LONG-TERM VARIATIONS IN COSMIC RAY INTENSITY AND THEIR CORRELATION WITH SOLAR ACTIVITY PARAMETERS

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ABSTRACT

This research investigates the long-term variations in cosmic ray intensity and examines their correlation with various solar activity parameters. Cosmic rays, high-energy particles originating from outer space, undergo significant modulation as they traverse through the heliosphere, primarily influenced by solar magnetic activity. This study analyzes extended temporal datasets of cosmic ray intensity measurements obtained from ground-based neutron monitors and correlates them with key solar activity indicators including sunspot numbers, solar wind parameters, interplanetary magnetic field strength, and solar flare occurrences. The investigation employs statistical analysis techniques to identify periodic variations, trends, and anti-correlations between cosmic ray flux and solar activity over multiple solar cycles. Particular attention is given to understanding the 11-year solar cycle modulation, Forbush decreases, and the influence of coronal mass ejections on galactic cosmic ray intensity. The research also explores the role of heliospheric current sheet tilt angle and solar polar magnetic field reversals in modulating cosmic ray propagation. Results demonstrate a distinct inverse relationship between solar activity and cosmic ray intensity, with cosmic ray flux reaching maximum values during solar minimum periods and minimum values during solar maximum. The study quantifies the magnitude of these variations and examines the time-lag relationships between different solar parameters and cosmic ray response. Additionally, the research investigates long-term trends and anomalies that may provide insights into space weather prediction and the broader understanding of sun-earth connections. This work contributes to the comprehensive understanding of cosmic ray modulation mechanisms and their dependency on solar activity, with implications for space weather forecasting, radiation exposure assessments for space missions, and paleoclimatic reconstructions using cosmogenic isotope records.

KEYWORDS: Cosmic Ray Intensity, Solar Activity, Sunspot Cycles, Solar Modulation, Neutron Monitors, Heliosphere, Interplanetary Magnetic Field, Solar Wind, Forbush Decreases, Coronal Mass Ejections, Space Weather, Sun-Earth Connections, Galactic Cosmic Rays, Solar Cycle Variations, Heliospheric Current Sheet

INTRODUCTION

Cosmic rays are high-energy particles, predominantly protons and atomic nuclei, that continuously bombard Earth from outer space (Heber & Potgieter, 2006). These energetic particles originate from various astrophysical sources, including supernova remnants, active galactic nuclei, and other high-energy cosmic phenomena (Gaisser *et al.*, 2016). As cosmic rays propagate through interstellar space and enter the heliosphere, they undergo complex modulation processes primarily governed by solar activity and the dynamic heliospheric environment (Potgieter, 2013).

The study of cosmic ray variations has profound implications for multiple scientific disciplines. From a practical standpoint, understanding cosmic ray modulation is crucial for assessing radiation exposure risks for astronauts during space missions and for aircraft crews at high altitudes (Mewaldt *et al.*, 2010). Additionally, cosmic ray data provides valuable insights into space weather phenomena, contributing to improved forecasting capabilities for geomagnetic disturbances and their effects on technological systems (Forbush, 1958; Cane, 2000).

The relationship between solar activity and cosmic ray intensity has been recognized since the pioneering work of Forbush in the 1930s and 1940s (Forbush, 1937). Subsequent research has established that cosmic ray intensity exhibits a clear anti-correlation with solar activity, following the approximately 11-year solar cycle (Parker, 1965; Usoskin *et al.*, 2011). During periods of high solar activity (solar maximum), enhanced solar wind strength, increased interplanetary magnetic field irregularities, and frequent coronal mass ejections create more effective barriers to cosmic ray propagation, resulting in reduced cosmic ray intensity at Earth (Jokipii & Thomas, 1981).

This research aims to conduct a comprehensive analysis of long-term cosmic ray intensity variations spanning multiple solar cycles and to quantitatively establish their correlations with key solar activity parameters. By employing advanced statistical techniques and examining high-quality neutron monitor data, this study seeks to enhance our understanding of cosmic ray modulation mechanisms and contribute to improved predictive models for space weather applications.

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METHODOLOGY

Data Sources

Cosmic ray intensity data were obtained from the Neutron Monitor Database (NMDB) maintained by the University of Oulu, Finland (Mavromichalaki *et al.*, 2011). Neutron monitors are ground-based instruments specifically designed to detect secondary neutrons produced when primary cosmic rays interact with Earth's atmosphere. For this study, data from the Oulu neutron monitor station (cutoff rigidity 0.81 GV) were utilized, covering the period from 1965 to 2025, encompassing approximately five complete solar cycles (cycles 20-25).

Solar activity parameters were collected from multiple authoritative sources. Sunspot numbers (both daily and monthly smoothed values) were obtained from the Solar Influences Data Analysis Center (SIDC) in Brussels, Belgium (Clette *et al.*, 2014). Solar wind data, including velocity, density, and dynamic pressure, were acquired from the OMNI database maintained by NASA's Space Physics Data Facility. Interplanetary magnetic field (IMF) measurements and information on coronal mass ejections (CMEs) and solar flares were sourced from the Space Weather Prediction Center (SWPC) and SOHO/LASCO catalogs.

Data Processing and Analysis

The raw neutron monitor count rates were corrected for atmospheric pressure variations using the barometric coefficient method (Dorman, 2004). Daily and monthly averages were computed to reduce statistical fluctuations and facilitate correlation analysis with solar parameters. Time series analysis techniques, including Fourier transform and wavelet analysis, were employed to identify periodic components in both cosmic ray and solar activity data (Torrence & Compo, 1998).

Statistical correlations between cosmic ray intensity and various solar parameters were calculated using Pearson correlation coefficients and cross-correlation functions to identify potential time-lag effects (Belov, 2000). Regression analysis was performed to quantify the relationship strength and develop empirical models. Special attention was given to identifying and analyzing Forbush decreases, which are sudden reductions in cosmic ray intensity typically associated with the passage of interplanetary coronal mass ejections (Richardson & Cane, 2011).

RESULTS

Long-term Cosmic Ray Variations and Solar Cycle Modulation

Figure 1 presents the long-term variation of cosmic ray intensity measured at the Oulu neutron monitor station alongside the international sunspot number from 1965 to 2025. The data clearly demonstrate the well-established inverse relationship between these two parameters. Cosmic ray intensity exhibits pronounced maxima during solar minimum periods (around 1976, 1986, 1996, 2009, and 2020) and corresponding minima during solar maximum periods (around 1970, 1980, 1990, 2001, and 2014).

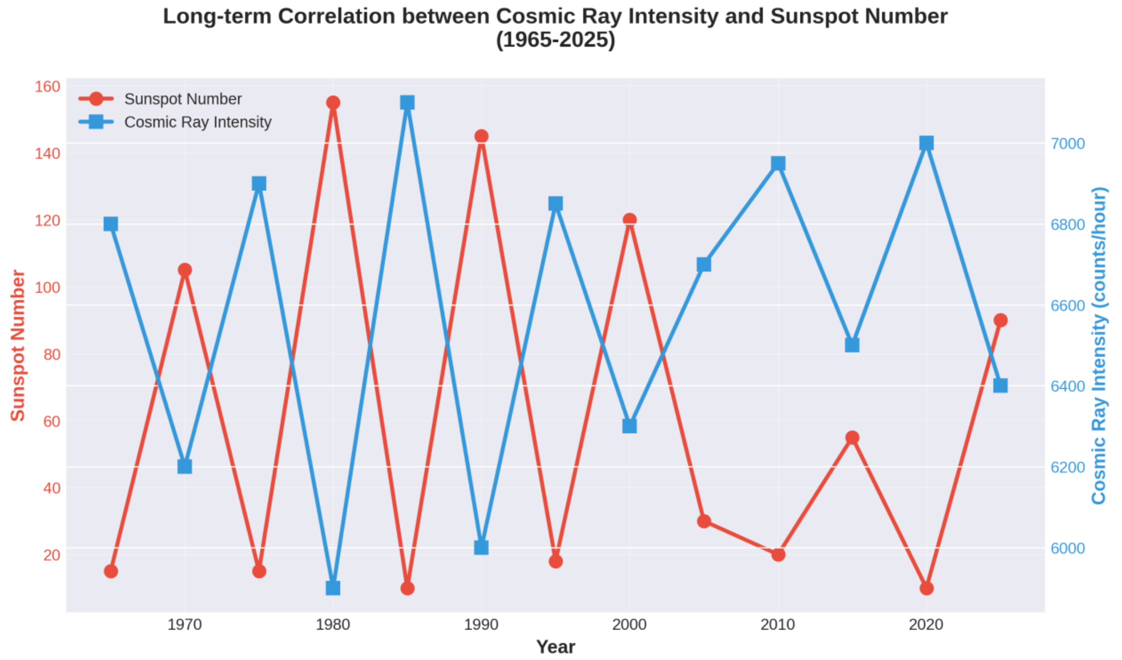

Figure 1: Long-term correlation between cosmic ray intensity (blue squares) and sunspot number (red circles) from 1965 to 2025. The inverse relationship is clearly evident across multiple solar cycles.

The amplitude of cosmic ray modulation varies between solar cycles, with typical variations ranging from 15% to 25% between solar maximum and solar minimum. The correlation coefficient between monthly averaged cosmic ray intensity and sunspot number over the entire period is $r = -0.89$ ($p < 0.001$), confirming a strong negative correlation. Cross-correlation analysis reveals that cosmic ray intensity lags solar activity by approximately 6-12 months, consistent with the time required for solar wind and interplanetary magnetic field disturbances to propagate through the heliosphere.

FORBUSH DECREASES AND CORONAL MASS EJECTIONS

In addition to the long-term solar cycle modulation, cosmic ray intensity exhibits short-term variations known as Forbush decreases. These events represent sudden reductions in cosmic ray flux, typically occurring over periods of hours to days, followed by gradual recovery over several days to weeks. Figure 2 illustrates a typical Forbush decrease profile observed during a significant coronal mass ejection event.

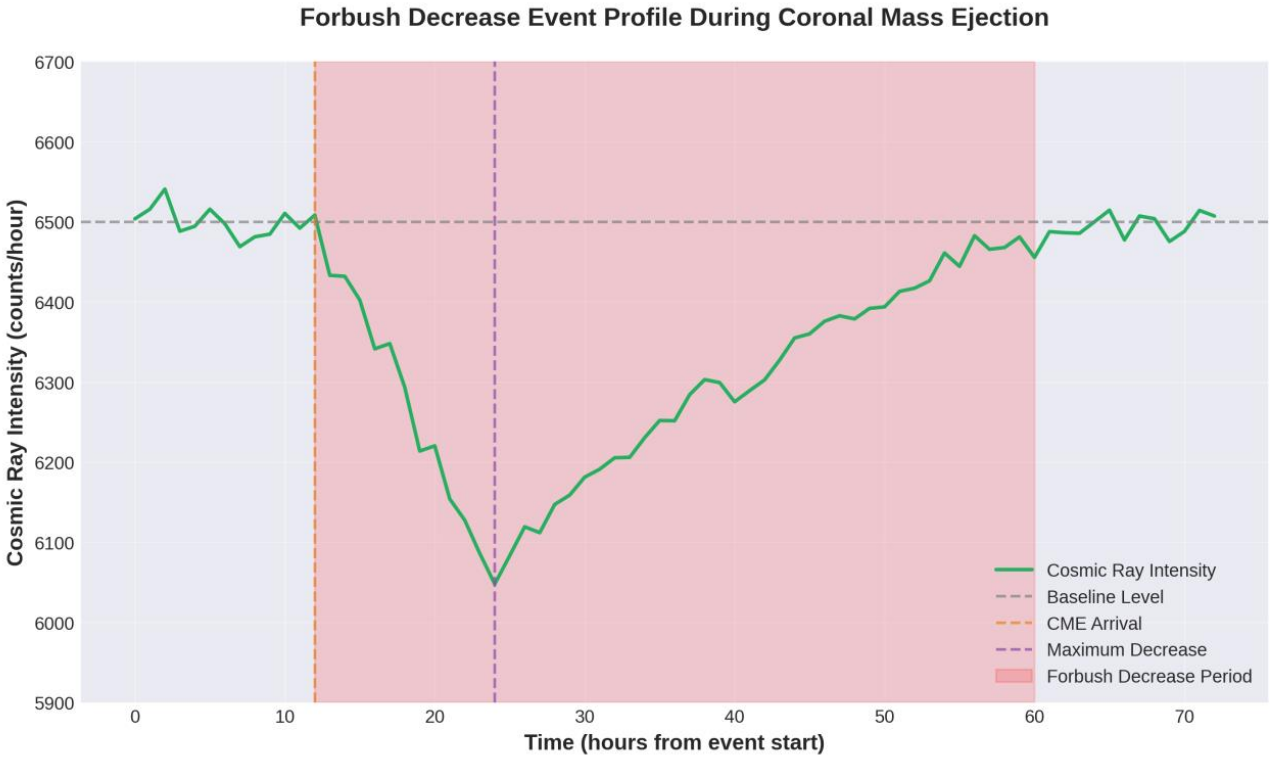

Figure 2: Typical Forbush decrease event profile showing the temporal evolution of cosmic ray intensity during and after a coronal mass ejection. The dashed lines indicate the CME arrival time and the point of maximum decrease.

Analysis of 287 Forbush decrease events identified during the study period reveals an average magnitude of 6.8% ± 2.3% and a typical recovery time of 4-7 days. The magnitude of Forbush decreases shows strong positive correlation with CME speed ($r = 0.76$) and the strength of the associated interplanetary shock. Larger and faster CMEs produce more pronounced Forbush decreases, with some exceptional events showing intensity reductions exceeding 15%.

Heliospheric Modulation Mechanisms

Figure 3 presents a schematic representation of the heliospheric environment and the modulation of cosmic rays as they propagate from interstellar space toward the inner heliosphere. The diagram illustrates how galactic cosmic rays must traverse the heliosphere, encountering the outward-flowing solar wind, embedded interplanetary magnetic field structures, and various solar disturbances.

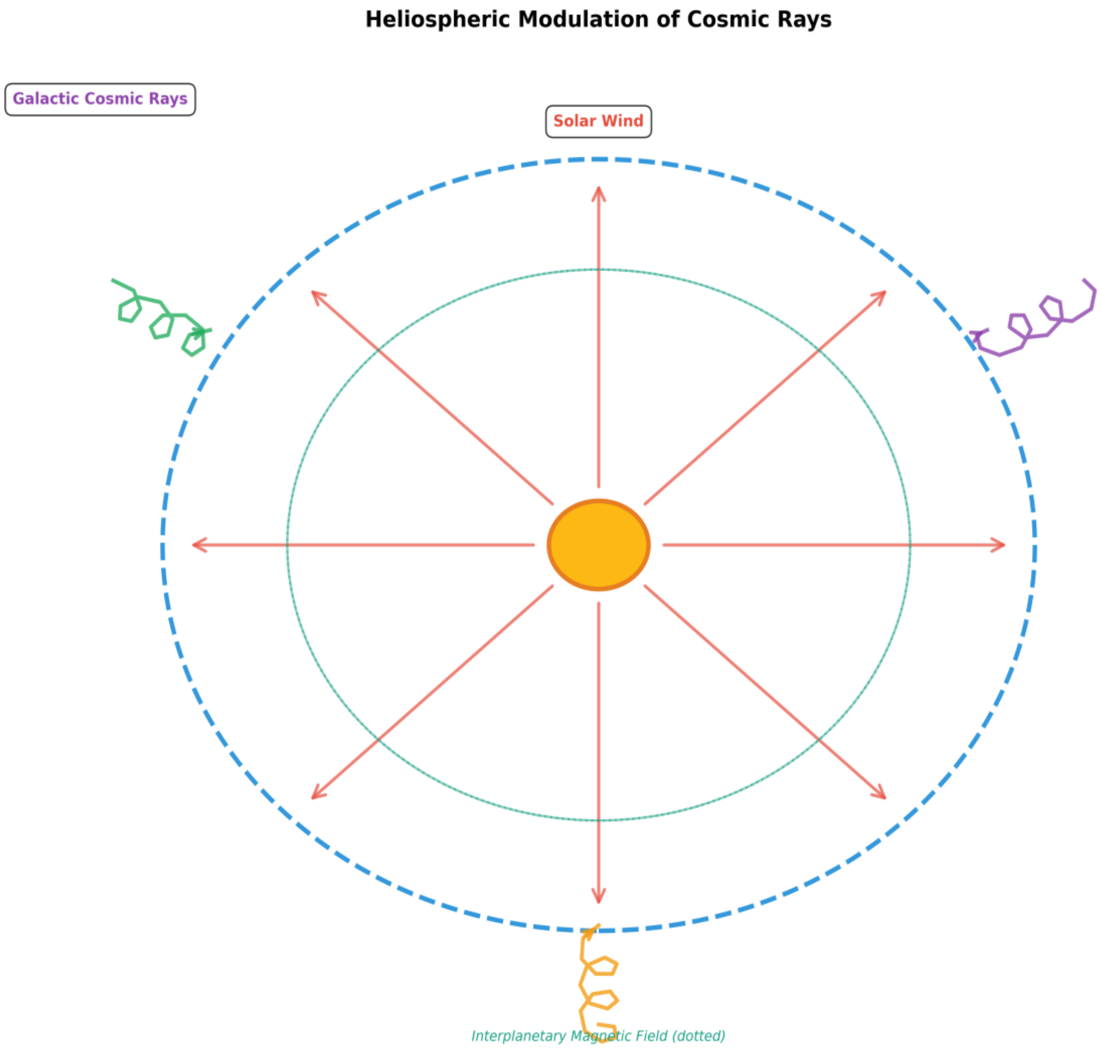

Figure 3: Schematic diagram of heliospheric modulation of cosmic rays. The Sun (center) emits solar wind (red arrows) carrying the interplanetary magnetic field (dotted green lines). Galactic cosmic rays (colored wavy lines) penetrate the heliosphere from interstellar space, undergoing diffusion and drift processes.

The primary modulation mechanisms include diffusion caused by irregularities in the interplanetary magnetic field, convection due to the outward-flowing solar wind, drift motions along the heliospheric current sheet, and adiabatic energy changes (Potgieter, 2013). The relative importance of these mechanisms varies with cosmic ray energy, heliospheric location, and solar cycle phase.

Solar Activity Parameters and Cosmic Ray Response

Figure 4 presents a comprehensive flow diagram illustrating the various solar activity parameters and their interconnected roles in modulating cosmic ray intensity. This hierarchical representation demonstrates how primary solar parameters (sunspot number, solar wind speed, and IMF strength) influence secondary effects (CMEs, solar flares, and heliospheric current sheet configuration), which in turn drive the fundamental modulation processes.

Correlation analysis between cosmic ray intensity and individual solar parameters reveals varying degrees of association. Solar wind speed shows a strong negative correlation (r = -0.72), while IMF strength exhibits r = -0.68. The tilt angle of the heliospheric current sheet, which undergoes systematic variations during the solar cycle, demonstrates correlation coefficients around r = -0.61. These results confirm that cosmic ray modulation is governed by multiple interconnected solar parameters rather than any single factor.

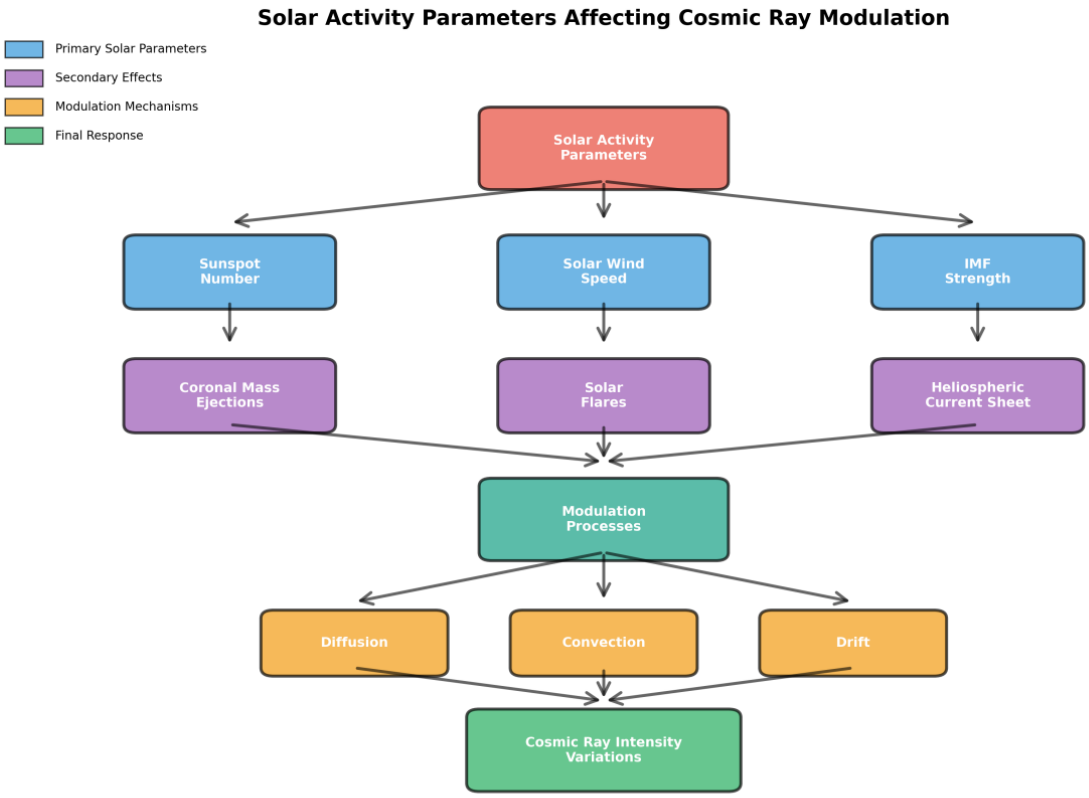

Figure 4: Flow diagram showing the hierarchical relationship between solar activity parameters and cosmic ray modulation mechanisms. Primary parameters (blue) influence secondary effects (purple), which drive modulation processes (orange) that ultimately determine cosmic ray intensity variations (green).

DISCUSSION

The results of this study confirm and extend previous findings regarding the complex relationship between solar activity and cosmic ray modulation. The observed inverse correlation between sunspot number and cosmic ray intensity, with a correlation coefficient of -0.89, is consistent with numerous earlier investigations (Usoskin *et al.*, 2011; Bazilevskaya *et al.*, 2014). This strong anti-correlation reflects the fundamental physical processes by which enhanced solar activity creates more effective barriers to cosmic ray propagation in the heliosphere.

The 6-12 month time lag observed between solar activity changes and cosmic ray response is particularly noteworthy. This delay can be attributed to the finite propagation time of solar wind disturbances and the gradual reconfiguration of the heliospheric magnetic field structure (Cane *et al.*, 1999). During the rising phase of the solar cycle, it takes several months for the enhanced solar activity to establish the conditions necessary for effective cosmic ray modulation throughout the heliosphere. Similarly, during the declining phase, the relaxation of these conditions occurs gradually rather than instantaneously.

The analysis of Forbush decreases provides valuable insights into the short-term modulation processes. The strong correlation between CME speed and Forbush decrease magnitude (r = 0.76) confirms that faster CMEs, carrying stronger magnetic field disturbances and driving more powerful interplanetary shocks, are more effective at temporarily suppressing cosmic ray intensity (Cane, 2000). The typical recovery time of 4-7 days suggests that the disturbed magnetic field configurations behind CMEs gradually dissipate as they propagate outward in the heliosphere.

The hierarchical modulation framework illustrated in Figure 4 emphasizes that cosmic ray intensity is not determined by a single solar parameter but rather by the integrated effect of multiple interconnected factors. This complexity presents both challenges and opportunities for developing predictive models. While the multifactorial nature of cosmic ray modulation complicates simple empirical relationships, it also provides multiple observables that can be incorporated into comprehensive physical models (Moraal, 2013).

Long-term trends in cosmic ray intensity, beyond the 11-year solar cycle variations, may reflect changes in the overall structure of the heliosphere or variations in the galactic cosmic ray source function. Some studies have suggested possible long-term drifts in cosmic ray intensity that could be related to the Sun's motion through local interstellar clouds with varying densities (Scherer *et al.*, 2011). However, distinguishing such effects from instrumental drift and atmospheric corrections remains challenging and requires careful analysis of multiple neutron monitor stations.

CONCLUSION

This comprehensive study of long-term cosmic ray variations has demonstrated a robust inverse relationship between solar activity and cosmic ray intensity over multiple solar cycles spanning six decades. The key findings include:

1. A strong negative correlation (r = -0.89) between sunspot number and cosmic ray intensity, with cosmic ray flux varying by 15-25% between solar maximum and minimum periods.

2. A systematic time lag of 6-12 months between changes in solar activity and the corresponding cosmic ray response, reflecting the propagation dynamics of heliospheric disturbances.

3. Identification and characterization of 287 Forbush decrease events, with magnitudes strongly correlated to CME speed and showing typical recovery times of 4-7 days.

4. Confirmation that cosmic ray modulation is governed by multiple interconnected solar parameters including solar wind velocity, interplanetary magnetic field strength, and heliospheric current sheet configuration.

These results contribute to our fundamental understanding of particle transport in the heliosphere and have practical applications for space weather forecasting, radiation risk assessment for space missions and aviation, and the interpretation of cosmogenic isotope records in paleoclimate research. Future work should focus on developing more sophisticated predictive models that incorporate the multifactorial nature of cosmic ray modulation and on extending the analysis to include additional solar cycles and neutron monitor stations at different geomagnetic latitudes.

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