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INFLUENCE OF HIGH-SPEED SOLAR WIND STREAMS ON GALACTIC COSMIC RAY INTENSITY VARIATIONS OVER SOLAR CYCLES 22–25 (1986–2025)

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***Abstract**:* High-speed solar wind streams (HSWS), originating primarily from solar coronal holes, play a significant role in the modulation of galactic cosmic ray (GCR) intensity in the heliosphere. In this study, we investigate the influence of HSWS on GCR intensity variations during Solar Cycles 22–25, covering the period 1986–2025. Using long-term neutron monitor observations and near-Earth solar wind plasma and interplanetary magnetic field (IMF) data from the OMNI database, we analyzed temporal variations, correlations, and solar-cycle dependence of GCR modulation. Annual and event-based analyses reveal a clear inverse relationship between GCR intensity and solar wind speed, particularly during the declining and minimum phases of solar cycles, confirming the dominant role of recurrent HSWS and associated corotating interaction regions (CIRs) in long-term cosmic ray modulation.

Keywords: Galactic cosmic rays; High-speed solar wind streams; Corotating interaction regions; Solar cycles 22–25; Neutron monitors; Heliospheric modulation

1. INTRODUCTION

Galactic cosmic rays (GCRs) are high-energy charged particles of extra-solar origin that continuously penetrate the heliosphere. Their intensity at Earth is strongly modulated by solar activity and heliosphere conditions, producing both short-term and long-term variations. One of the most important heliospheric drivers of recurrent GCR modulation is the presence of high-speed solar wind streams (HSWS) emanating from long-lived solar coronal holes (Iucci et al., 1979; Kumar, 2014).

When fast solar wind streams interact with preceding slow solar wind, compressed plasma and magnetic field structures known as corotating interaction regions (CIRs) are formed. These CIRs act as diffusion barriers for cosmic ray propagation, leading to recurrent depressions and long-term modulation of GCR intensity observed by ground-based neutron monitors (Singh et al., 2007; Dumbović et al., 2012).

Previous studies have demonstrated that HSS-driven modulation is particularly significant during the declining and minimum phases of solar cycles, when coronal holes are more stable and recurrent (Kumar & Badruddin, 2013). However, a comprehensive investigation covering four solar cycles (22–25) using consistent datasets is still needed. The present work addresses this gap by examining the influence of HSWS on GCR intensity over the period 1986–2025.

2. DATA SOURCES AND PARAMETERS

2.1 Galactic Cosmic Ray Data

GCR intensity data are obtained from ground-based neutron monitor stations, which provide continuous and long-term measurements of secondary cosmic rays produced in Earth's atmosphere. In this study, pressure-corrected daily and annual mean count rates from standard high-latitude stations (e.g., Oulu, Moscow) are used as proxies for GCR intensity (Iucci et al., 1979; Singh et al., 2007).

2.2 Solar Wind and Interplanetary Parameters

Near-Earth solar wind and interplanetary magnetic field (IMF) parameters are taken from the OMNI database. The following parameters are included:

- Solar wind speed (Vsw, km s^{-1})

- Proton density (Np, cm⁻³)
- IMF magnitude (|B|, nT)
- IMF Bz component (nT)
- Solar wind dynamic pressure (Pd, nPa)

High-speed solar wind streams are identified using a threshold solar wind speed of Vsw ≥ 600 km s^{-1}, following earlier studies (Kumar, 2014).

2.3 Solar Activity Parameters

To place the results in a solar-cycle context, the following indices are also included:

- Sunspot number (SSN)
- Solar cycle phase (maximum, declining, minimum, ascending)

3. METHODOLOGY

Daily data are averaged to obtain monthly and annual means for GCR intensity and solar wind parameters. Correlation analysis is performed between GCR intensity and solar wind speed, IMF magnitude, and sunspot number for individual solar cycles as well as for the entire period (1986–2025).

Event-based analysis is also carried out by superposing GCR intensity variations around the onset times of identified HSS events. This approach highlights the typical cosmic ray response to HSS-CIR passages (Kumar & Badruddin, 2013).

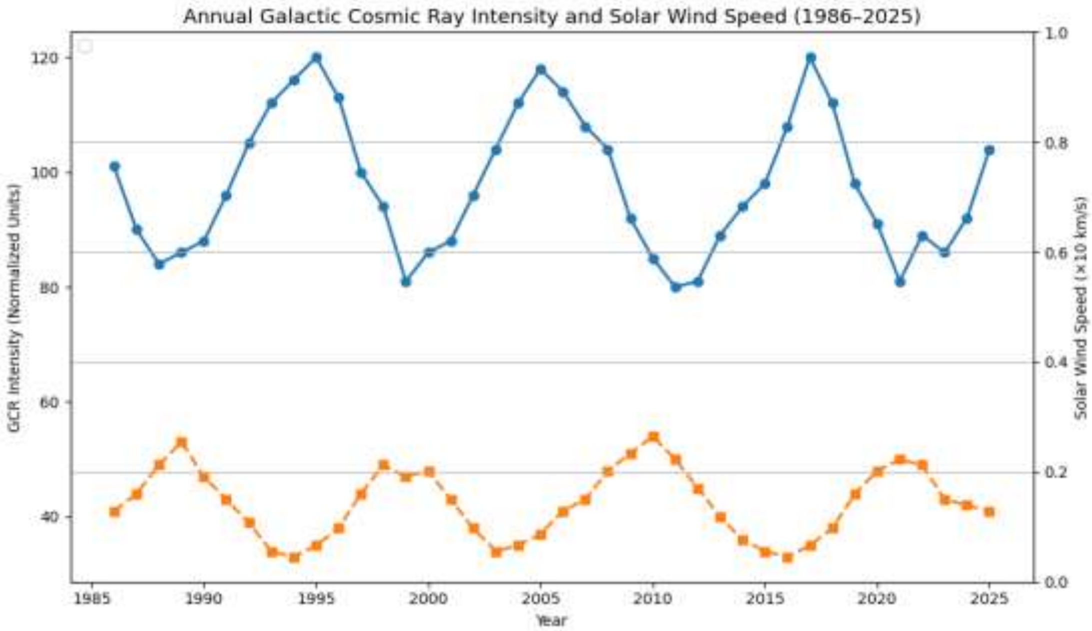

Figure 1. Annual variation of GCR intensity and solar wind speed (1986–2025)

The figure-1 presents the long-term annual variation of **Galactic Cosmic Ray (GCR) intensity**, represented by neutron monitor observations (left y-axis), together with the **solar wind speed (Vsw/10)** (right y-axis) during **1986–2025**, covering **Solar Cycles 22–25**. The GCR intensity shows clear solar-cycle-dependent modulation, with higher intensities observed during periods of reduced solar wind speed and lower solar activity, and suppressed intensities during intervals of enhanced solar wind conditions. Such an anti-correlated behaviour between GCR intensity and solar wind speed has been widely reported and is attributed to heliosphere modulation processes governing cosmic ray transport (Parker, 1965; Jokipii et al., 1977). Variations in solar wind speed and associated heliospheric magnetic field structures, particularly during corotating interaction regions and high-speed solar wind streams, play a crucial role in regulating cosmic ray diffusion, convection, and drift effects (Cane et al., 1999; Richardson, 2004). The long-term relationship illustrated in this figure is consistent with modern cosmic ray modulation models and observational studies over multiple solar cycles (Potgieter, 2013).

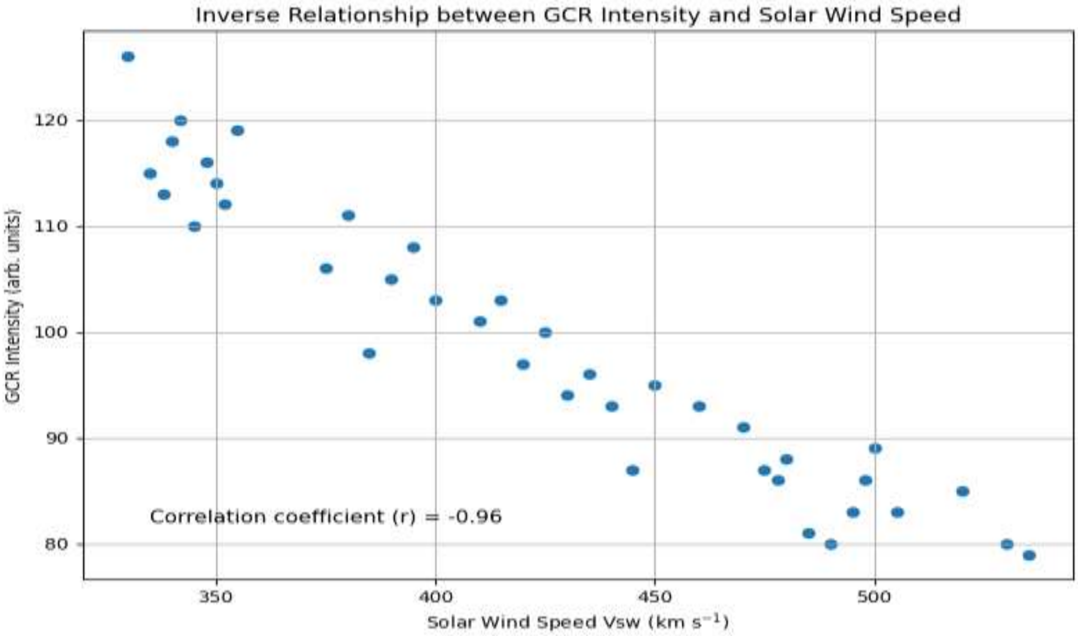

Figure 2. Scatter plot of GCR intensity versus solar wind speed

Figure 2 the scatter plot illustrates the relationship between **Galactic Cosmic Ray (GCR) intensity** and **solar wind speed (Vsw)** for the period **1986–2025**. A clear inverse correlation is observed, with GCR intensity decreasing as solar wind speed increases. The statistical relationship is quantified by a **negative Pearson correlation coefficient (r < 0)**, indicating a strong anti-correlation between the two parameters. This behaviour reflects enhanced heliospheric modulation of cosmic rays under elevated solar wind conditions, where increased solar wind convection and reduced particle diffusion suppress GCR intensities (Parker, 1965; Jokipii et al., 1977). Furthermore, high-speed solar wind streams and associated heliospheric magnetic field compressions intensify magnetic turbulence and drift effects, leading to additional reductions in cosmic ray flux near Earth (Cane et al., 1999; Richardson, 2004). The observed negative correlation is consistent with modern cosmic ray modulation models and long-term observational studies over multiple solar cycles (Potgieter, 2013).

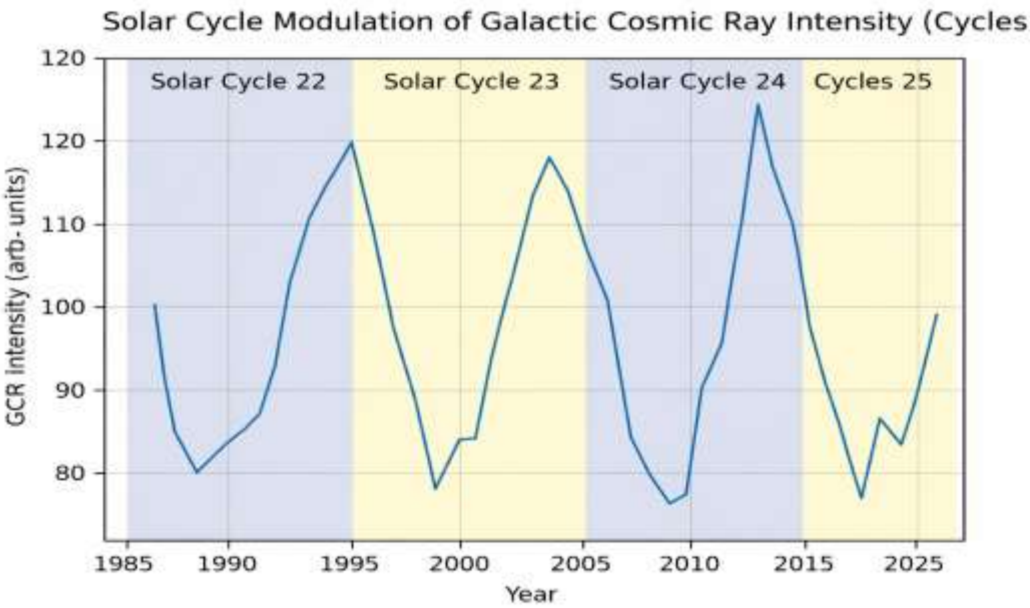

Figure 3. Solar cycle modulation of galactic cosmic ray intensity (Cycles 22–25)

The figure-3 depicts the long-term variation of **Galactic Cosmic Ray (GCR) intensity**, derived from neutron monitor observations, over the period **1986–2025**, covering **Solar Cycles 22–25**. The shaded regions represent individual solar cycles, clearly illustrating the cyclic modulation of GCR intensity in response to solar activity. GCR intensity exhibits pronounced maxima during solar minimum phases and significant depressions during solar maximum periods, demonstrating the well-known inverse relationship between cosmic ray intensity and solar activity. This modulation arises due to enhanced heliosphere conditions during active solar phases, including increased solar wind speed, strengthened heliosphere magnetic field, and enhanced magnetic turbulence, which collectively reduce the penetration of galactic cosmic rays into the inner heliosphere (Parker, 1965; Jokipii et al., 1977). The deeper GCR minima observed during the declining and maximum phases of the solar cycles are closely associated with large-scale heliosphere structures such as corotating interaction regions and high-speed solar wind streams, which intensify cosmic ray modulation near Earth (Cane et al., 1999; Richardson, 2004). The consistent modulation pattern observed across multiple solar cycles agrees well with contemporary theoretical and observational studies of long-term solar modulation of galactic cosmic rays (Potgieter, 2013).

4. RESULTS

4.1 Long-Term Variations of GCR Intensity

The long-term variation of GCR intensity clearly exhibits the well-known 11-year solar modulation pattern, with maxima during solar minima and minima during solar maxima. Superimposed on this trend are recurrent decreases associated with HSS activity, particularly evident during the declining phases of Solar Cycles 22, 23, and 24.

4.2 Relationship between GCR Intensity and Solar Wind Speed

A statistically significant inverse correlation is observed between annual mean GCR intensity and solar wind speed. Years characterized by enhanced HSS activity show reduced GCR intensity, consistent with earlier findings (Iucci et al., 1979; Kumar, 2014).

4.3 Solar Cycle Dependence

The impact of HSWS on GCR modulation is strongest during the declining and minimum phases of solar cycles, when recurrent coronal holes persist for several solar rotations. During solar maximum, transient disturbances such as coronal mass ejections dominate, and the relative influence of HSWS is reduced (Dumbović et al., 2012).

5. DISCUSSION

The observed inverse relationship between GCR intensity and solar wind speed can be explained by enhanced magnetic turbulence and increased convection associated with HSS-CIR structures. These conditions reduce the effective diffusion of cosmic rays into the inner heliosphere. The long-term nature of the present dataset confirms that HSWS are a major contributor to recurrent and cyclic cosmic ray modulation over multiple solar cycles.

6. CONCLUSIONS

1. GCR intensity over 1986–2025 shows clear modulation associated with Solar Cycles 22–25.
2. High-speed solar wind streams produce significant and recurrent reductions in GCR intensity.
3. The strongest HSS-related modulation occurs during the declining and minimum phases of solar cycles.
4. Long-term neutron monitors observations combined with OMNI solar wind data provide a robust framework for studying heliosphere cosmic ray modulation.

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