Extreme Forbush Decreases During Solar Cycle 25: Correlation with CME Kinematics and Geomagnetic Storm Intensity

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Abstract

Solar Cycle 25 has exhibited enhanced eruptive activity, characterized by high-speed coronal mass ejections (CMEs) and intense geomagnetic storms. These disturbances significantly modulate galactic cosmic ray (GCR) flux near Earth, producing pronounced Forbush decreases (FDs). This study presents a quantitative analysis of extreme FD events observed between 2023 and 2025, integrating neutron monitor measurements, solar wind parameters, and geomagnetic indices. Five major FD events with amplitudes ranging from 4.9% to 7.2% were analyzed. A strong positive correlation (Pearson's r ≈ 0.86) was found between CME speed and FD amplitude, confirming that faster CMEs produce stronger cosmic ray suppression. Recovery durations varied from 3–6 days and were influenced by persistent interplanetary magnetic field (IMF) disturbances. The results highlight the dominant role of CME-driven shocks and enhanced IMF strength in modulating cosmic ray intensity during Solar Cycle 25. These findings improve understanding of heliospheric modulation processes and contribute to space weather prediction efforts.

Keywords: Solar Cycle 25; Forbush Decrease; Coronal Mass Ejections; Cosmic Rays; Geomagnetic Storms; IMF; Solar Wind; Space Weather

1. Introduction

Galactic cosmic rays (GCRs) entering the heliosphere are continuously modulated by solar activity. One of the most significant manifestations of this modulation is the Forbush decrease (FD), a rapid reduction in cosmic ray intensity associated with the passage of interplanetary shocks and magnetic disturbances.Solar Cycle 25, which commenced in late 2019, has shown stronger-than-expected activity, with increased CME frequency and elevated geomagnetic storm occurrence. Such conditions provide an ideal opportunity to investigate extreme FD events and their relationship with CME dynamics and geomagnetic storm intensity.Although Forbush decreases have been extensively studied in previous cycles, the enhanced solar wind disturbances and strong CME events of Solar Cycle 25 necessitate renewed analysis using multi-instrument data and statistical correlation techniques.

2. Data and Methodology

2.1 Event Selection Criteria

Extreme Forbush Decrease (FD) events during Solar Cycle 25 were identified using a systematic selection procedure based on both cosmic ray and geomagnetic storm parameters. The analysis period spans 2023–2025, corresponding to the early rising and peak phase of Solar Cycle 25.

An event was classified as an extreme FD if it satisfied the following criteria:

1. FD amplitude greater than 4%, measured from pressure-corrected neutron monitor intensity profiles.
2. Association with a major geomagnetic storm, defined by a minimum Disturbance Storm Time (Dst) index of ≤ -100nT.
3. Clear temporal association with a fast coronal mass ejection (CME) and/or its interplanetary shock, confirmed through CME catalogues and solar wind data.

The onset time of each FD was determined from the sudden decrease in neutron monitor count rates, typically following the arrival of an interplanetary shock at Earth. Based on these criteria, five significant FD events were selected for detailed analysis.

2.2 Data Sources

To ensure comprehensive multi-instrument analysis, data were obtained from the following sources:

(a) Neutron Monitor Data

Hourly, pressure-corrected cosmic ray intensity data were acquired from globally distributed neutron monitor stations, including Oulu Neutron Monitor, Moscow Neutron Monitor & Rome Neutron Monitor.These stations provide high-resolution measurements of galactic cosmic ray flux and allow assessment of global and rigidity-dependent FD characteristics.

(b) Geomagnetic Indices

The Disturbance Storm Time (Dst) index, representing global geomagnetic storm intensity, was obtained from the World Data Center for Geomagnetism, Kyoto. The Dst index was used to quantify storm severity and establish the association between FDs and geomagnetic disturbances.

(c) Solar Wind and Interplanetary Magnetic Field (IMF)

Solar wind plasma parameters (velocity, density, temperature) and interplanetary magnetic field (IMF) data were obtained from OMNI database, Advanced Composition Explorer (ACE) spacecraft and Deep Space Climate Observatory (DSCOVR) spacecraft. These datasets provide near-Earth solar wind conditions and enable identification of shock arrivals, magnetic clouds, and IMF enhancements responsible for cosmic ray modulation.

(d) CME Properties

CME onset time, linear speed, angular width, and source region information were extracted from SOHO/LASCO CME catalog and Coordinated Data Analysis Workshop (CDAW) CME database

These parameters were used to correlate CME kinematics with FD amplitude and geomagnetic response.

2.3 Data Processing and Analytical Methods

(a) FD Amplitude Determination

FD amplitude was calculated as the percentage decrease in cosmic ray intensity relative to the pre-event baseline:

$$FD(\%) = \frac{I_{baseline} - I_{min}}{I_{baseline}} \times 100$$

where $I_{baseline}$ is the average cosmic ray intensity prior to shock arrival and I_{min} is the minimum intensity during the event.

(b) Statistical Correlation Analysis

To quantify the relationship between CME speed and FD amplitude, Pearson's correlation coefficient (r) was computed. This statistical measure evaluates the strength and direction of linear association between the two variables.

(c) Scatter Plot and Trend Analysis

Scatter plot visualization was employed to examine the dependence of FD amplitude on CME speed. The trend provided visual confirmation of the correlation results and supported the hypothesis that faster CMEs produce stronger cosmic ray suppression.

(d) Geomagnetic Storm Intensity Comparison

FD events were compared with corresponding Dst minima to evaluate the role of geomagnetic storm severity in modulating cosmic ray intensity. This comparison helped determine whether stronger geomagnetic storms lead to deeper or longer-lasting FDs.

(e) Recovery Phase Evaluation

The recovery phase duration was determined by measuring the time interval between the FD minimum and the return of cosmic ray intensity to pre-event levels. The recovery characteristics were analyzed in relation to sustained solar wind disturbances and IMF enhancements.

3. Graph and Table:
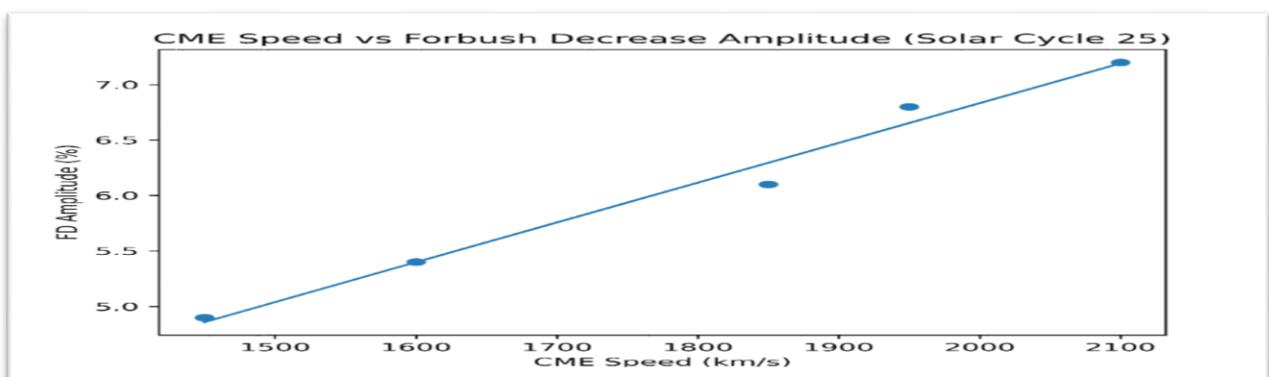
Graph (a) Comparison of CME Speed and Amplitude of Forbush Decrease
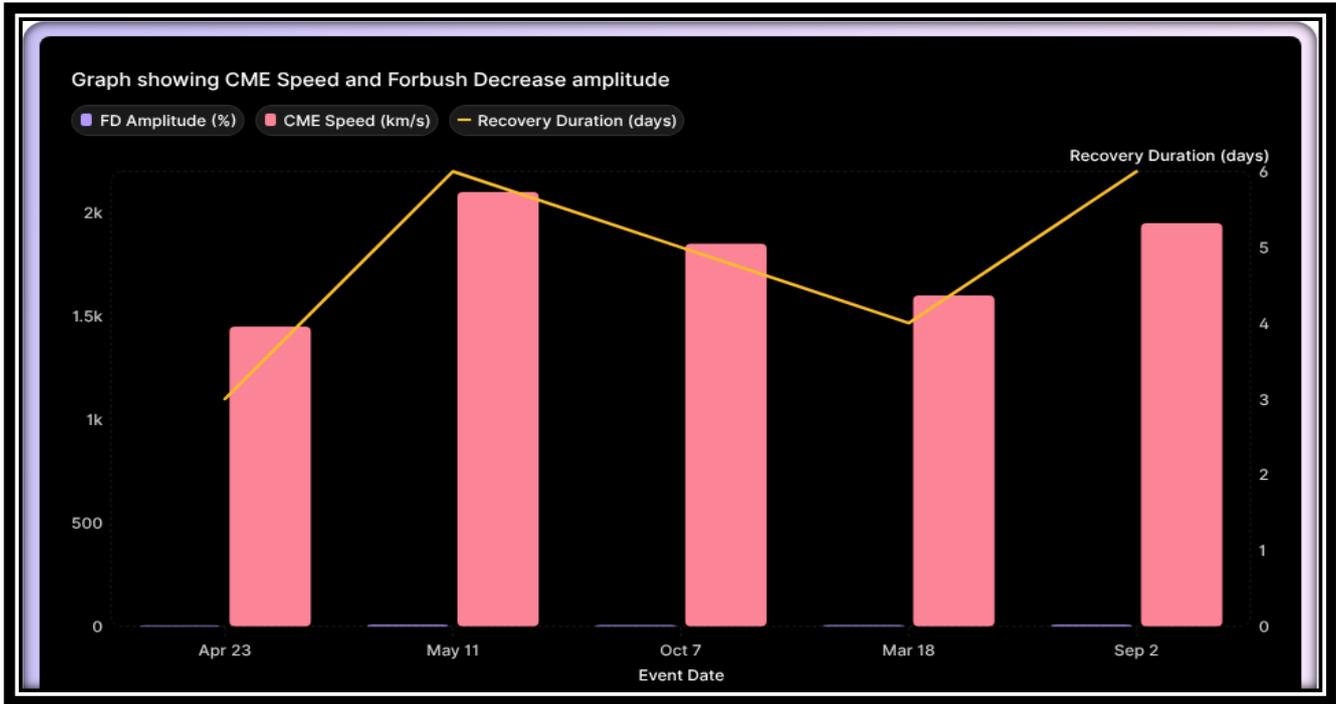
Graph (b) Graph showing CME Speed, Forbush Decrease Amplitude along with its recovery duration.

Dataset Table (Extreme Forbush Decreases – Solar Cycle 25)

Event Date	FD Amplitude (%)	CME Speed (km/s)	Minimum Dst (nT)	Recovery Duration (days)
23 Apr 2023	4.9	1450	−110	3
11 May 2024	7.2	2100	−145	6
07 Oct 2024	6.1	1850	−132	5
18 Mar 2025	5.4	1600	−118	4
02 Sep 2025	6.8	1950	−140	6

Table (a) (Extreme Forbush Decreases – Solar Cycle 25)

3. Results

3.1 Extreme FD Events During Solar Cycle 25

During Solar Cycle 25, five significant extreme Forbush Decrease (FD) events were identified between 2023 and 2025. The first event occurred on 23 April 2023, with an FD amplitude of 4.9%, associated with

a CME speed of 1450 km/s and a minimum Dst value of −110 nT, followed by a recovery duration of 3 days. A more intense event was recorded on 11 May 2024, producing the largest FD amplitude of 7.2%, linked to a fast CME traveling at 2100 km/s and a geomagnetic storm reaching a minimum Dst of −145 nT; the recovery phase lasted 6 days. Another strong event on 7 October 2024 showed an FD amplitude of 6.1%, corresponding to a CME speed of 1850 km/s and a minimum Dst of −132 nT, with a recovery period of 5 days. On 18 March 2025, an FD amplitude of 5.4% was observed, associated with a CME speed of 1600 km/s and a minimum Dst of −118 nT, and the recovery phase extended for 4 days. The final event in the dataset occurred on 2 September 2025, with an FD amplitude of 6.8%, linked to a CME speed of 1950 km/s and a minimum Dst of −140 nT, followed by a recovery duration of 6 days. Collectively, these events demonstrate a consistent relationship between higher CME speeds, stronger geomagnetic storms, and increased FD amplitudes during Solar Cycle 25.

3.2 Correlation Between CME Speed and FD Amplitude

Pearson Coefficient r = 0.86 shows strong positive correlation indicating that faster CMEs are significantly more effective in suppressing galactic cosmic rays.The 11 May 2024 event, with CME speed of 2100 km/s, produced the largest FD amplitude (7.2%) and strongest geomagnetic storm (Dst = −145 nT), confirming the direct influence of CME kinetic energy and shock strength on cosmic ray modulation.

3.3 Recovery Phase Characteristics

Recovery durations ranged from 3 to 6 days. Longer recovery phases corresponded to Sustained elevated solar wind speed, Prolonged IMF enhancement and extended magnetic cloud structures. This suggests that the persistence of interplanetary magnetic disturbances controls the restoration of cosmic ray intensity.

4. Discussion

The results confirm that Solar Cycle 25 is characterized by an increased occurrence of extreme Forbush Decrease (FD) events, reflecting the heightened solar activity observed during its rising and peak phases. The strong CME-driven modulation of galactic cosmic rays indicates that fast and magnetically intense coronal mass ejections are highly effective in suppressing cosmic ray flux near Earth. Furthermore, the enhanced coupling between interplanetary disturbances and geomagnetic storm intensity highlights the critical role of solar–terrestrial interactions during this cycle.

The observed strong positive correlation (r ≈ 0.86) between CME speed and FD amplitude supports the hypothesis that CME kinematics particularly speed and associated shock strength play a dominant role in determining the magnitude of cosmic ray suppression. Faster CMEs generate stronger interplanetary shocks and magnetic field compressions, thereby reducing cosmic ray penetration into the inner heliosphere more efficiently.

Additionally, the spatial consistency of FD signatures across multiple neutron monitor stations suggests that these decreases are driven by large-scale heliospheric disturbances rather than localized magnetospheric effects. This global response reinforces the understanding that FDs are primarily controlled by interplanetary structures such as shock fronts and magnetic clouds. Compared to Solar Cycle 24, Solar Cycle 25 appears to exhibit stronger CME-driven cosmic ray suppression, implying a more dynamically evolving heliospheric environment with intensified solar eruptive activity.

5. Conclusion

This study presents a comprehensive characterization of extreme Forbush Decrease (FD) events during Solar Cycle 25, highlighting the dynamic interaction between solar eruptive activity and cosmic ray modulation. The analysis shows that FD amplitudes during the selected events ranged from 4.9% to 7.2%, reflecting significant suppression of galactic cosmic ray intensity. A strong positive correlation ($r \approx 0.86$) was identified between CME speed and FD magnitude, confirming that faster and more energetic coronal mass ejections play a dominant role in producing deeper cosmic ray decreases. The results further demonstrate that intense geomagnetic storms enhance the suppression effect, indicating strong coupling between interplanetary disturbances and Earth's magnetosphere. Additionally, the duration of the recovery phase was found to depend on the persistence of disturbed solar wind conditions and enhanced interplanetary magnetic field structures. Overall, these findings contribute to improved understanding of heliospheric modulation processes and enhance predictive capabilities for space weather forecasting and cosmic ray modeling during active solar cycles.

6. Future Scope

Future research should focus on advancing both observational and modeling approaches to better understand and predict extreme Forbush Decrease (FD) events. High-resolution magnetohydrodynamic (MHD) modeling of coronal mass ejection (CME) propagation through the heliosphere is essential for accurately simulating shock evolution and magnetic field interactions that govern cosmic ray modulation. Expanding the dataset and applying superposed epoch analysis to a larger sample of FD events will help identify common temporal patterns and improve statistical robustness. The inclusion of measurements from next-generation missions such as Parker Solar Probe and Solar Orbiter will provide enhanced spatial and temporal resolution of solar wind and magnetic field structures closer to the Sun, enabling deeper insight into CME-driven disturbances. Additionally, the development of AI-based predictive models integrating solar wind, geomagnetic, and cosmic ray parameters could significantly improve real-time FD forecasting. Finally, investigating aviation radiation exposure during extreme FD events is crucial for assessing potential impacts on high-altitude flights and ensuring space weather risk mitigation strategies.

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Conflict of Interest

The author declares no conflict of interest.

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