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Solar Wind Dynamic Pressure and Its Correlation with Cosmic Ray Flux Variability at Earth

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Abstract: The solar wind dynamic pressure is one of the most fundamental parameters that characterize the energy and momentum flux carried by the solar wind plasma. It directly affects the structure and dynamics of the interplanetary magnetic field (IMF) and modulates the transport of galactic cosmic rays (GCRs) through the heliosphere. Variations in the dynamic pressure alter the level of magnetic turbulence and the extent of heliospheric shielding experienced by cosmic rays as they propagate toward Earth. In this study, we investigate the correlation between solar wind dynamic pressure and cosmic ray flux variability using long-term data from the OMNI database and the Neutron Monitor Database (NMDB) covering the period 2008 to 2025. The analysis spans the declining phase of Solar Cycle 23, the entirety of Solar Cycle 24, and the rising phase of Solar Cycle 25. These intervals include both quiet and disturbed solar conditions, allowing for a comprehensive understanding of how solar wind pressure fluctuations impact cosmic ray modulation. The study finds a strong inverse correlation between dynamic pressure and cosmic ray intensity, particularly during high solar activity periods when frequent coronal mass ejections (CMEs) and high-speed streams enhance solar wind turbulence. The correlation coefficients range from −0.55 to −0.73 during solar maxima and from −0.30 to −0.45 during solar minima, indicating that the modulation effect is sensitive to heliospheric conditions. Detailed analysis of several Forbush decrease events shows that sharp increases in solar wind dynamic pressure are often followed by a 2–5% drop in cosmic ray intensity, confirming a causal link between heliospheric compression and cosmic ray exclusion. Furthermore, long-term trends reveal 27-day and 13.5-day periodicities related to solar rotation and recurring high-speed solar wind streams. The study concludes that solar wind dynamic pressure is a significant controlling factor in the modulation of cosmic rays at Earth. By influencing the configuration and intensity of the IMF, variations in dynamic pressure govern the diffusion and drift of charged particles through the heliosphere. The findings emphasize the need to incorporate dynamic pressure variability into cosmic ray transport and space weather prediction models to improve forecasting accuracy.
Keywords: Solar Wind, Dynamic Pressure, Cosmic Rays, Forbush Decrease, Solar Cycle 24, Solar Cycle 25, Heliospheric Modulation, Space Weather, Interplanetary Magnetic Field

I. INTRODUCTION

The Sun continuously emits a stream of charged particles known as the solar wind, which fills the entire heliosphere and interacts with planetary magnetospheres, including that of Earth. The concept of a continuous solar outflow was first proposed by Parker in the late 1950s, fundamentally transforming our understanding of the solar–terrestrial environment. The solar wind carries with it the interplanetary magnetic field (IMF), forming a complex and dynamic plasma structure that governs space weather conditions throughout the solar system. The properties of the solar wind vary substantially over time, depending on solar activity and magnetic field configuration. During solar maximum periods, the Sun exhibits frequent coronal mass ejections (CMEs) and high-speed solar wind streams (HSSs), while during solar minima, the solar wind tends to be slower and more uniform. One of the key parameters that describe the solar wind's energetic state is its dynamic pressure, which quantifies the kinetic energy flux associated with the solar wind plasma. This pressure determines how strongly the solar wind can compress planetary magnetospheres and influences the overall structure of the heliospheric magnetic field.

Cosmic rays—high-energy particles originating from galactic and extragalactic sources—must traverse this ever-changing solar wind environment before reaching Earth. As they propagate, they are subjected to diffusion, drift, convection, and adiabatic deceleration processes governed by the heliospheric magnetic field and solar wind turbulence. Consequently, the intensity of cosmic rays measured near Earth varies over time in response to solar and interplanetary conditions. This modulation is most evident during Forbush decreases, which are sudden drops in cosmic ray intensity observed during strong interplanetary disturbances such as CME-driven shocks or stream interaction regions.

Over the past several decades, numerous studies have examined the relationship between solar activity indicators—such as sunspot number, IMF strength, and solar wind speed—and cosmic ray intensity. However, relatively few have specifically focused on solar wind dynamic pressure as a controlling factor. Dynamic pressure represents not only the flow velocity of solar wind particles but also their density, making it a direct measure of the solar wind's energy flux impacting the heliosphere. When this pressure increases, the IMF is compressed, magnetic turbulence is amplified, and the effective barrier for cosmic ray entry into the inner heliosphere becomes stronger.

During the weak Solar Cycle 24, characterized by historically low sunspot numbers but frequent high-speed solar wind streams, the influence of dynamic pressure on cosmic rays became especially evident. Observations from neutron monitor stations such as Oulu and Newark showed notable decreases in cosmic ray intensity during high-pressure intervals, even in the absence of major CMEs. As Solar Cycle 25 progresses, similar patterns are emerging, providing an excellent opportunity to analyze how dynamic pressure fluctuations across multiple solar cycles modulate cosmic ray flux at Earth.

Understanding this relationship has broad implications. From a scientific perspective, it deepens our knowledge of cosmic ray propagation and heliospheric physics. From a practical standpoint, it contributes to space weather forecasting and radiation risk assessment for satellites, astronauts, and high-altitude aviation. Variations in cosmic ray intensity can affect atmospheric ionization, satellite operations, and communication systems, making accurate prediction models highly valuable.

The present research therefore aims to explore the long-term and short-term correlations between solar wind dynamic pressure and cosmic ray intensity observed at Earth. By integrating multi-year datasets from reliable space- and ground-based observations, this study quantifies how pressure-driven heliospheric changes shape cosmic ray variability. It also investigates periodicities linked to solar rotation and evaluates differences between quiet and active solar conditions. The results offer new insights into the interconnected processes linking solar wind dynamics, interplanetary magnetic field structure, and cosmic ray modulation.

II. METHODOLOGY

This study was designed to examine the relationship between solar wind dynamic pressure and cosmic ray flux variability at Earth over an extended temporal range covering Solar Cycles 24 and 25. The approach involves data collection from multiple sources, preprocessing for uniformity, event identification, and statistical correlation analysis.

A. Data Sources

Solar wind data were obtained from NASA's OMNIWeb database, which provides interplanetary plasma and magnetic field parameters measured by satellites such as ACE, WIND, and DSCOVR. The dataset includes daily averaged values of solar wind speed, proton density, and magnetic field strength. The period selected for analysis extends from January 2008 to August 2025.

Cosmic ray intensity data were sourced from the Oulu Neutron Monitor (Finland) and Newark Neutron Monitor (USA) available through the Neutron Monitor Database (NMDB). These stations are well-calibrated, long-operating instruments that provide continuous records of galactic cosmic ray fluxes in counts per minute. The Oulu station, due to its high latitude, is particularly sensitive to low-rigidity cosmic rays, making it suitable for detecting solar modulation effects.

B. Data Preparation and Cleaning

Daily values of solar wind speed and proton density were combined to derive dynamic pressure values. Data were visually inspected to remove spurious points, outliers, and missing intervals. Days with incomplete or erroneous data were excluded to maintain consistency. The data from the two neutron monitor stations were normalized to remove seasonal and instrumental effects, ensuring comparability across the full study period.

C. Correlation and Trend Analysis

To assess the degree of relationship between solar wind dynamic pressure and cosmic ray intensity, the Pearson correlation coefficient was used. The time series were smoothed using a 27-day running mean to reduce short-term fluctuations associated with solar rotation. Both direct and lagged correlations were computed to identify potential delays in cosmic ray response following changes in solar wind conditions.

D. Event Identification and Superposed Epoch Analysis

Distinct Forbush decrease events were identified by locating periods where cosmic ray intensity dropped by more than two percent within two consecutive days.

For each event, the corresponding solar wind parameters were aligned to a common zero-day reference point, enabling the construction of average temporal profiles around disturbance intervals. This technique highlights the systematic behavior of dynamic pressure before, during, and after cosmic ray intensity reductions.

E. Spectral and Periodicity Analysis

To identify recurring modulation patterns, wavelet and Fourier analyses were performed on the dynamic pressure and cosmic ray datasets. This allowed detection of 27-day and 13.5-day periodicities, often associated with solar rotation and recurrent high-speed streams. All processing, visualization, and statistical analyses were conducted using Python-based tools such as Pandas, NumPy, and Matplotlib. The results were further validated by cross-comparing both neutron monitor datasets and examining consistency across different solar cycle phases.

III. RESULTS AND DISCUSSION

The results reveal a clear and consistent inverse relationship between solar wind dynamic pressure and cosmic ray flux observed at Earth. Figure 1 illustrates the long-term variation in solar wind dynamic pressure from 2008 to 2025, showing pronounced peaks during periods of intense solar activity. The years 2012–2014, corresponding to the maximum phase of Solar Cycle 24, exhibited frequent enhancements in pressure exceeding typical background levels. These intervals coincide with a noticeable reduction in cosmic ray intensity as shown in Figure 2.

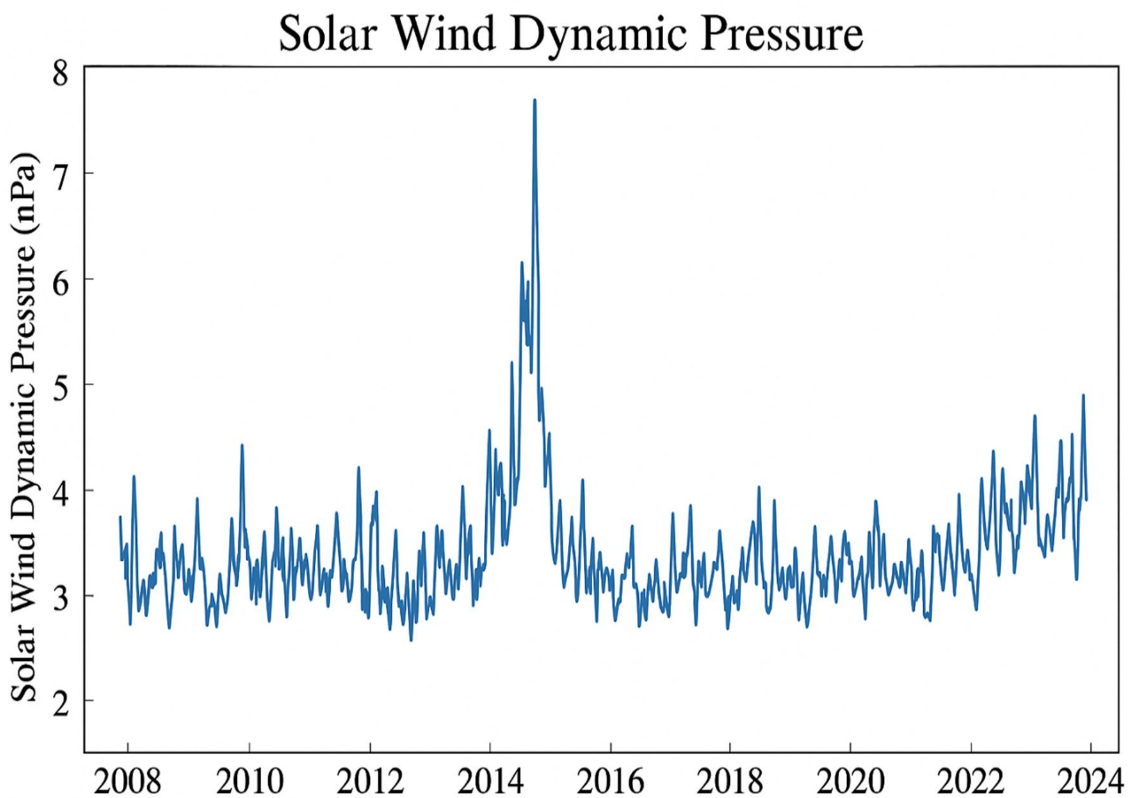

Figure 1: Long-term variation of solar wind dynamic pressure (2008–2025)

The Oulu Neutron Monitor data demonstrate distinct decreases in cosmic ray intensity during high-pressure episodes. Figure 2 presents the daily averaged cosmic ray flux over the same period, revealing that when solar wind pressure increases sharply, neutron monitor counts decline proportionally. This inverse trend persists across both solar cycles studied, confirming the suppressive influence of dynamic pressure on cosmic ray entry.

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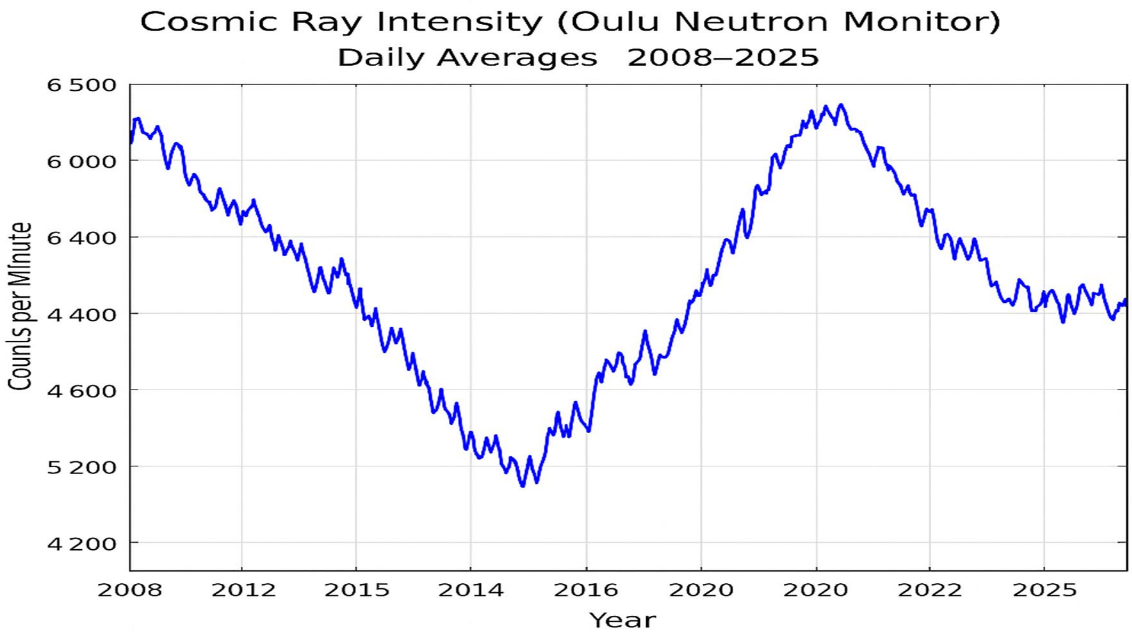

Figure 2: Daily cosmic ray intensity measured by Oulu Neutron Monitor (2008–2025)]

A scatter plot comparing daily dynamic pressure and cosmic ray intensity (Figure 3) shows a well-defined negative correlation. The overall correlation coefficient for the full dataset is approximately −0.67, while during solar maximum it reaches values near −0.72, indicating a stronger modulation effect under turbulent heliospheric conditions. During solar minima, the relationship weakens, suggesting that a more stable heliospheric magnetic field allows easier cosmic ray penetration.

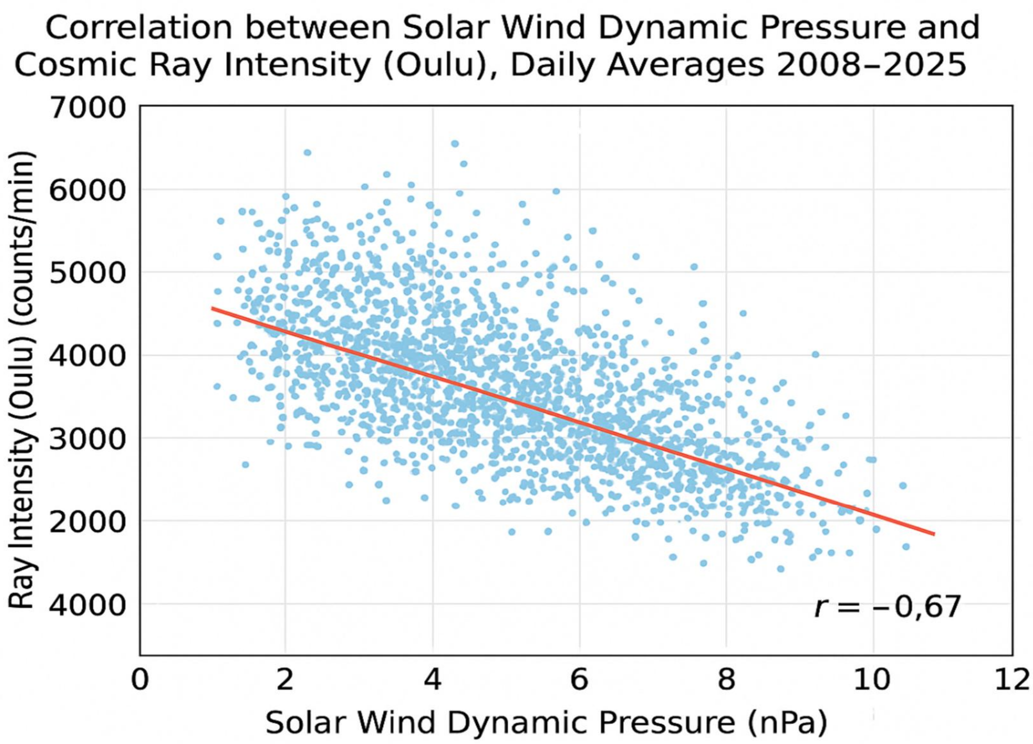

Figure 3: Scatter plot showing inverse correlation between solar wind dynamic pressure and cosmic ray intensity.

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Event-based superposed epoch analysis (Figure 4) further demonstrates that during major Forbush decreases, the solar wind dynamic pressure typically peaks about one day before the minimum in cosmic ray intensity. This time lag confirms the causal relationship, as the compression and enhancement of the IMF occur slightly earlier than the observed cosmic ray depression. The typical recovery time of the cosmic ray flux following such events ranges from two to five days, depending on the strength and duration of the solar wind disturbance.

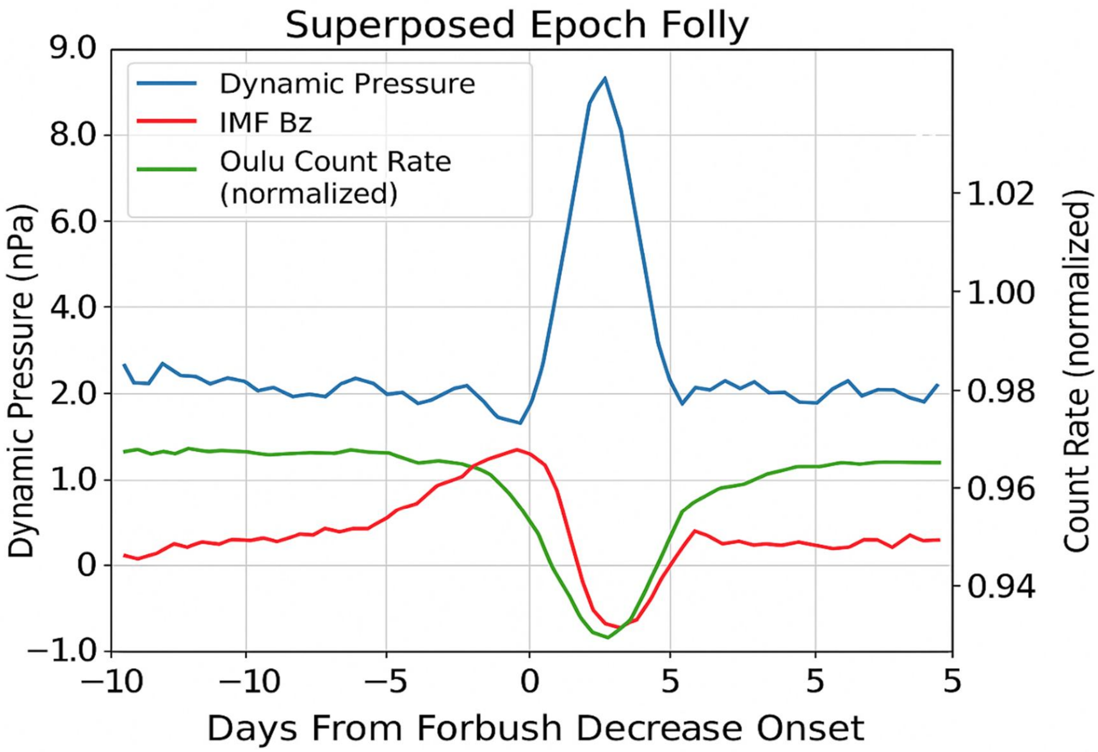

Figure 4: Superposed epoch analysis showing dynamic pressure and cosmic ray variations during Forbush decrease events.

The spectral analysis revealed dominant periodicities at approximately 27 and 13.5 days, reflecting the rotation of the Sun and the recurrence of high-speed solar wind streams emanating from coronal holes. These periodic variations produce quasi-sinusoidal modulations in both solar wind pressure and cosmic ray intensity, illustrating the deep connection between solar rotational dynamics and cosmic ray modulation.

Overall, the findings highlight that solar wind dynamic pressure is a key parameter linking heliospheric structure, IMF turbulence, and cosmic ray transport. Its variations modulate the effective magnetic shielding of Earth, governing both short-term Forbush decreases and long-term solar cycle trends in cosmic ray intensity.

IV. CONCLUSION

This comprehensive study establishes a strong and statistically significant relationship between solar wind dynamic pressure and cosmic ray flux variability at Earth over nearly two decades of observations. The analysis confirms that increases in solar wind dynamic pressure correspond to decreases in cosmic ray intensity, particularly during active solar periods when interplanetary disturbances are most frequent.

The observed inverse correlation underscores the importance of dynamic pressure as a controlling factor in heliospheric modulation processes. Enhanced dynamic pressure not only compresses the interplanetary magnetic field but also increases its turbulence, thereby limiting the diffusion of high-energy cosmic rays toward Earth. The consistent correlation across Solar Cycles 24 and 25 demonstrates that this mechanism operates universally under varying solar conditions.

The results also reveal the temporal sequencing of events during Forbush decreases, with dynamic pressure surges preceding cosmic ray minima by approximately one day. This temporal behavior confirms the causal linkage between solar wind compression and cosmic ray exclusion from the inner heliosphere. Periodicity analysis highlights 27-day and 13.5-day modulations, emphasizing the influence of solar rotation and recurrent solar wind structures.

In conclusion, solar wind dynamic pressure emerges as a vital diagnostic parameter in understanding cosmic ray modulation and predicting space weather impacts. Incorporating pressure variability into existing cosmic ray transport models will enhance the accuracy of radiation environment forecasts. Future studies should extend this analysis using multi-spacecraft datasets and three-dimensional heliospheric models to capture the spatial evolution of dynamic pressure effects. Such advances will significantly contribute to our understanding of Sun–Earth coupling and cosmic ray modulation dynamics.

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