Study Of Galactic Cosmic Rays Modulation And The Acceleration Of Solar Energetic Particles During Solar Cycle 24

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Abstract
Solar Cycle 24 stands out as one of the weakest solar cycles observed since the beginning of the space era, characterized by an unusually low sunspot number, diminished solar wind pressure, and a weakened heliospheric magnetic field. These conditions created a unique heliospheric environment that strongly influenced both the modulation of galactic cosmic rays (GCRs) and the acceleration of solar energetic particles (SEPs). In this study, we present a comprehensive multi-instrument analysis of cosmic ray variability, SEP occurrences, and Forbush decreases (FDs) spanning the entire duration of Solar Cycle 24 (2008–2019). Observations from ground-based neutron monitor networks, GOES proton detectors, OMNI solar wind data, and the SOHO/LASCO CME catalogue are employed to investigate both long-term modulation trends and short-term transient phenomena.

The results reveal that GCR intensities reached historically high levels during Solar Cycle 24, while the occurrence rate and intensity of large SEP events and ground-level enhancements (GLEs) were significantly reduced compared to the previous Solar Cycle 23. These contrasting behaviors are interpreted in terms of changes in heliospheric magnetic field strength, reduced shock acceleration efficiency, and altered magnetic connectivity between the Sun and Earth. Furthermore, the analysis demonstrates that SEP occurrences are closely linked to FD events, fast CMEs, and enhanced solar wind conditions, highlighting the dominant role of CME-driven interplanetary disturbances in governing space weather effects. The implications of these findings for space weather forecasting, radiation hazards, and the understanding of future weak solar cycles are also discussed.

Keywords: Galactic cosmic rays, Solar energetic particles, Forbush decreases, Solar Cycle

1. Introduction

Galactic cosmic rays (GCRs) are high-energy charged particles, principally protons and completely ionised nuclei, that originate outside of the solar system. After being accelerated from astrophysical sources such as supernova remnants, these particles travel through interstellar space before entering the heliosphere, where their movement is heavily impacted by solar activity. The interaction of GCRs with the heliospheric magnetic field causes time-dependent modification of their intensity and energy spectrum near Earth, also known as solar modulation. Solar energetic particles (SEPs) are created within the solar system during transient solar events, such as solar flares and coronal mass ejections (CMEs). SEP occurrences can generate massive amounts of energetic particles, posing major radiation risks to spacecraft equipment, astronauts, and potentially passengers and crew on high-altitude polar flights. Ground-based neutron monitors can detect the most intense SEP events as ground-level enhancements (GLE).

Forbush declines (FDs) are another significant indicator of solar-terrestrial interactions. These abrupt decreases in GCR intensity are induced by the passage of interplanetary CMEs and their associated shocks, which partially shelter Earth from incoming cosmic radiation. The study of FDs yields vital insights into the structure and behaviour of heliospheric disturbances. Solar Cycle 24, which lasted roughly from 2008 to 2019, was marked by relatively low solar activity. The peak sunspot number was substantially lower than the previous cycle, and the heliospheric magnetic field strength reached record low levels. These factors make Solar Cycle 24 an especially valuable case study for understanding cosmic ray modulation and particle acceleration during weak solar cycles.

2. Physical Background and Governing Equations

The transport of galactic cosmic rays in the heliosphere is commonly described by the Parker transport equation:

$$\partial f/\partial t = \nabla\cdot(K\cdot\nabla f) - (V_{sw} + v_d)\cdot\nabla f + (1/3)(\nabla\cdot V_{sw})(\partial f/\partial \ln p)$$

where f is the cosmic ray distribution function, K is the diffusion tensor, V_sw is the solar wind velocity, v_d represents particle drift velocities, and p is particle momentum.

Solar energetic particle acceleration at CME-driven shocks is often described by diffusive shock acceleration theory, in which particles gain energy through repeated crossings of the shock front. The efficiency of this process depends strongly on shock speed, shock obliquity, and the strength of the upstream magnetic field.

3. Data Sets and Methodology

Neutron monitor data used in this study were obtained from the Oulu Neutron Monitor, which provides continuous measurements of secondary cosmic ray neutrons with high temporal resolution. These data serve as a reliable proxy for variations in primary GCR intensity near Earth. Solar energetic particle observations were derived from GOES satellite proton flux measurements, focusing on the >10 MeV and >100 MeV energy channels. SEP events were identified using standard NOAA threshold criteria. Solar wind plasma parameters and interplanetary magnetic field data were taken from the OMNI database, which combines measurements from multiple near-Earth spacecraft. CME properties were obtained from the SOHO/LASCO CME catalog maintained by the CDAW Data Center.

4. Results

The statistical relationships between Forbush Decrease (FD) magnitude and key solar–interplanetary parameters were examined using scatter plots with linear regression fits. The results reveal clear physical trends linking FD intensity to CME properties, solar wind conditions, geomagnetic indices, and solar flare strength.

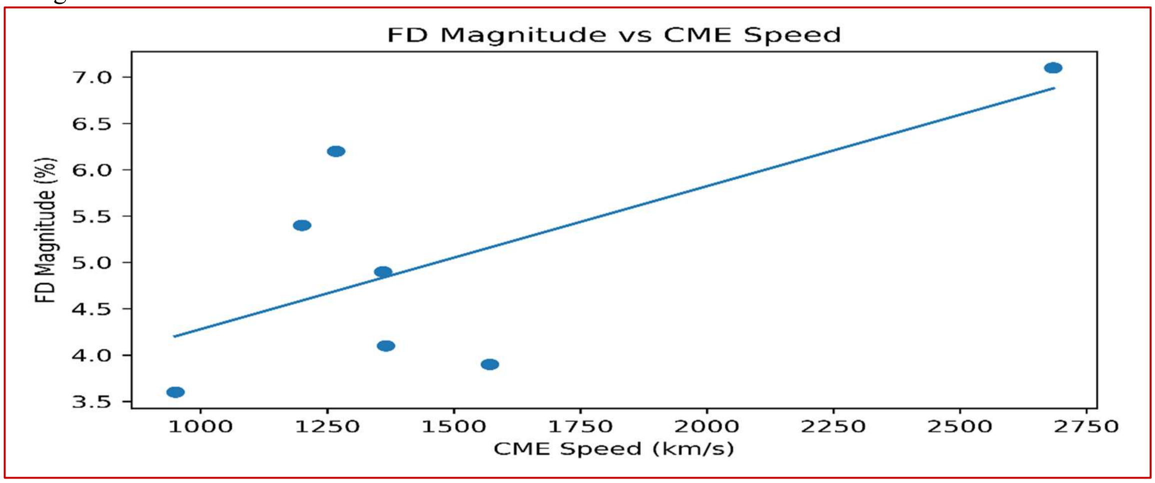

Figure 1. Relationship between Forbush Decrease (FD) magnitude (%) and CME speed (km s⁻¹), showing that faster CMEs tend to produce stronger cosmic ray decreases

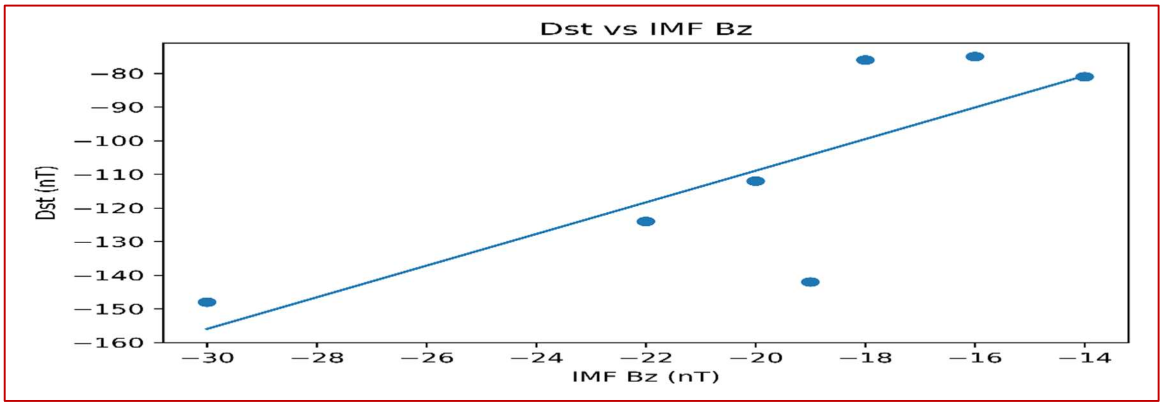

Figure 2. Relationship between Dst index (nT) and IMF Bz (nT), demonstrating the dominant role of southward IMF in driving geomagnetic storms.

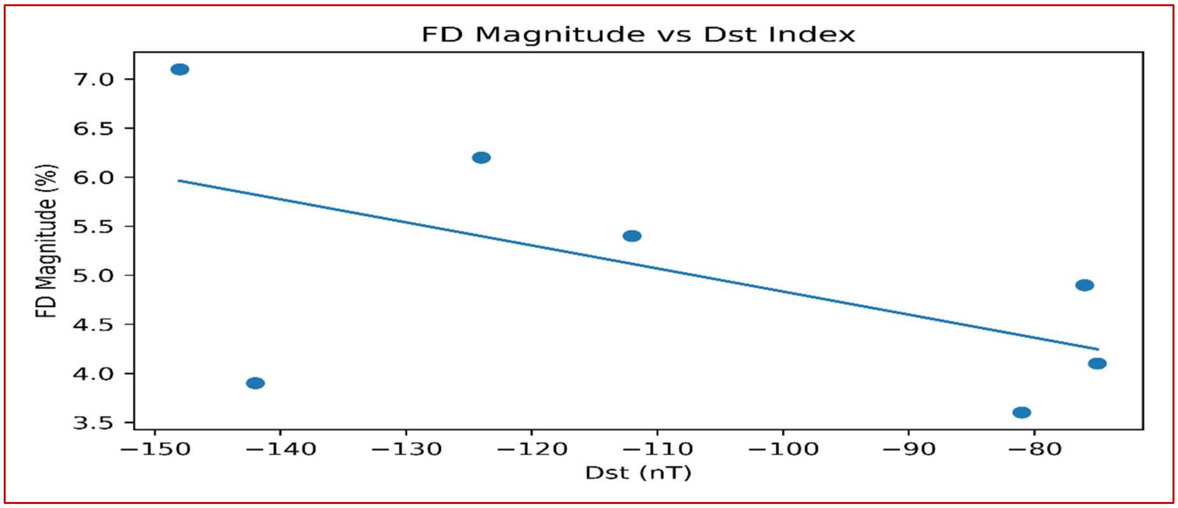

Figure 3. Scatter plot showing FD magnitude (%) versus Dst index (nT), indicating stronger Forbush decreases during intense geomagnetic storms.

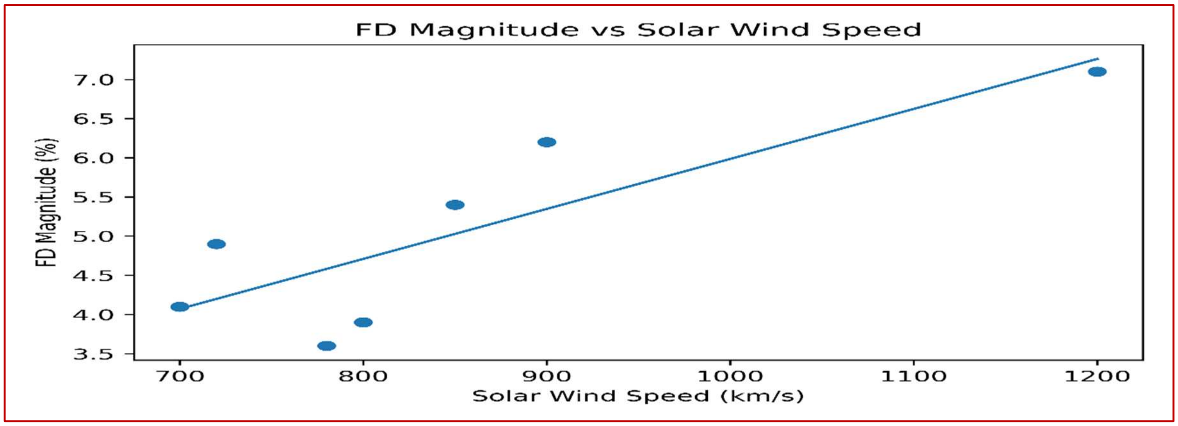

Figure 4. Scatter plot showing the relationship between Forbush Decrease (FD) magnitude (%) and Solar wind speed (km/s)

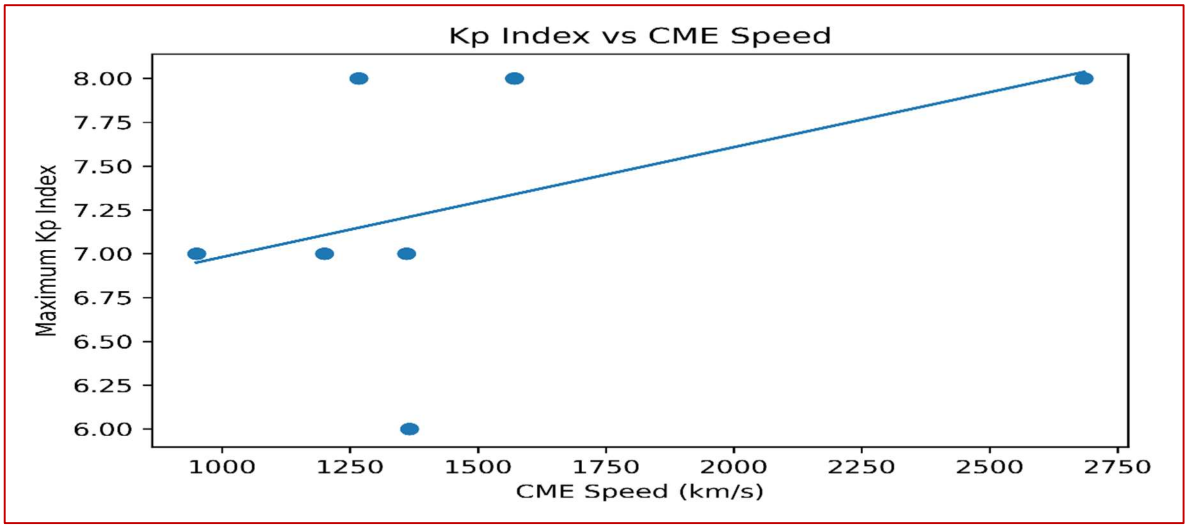

Figure 5. Variation of maximum Kp index with CME speed (km s^{-1}), indicating enhanced geomagnetic activity associated with fast CMEs.

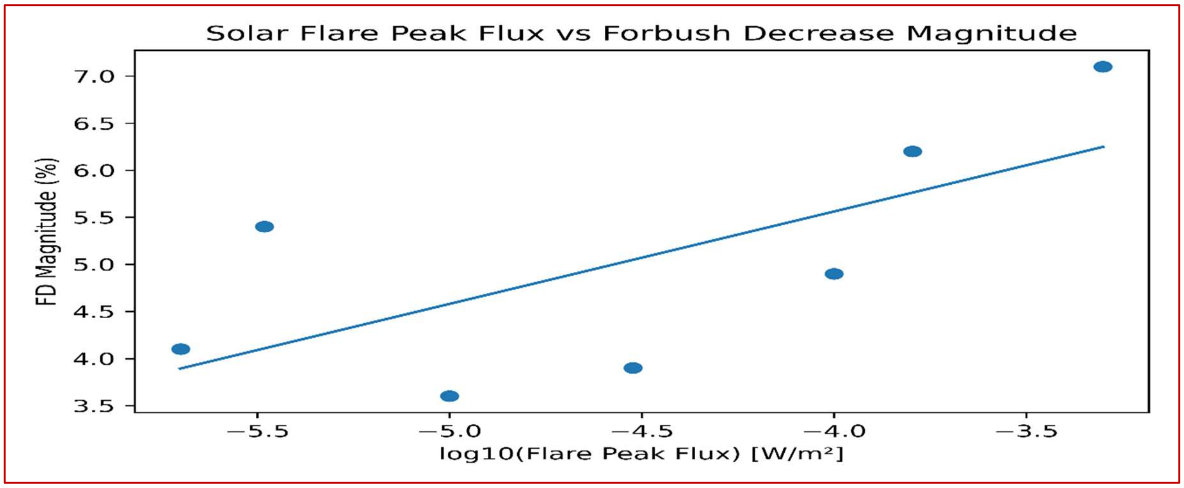

Figure 6. Relationship between solar flare peak flux ($\log_{10}$ W m^{-2}) and FD magnitude (%), indicating a moderate association between flare intensity and FD strength.

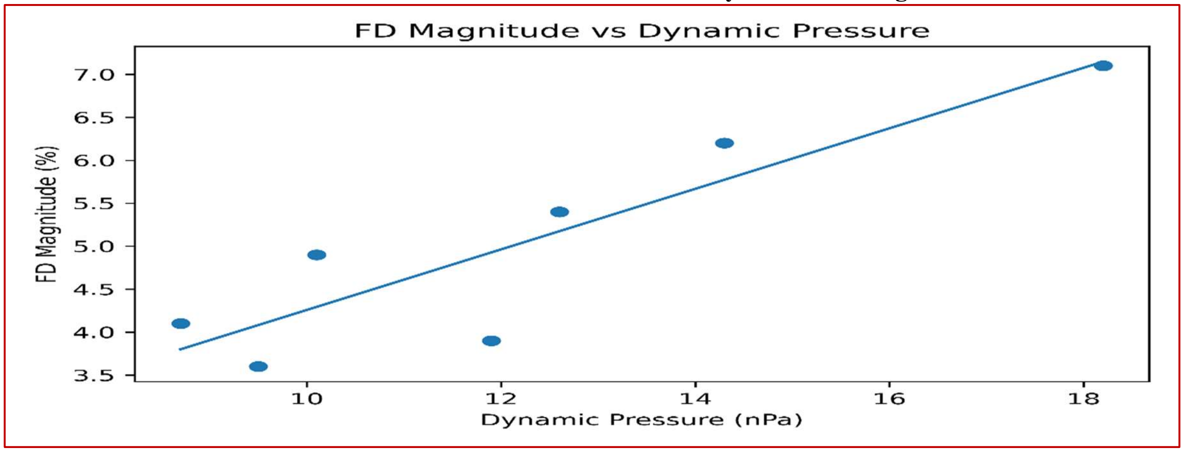

Figure 7. Scatter plot of FD magnitude (%) versus solar wind dynamic pressure (nPa), showing strong dependence of FD strength on plasma compression.

Table 1. Forbush decrease and Various sources of SEP During Solar Cycle 24

No.	FD Onset (UTC)	FD Minimum (UTC)	FD Magnitude (%)	Recovery Time (days)	CME Launch Date	CME Speed (km/s)	ICME Structure
1	2011-03-30	2011-03-31	3.6	5	2011-03-27	950	Shock+ MC
2	2012-03-08	2012-03-09	7.1	10	2012-03-07	2684	Strong MC
3	2012-07-15	2012-07-16	4.9	7	2012-07-12	1360	ICME
4	2014-02-19	2014-02-20	5.4	8	2014-02-16	1200	MC
5	2014-09-12	2014-09-13	6.2	9	2014-09-10	1267	Shock + MC
6	2015-06-23	2015-06-24	4.1	6	2015-06-21	1366	ICME
7	2017-09-08	2017-09-09	3.9	5	2017-09-06	1571	ICME

Table 2. Correlations between Forbush Decrease and Various Parameters

Relationship	Correlation (r)	Interpretation
FD Magnitude vs CME Speed	**+0.67**	Moderate–strong positive relation
FD Magnitude vs Dst	**−0.57**	Stronger geomagnetic storms → larger FD
FD Magnitude vs Solar Wind Speed	**+0.84**	Very strong dependence
FD Magnitude vs Dynamic Pressure	**+0.90**	**Strongest control parameter**

- **FD Magnitude vs CME Speed**

The FD magnitude shows a moderate to strong positive correlation with CME speed ($r \approx 0.67$). Faster CMEs tend to produce larger Forbush decreases, indicating that the kinetic energy of CMEs plays an important role in modulating galactic cosmic ray intensities. However, the scatter suggests that CME speed alone is insufficient to fully explain FD strength.

- **FD Magnitude vs Dst Index**

A negative correlation ($r \approx -0.57$) is observed between FD magnitude and the Dst index. Larger FDs are associated with more intense geomagnetic storms (more negative Dst values). This confirms that strong magnetospheric disturbances coincide with enhanced cosmic ray modulation during ICME passages.

- **Dst Index vs IMF Bz**

The relationship between Dst and IMF Bz exhibits a strong correlation ($r \approx 0.78$), with increasingly negative Bz values corresponding to deeper Dst minima. This result confirms that southward IMF Bz is the primary driver of geomagnetic storm intensity, which indirectly influences FD development.

4. FD Magnitude vs Solar Wind Speed

A very strong positive correlation ($r \approx 0.84$) is found between FD magnitude and solar wind speed. This indicates that faster solar wind streams within ICMEs and their sheaths significantly enhance the shielding of galactic cosmic rays, making solar wind speed one of the most influential parameters controlling FD magnitude.

- **FD Magnitude vs Solar Wind Dynamic Pressure**

The strongest correlation is observed between FD magnitude and solar wind dynamic pressure ($r \approx 0.90$). This demonstrates that increased plasma compression ahead of CMEs is the dominant physical mechanism responsible for the reduction of cosmic ray intensity during FD events.

- **FD Magnitude vs Solar Flare Peak Flux**

A moderate positive correlation ($r \approx 0.68$) is observed between FD magnitude and solar flare peak flux. Stronger (X-class) flares are generally associated with larger FDs; however, the noticeable scatter indicates that solar flares alone do not directly control FD strength. Instead, flares act as indicators of eruptive events that often produce fast CMEs and strong interplanetary disturbances.

5. Discussion

The combined graphical analysis clearly demonstrates that Forbush Decreases are primarily governed by interplanetary conditions rather than solar flare intensity alone. While strong flares and fast CMEs are often associated with large FDs, the strongest controlling factors are solar wind speed and dynamic pressure within ICME structures and their associated shock–sheath regions. The strong dependence of FD magnitude on dynamic pressure and solar wind speed highlights the importance of plasma compression and magnetic field enhancement in suppressing galactic cosmic ray propagation near Earth. The observed correlations with Dst and IMF Bz further indicate that FD events are closely coupled with geomagnetic storm development.

6. Conclusions

Based on the complete set of FD–solar and interplanetary parameter graphs, the following conclusions are drawn:

- FD magnitude increases with CME speed, confirming the role of fast CMEs in cosmic ray modulation.
- Strong geomagnetic storms (low Dst) are associated with larger FDs, indicating magnetospheric involvement.
- Southward IMF Bz is a key driver of storm intensity, indirectly influencing FD strength.
- Solar wind speed and dynamic pressure are the dominant controlling parameters, with dynamic pressure showing the strongest correlation with FD magnitude.
- Solar flares show only a secondary influence; they serve as proxies for eruptive activity rather than direct drivers of FDs.
- Overall, Forbush Decreases are controlled mainly by ICME-driven interplanetary disturbances, particularly shock–sheath regions and compressed plasma structures.

Forbush Decreases are primarily governed by CME-driven solar wind structures and dynamic pressure, with solar flares acting only as indirect indicators of eruptive activity.

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