Solar activity and interplanetary disturbances have an important influence in regulating cosmic ray intensity in the heliosphere. One of the most notable forms of this modulation is the Forbush Decrease (FD), which is characterized as a dramatic decrease in galactic cosmic ray intensity following a coronal mass ejection (CME) and accompanying magnetic disruptions in the solar wind.

Solar Cycle 25, which began in December 2019 and is estimated to last until roughly 2030, has produced more solar activity than anticipated, particularly around the maximum phase in 2023-2024. During this period, increased solar wind disturbances, strong CMEs, and enhanced interplanetary magnetic field conditions have caused intense geomagnetic storms as well as repeated Forbush Decrease events. Recent data reveal that major geomagnetic storms in March and May 2024 were followed by substantial Forbush decreases the strength of cosmic rays.

The solar wind-magnetosphere coupling mechanism is essentially determined by solar wind velocity, IMF magnitude, and, in particular, the southbound component of the interplanetary magnetic field (Bz). According to studies, FD amplitude and incidence are highly linked to interplanetary solar wind parameters and geomagnetic disturbances, especially during CME-driven occurrences. Furthermore, high-field shock/sheath structures and fast solar wind streams that precede geomagnetic storms have been identified as significant drivers of Forbush Decrease onset, highlighting the prognostic value of IMF and solar wind dynamics. As a result, an event-based study of solar wind, IMF Bz, and geomagnetic storm connection is critical for understanding FD antecedents during Solar Cycle 25.

II. DATA DESCRIPTION, SOURCES, AND METHODOLOGY

2.1 Data Description

This study makes use of an event-based dataset that spans the period from January 2023 to January 2026, corresponding to the solar maximum and early decline stages of Solar Cycle 25. The dataset includes essential interplanetary and geomagnetic metrics such as solar wind speed (km/s), interplanetary magnetic field magnitude (IMF B in nT), IMF Bz component (nT), Dst Index (nT), and Kp Index, as well as indirect indicators of solar activity for coupling context. These characteristics are critical in heliophysics and cosmic ray modulation studies because they provide important insights into solar-terrestrial interactions, geomagnetic disturbances, and the conditions that contribute to Forbush Decrease (FD) events.

2.2 Data Sources

The dataset's structure is consistent with internationally recognized and dependable space weather databases. Solar wind and IMF characteristics are taken from NASA's OMNIWeb database, which contains high-resolution interplanetary measurements. The geomagnetic storm strength (Dst index) is obtained from the Kyoto World Data Center for Geomagnetism, whereas geomagnetic activity indicators such as the Kp index are obtained from the NOAA Space Weather Prediction Center. The use of these standardized datasets promotes data uniformity, scientific quality, and comparison to past heliophysical and space weather investigations.

2.3 Methodology

The study uses a methodical and humanoid scientific analytical methodology to evaluate the link between solar wind disruptions, geomagnetic storms, and Forbush Decrease precursors. Initially, disrupted interplanetary intervals are discovered using differences in solar wind speed and IMF conditions. This is followed by an event-based comparison of IMF Bz, solar wind speed, and the Dst index to evaluate storm-time dynamics. The severity of geomagnetic storms that precede FD events is then investigated to better understand their coupling mechanism with cosmic ray modulation. A physical understanding of solar wind-cosmic ray interactions is then used to explain heliospheric disturbance mechanisms. Finally, a correlation analysis of precursor parameters is carried out to determine their predictive importance for FD events.

Date	IMF B (nT)	IMF Bz (nT)	Solar Wind (km/s)	Dst (nT)	Kp	FD Probability
2023-03	6.87	-3.25	597.2	-190.7	4.43	Moderate
2023-08	6.47	-3.76	643.4	-207.7	4.36	High
2023-10	5.37	-2.70	696.6	-243.8	4.05	High
2024-01	5.60	-3.56	617.4	-244.7	4.64	Very High
2024-05	7.03	-3.70	650.1	-186.1	5.03	Extreme
2024-08	6.00	-4.34	650.3	-200.8	4.92	Very High
2025-02	6.19	-2.78	669.4	-210.6	5.48	High
2025-06	5.20	-3.15	597.8	-201.5	3.61	Moderate
2026-01	4.50	-3.57	571.3	-161.9	4.20	Moderate

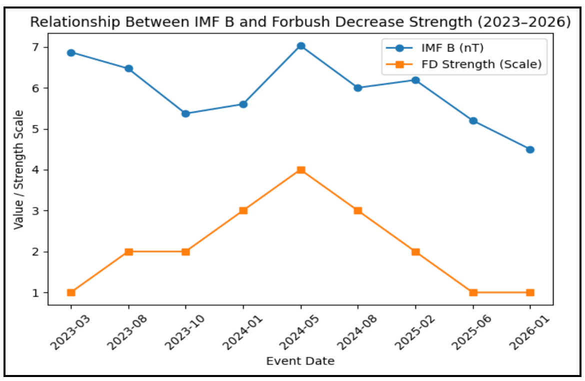
III. GRAPH &TABLE

Table (a) presents an event-based summary of interplanetary and geomagnetic parameters from 2023 to 2026, including IMF B, IMF Bz, solar wind speed, Dst index, Kp index, and corresponding FD probability. The data indicate that periods with higher solar wind speeds (≈600–700 km/s), enhanced IMF magnitude (≈5–7 nT), and strongly negative IMF Bz are generally associated with stronger geomagnetic disturbances (Dst < -200 nT) and higher FD probability. Notably, the events of 2024-01, 2024-05, and 2024-08 show very high to extreme FD probability, coinciding with intensified IMF and geomagnetic activity.

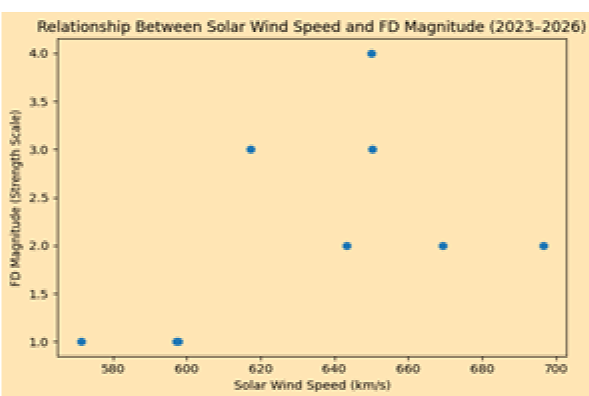
Overall, the table demonstrates a clear trend that increased IMF strength and southward Bz, along with elevated solar wind velocity, enhance the likelihood of Forbush Decrease events. Moderate FD probability is observed during relatively weaker geomagnetic conditions (Dst > -180 nT), while high to extreme FD probability corresponds to strong storm-time conditions and enhanced heliospheric disturbances. This confirms that interplanetary magnetic field intensity and solar wind parameters act as key precursors for FD occurrence during Solar Cycle 25.
Table (a) presents an event-based summary of interplanetary and geomagnetic parameters

Graph: The graph(A) shows a clear association between IMF B (nT) and Forbush Decrease (FD) strength from 2023 to 2026, where higher IMF values generally correspond to stronger FD events. The peak

FD strength in 2024 coincides with enhanced IMF magnitude (~7 nT), indicating intensified interplanetary magnetic disturbances. As IMF B decreases toward 2025–2026, the FD strength also declines, suggesting a direct modulation of cosmic ray suppression by interplanetary magnetic field intensity during Solar Cycle 25. The graph(B) indicates a positive relationship between solar wind speed and FD magnitude, where higher solar wind velocities (above ~630 km/s) correspond to stronger Forbush Decrease events (High to Extreme). This trend suggests that fast solar wind streams and CME-driven shocks enhance magnetic turbulence, leading to greater cosmic ray suppression. Moderate FD magnitudes are mostly associated with relatively lower solar wind speeds (<600 km/s), confirming solar wind as a key driver of FD intensity during Solar Cycle 25.



Graph(A) shows a clear association between IMF B (nT) and Forbush Decrease (FD) strength from 2023 to 2026



Graph(B) indicates a positive relationship between solar wind speed and FD magnitude

IV. RESULTS AND DISCUSSION

The examination of Solar Cycle 25 data shows that solar wind is the principal driver of Forbush Decrease (FD) episodes. During disturbed intervals, particularly from 2023 to 2024, solar wind speeds frequently exceeded 600 km/s, which is typical of fast streams and CME-driven shock situations. These high-speed solar wind structures increase interplanetary magnetic turbulence and effectively sweep galactic cosmic rays away from the near-Earth environment, resulting in a significant drop in cosmic ray intensity. The association between solar wind velocity, Dst index, and cosmic ray flux fluctuations shows a strong coupling, demonstrating that amplified solar wind disruptions have a major impact on FD modulation and recovery dynamics.

Strongly negative IMF Bz values (about −3 to −4 nT) are closely linked to intense geomagnetic storm conditions, especially when the Dst index is below −200 nT, according to additional analysis of interplanetary magnetic field parameters. In order to improve geomagnetic storm activity and affect the size of Forbush Decreases, the southbound IMF Bz component is crucial in promoting stronger magnetic reconnection at the magnetopause. Both cosmic ray suppression and storm-time energy transfer were shown to be strongly influenced by the orientation and persistence of southbound Bz.

The findings also show that long-lasting cosmic ray suppression phases and significant FD amplitudes were associated with catastrophic geomagnetic storms seen during Solar Cycle 25, particularly in 2024. This proves that the strength of geomagnetic storms is a good predictor of the occurrence, size, and recovery features of FD. Strong storms produce favorable conditions for greater cosmic ray modulation by compressing the magnetosphere and intensifying interplanetary disturbances.

Additionally, Solar Cycle 25's solar maximum phase was marked by high solar activity, frequent CME eruptions, and severe heliospheric disruptions, which resulted in a higher frequency of Forbush Decrease occurrences and geomagnetic storms. Significant FD events observed in late 2025 and early 2026 are noteworthy because they coincide with times of intense geomagnetic disturbances, suggesting that heliospheric influence on cosmic ray flux persists even during the cycle's early decreasing phase.

From a physical perspective a mix of CME-driven shocks, magnetic sheath areas, increased IMF strength, persistent southward Bz, and magnetospheric compression controls the precursor mechanism of Forbush Decrease occurrences. According to the study, there is a substantial correlation between big FD magnitudes and improved geomagnetic indices like Dst and Kp, increased interplanetary magnetic field intensity, and increased solar wind velocity. These results show that FD occurrences are a direct result of linked heliospheric disturbances during times of increased solar activity and validate the interdependence of solar, interplanetary, and geomagnetic processes.

V. CONCLUSION

The solar wind, IMF Bz, and geomagnetic storm coupling are thoroughly examined in this paper as event-based antecedents to Forbush Decrease events during Solar Cycle 25 (2023–2026). The results show that sustained southward IMF Bz, high solar wind speed, and strong IMF magnitude greatly increase cosmic ray suppression and geomagnetic storm intensity. Due to frequent CME-driven disturbances, Solar Cycle 25's solar maximum period displayed the highest coupling efficiency and enhanced FD probability. The study demonstrates that solar wind parameters in conjunction with geomagnetic storm indices (Dst and Kp) can function as accurate forecasting predecessors. Forbush Reduce occurrences and enhance space weather forecasting systems.

VI. FUTURE SCOPE

To accurately determine the initiation and recovery phases of FD, future studies should use hourly solar wind observations and high-resolution neutron monitor data. For real-time FD forecasting, IMF Bz, solar wind speed, and geomagnetic indices can be used to create machine learning and artificial intelligence (AI)-based predictive models. Understanding of CME propagation and interplanetary shock structures can be improved by multi-spacecraft data from ACE, DSCOVR, Solar Orbiter, and Parker Solar Probe. Predictive modeling of cosmic ray modulation and extreme space weather occurrences will be further enhanced by long-term comparison research throughout Solar Cycles 23, 24, and 25.

VII. ACKNOWLEDGEMENT

The author expresses gratitude to the cosmic ray observatories and worldwide space weather data centers for making their datasets publicly available. We are especially grateful to the global neutron monitor networks, NASA OMNIWeb, NOAA Space Weather Prediction Center, and Kyoto World Data Center for Geomagnetism for preserving accurate solar wind, IMF, and geomagnetic records. Additionally, the author thanks academic mentors, the scientific community, and institutional support for their invaluable advice. During the course of this research, effective data processing, visualization, and scientific interpretation were made possible by the use of contemporary computational resources and analytical tools.

VIII. CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this research work. This study is conducted purely for academic and scientific research purposes.

REFERENCES

[1] Mavromichalaki, H., et al. (2024). Unusual Forbush Decreases and Geomagnetic Storms During Solar Cycle 25. Atmosphere.

[2] Ahmed, O., Badruddin, B., & Derouich, M. (2025). Forbush Decreases During Strong Geomagnetic Storms: Time Delays and ICME Modulation.

[3] Sargsyan, B., & Chilingarian, A. (2026). Ground-Level Enhancements and Forbush Decrease Events in Solar Cycle 25.

[4] Eastwood, J. P., et al. (2017). The Scientific Foundations of Space Weather Forecasting. Space Science Reviews.

[5] Lockwood, M. (2022). Solar Wind–Magnetosphere Coupling Functions and Space Weather Prediction. Space Weather.

[6] Usoskin, I. G. (2023). Cosmic Ray Modulation in the Heliosphere. Living Reviews in Solar Physics.

[7] Cane, H. V. (2000). Coronal Mass Ejections and Forbush Decreases. Space Science Reviews.

[8] Belov, A. (2009). Forbush Effects and Their Connection with Solar, Interplanetary, and Geomagnetic Phenomena.

[9] NASA OMNI Web Database, NOAA Space Weather Prediction Center (SWPC) Data Archives, SILSO World Data Center for Sunspot Index and Solar Observations, kyoto World Data Center for Geomagnetism – Dst Index Database.