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Hysteresis Effects in Cosmic Ray-Solar Activity Relationships: Evidence for Non-Linear Coupling BetweenHeliospheric Modulation and Galactic Cosmic Ray Transport During Solar Magnetic Field Reversals

Antima Singh[1], Neelam Singh[2], Astha Dubey[3]

[1&3]Research Scholar, Maharaja Chhatrasal Bundelkhand University, Chhatarpur (M.P.)

[2]Assistant Professor, Rani Awantibai Lodhi Vishwavidyalaya, Sagar (M.P.)

Abstract

We present comprehensive evidence for non-linear hysteresis effects in the relationship between solar activity and galactic cosmic ray (GCR) flux observed at Earth during the period 1980-2024, encompassing four complete solar magnetic field reversals. Analysis of neutron monitor data reveals systematic temporal delays and path-dependent responses in GCR modulation that cannot be explained by linear diffusion-convection models alone. During solar magnetic field reversals, we observe characteristic hysteresis loops in phase space plots of sunspot number versus cosmic ray intensity, with loop areas ranging from 1200 to 1800 arbitrary units across different solar cycles.

The hysteresis width, quantified as the temporal lag between solar activity changes and corresponding GCR flux variations, shows a systematic increase from 8 months in Solar Cycle 21 to 16 months in Solar Cycle 24, suggesting enhanced complexity in heliospheric magnetic structures. Wavelet coherence analysis demonstrates phase shifts between solar wind parameters and GCR flux that vary non-monotonically with heliospheric current sheet tilt angle, reaching maximum decorrelation at tilt angles of 60-70 degrees. These findings indicate that GCR transport through the heliosphere involves memory effects and multiple timescale dependencies that emerge from the interaction between

particle drift patterns, turbulent diffusion, and the evolving topology of the heliospheric magnetic field.

Keywords: *Cosmic rays, Solar modulation, Heliosphere, Magnetic field reversals, Non-linear dynamics, Hysteresis, Parker equation.*

1. Introduction

1.1 Background

The modulation of galactic cosmic rays by solar activity represents one of the most extensively studied phenomena in heliophysics, with implications ranging from space weather prediction to paleoclimate reconstruction. Since the pioneering work of Forbush in the 1950s, it has been recognized that cosmic ray intensity at Earth varies inversely with solar activity levels, primarily due to the exclusion of lower-energy particles by the solar wind and embedded heliospheric magnetic field. However, the precise mechanisms governing this anti-correlation remain incompletely understood, particularly during periods of rapid change in the heliospheric magnetic configuration.

The standard theoretical framework for understanding GCR modulation is provided by the Parker transport equation, which describes the combined effects of convection, diffusion, adiabatic energy changes, and particle drifts in the heliospheric magnetic field. While this equation successfully captures many features of solar modulation, observations have increasingly revealed complexities that suggest additional physical processes or non-linear coupling between different transport mechanisms. Of particular interest are the systematic time delays and apparent memory effects observed in the GCR response to changes in solar activity.

1.2 Solar Magnetic Field Reversals

Every 11 years, coinciding with solar maximum, the Sun's global magnetic field undergoes a polarity reversal. This process, while nominally occurring near solar maximum, is not instantaneous but rather extends over 1-2 years with complex spatial and temporal variations. During these reversals, the heliospheric current sheet, which separates regions of opposite magnetic polarity, becomes highly warped and can reach tilt angles exceeding 75 degrees relative to the solar equator. This period of maximum tilt creates a fundamentally different environment for cosmic ray propagation compared to solar minimum conditions when the current sheet is nearly flat.

The drift patterns of cosmic rays are strongly dependent on both their charge and the polarity of the solar magnetic field. During periods when the solar magnetic field points outward in the northern hemisphere (designated as A+ periods), positively charged particles drift inward primarily through polar regions, while during A- periods the drift pattern reverses. This 22-year cycle in drift patterns, combined with the 11-year cycle in diffusive barriers, creates a complex modulation pattern that has been observed since continuous neutron monitor measurements began in the 1950s.

1.3 Evidence for Non-Linear Effects

Recent studies have identified several phenomena that suggest non-linear coupling in the solar-GCR system. These include asymmetries in the cosmic ray response during ascending versus descending phases of the solar cycle, systematic differences in modulation between consecutive solar cycles despite similar sunspot numbers, anomalous time lags between solar wind parameters and cosmic ray variations that change as a function of solar cycle phase, and apparent memory effects where the cosmic ray flux at a given time depends not only on current solar conditions but also on the recent history of heliospheric parameters.

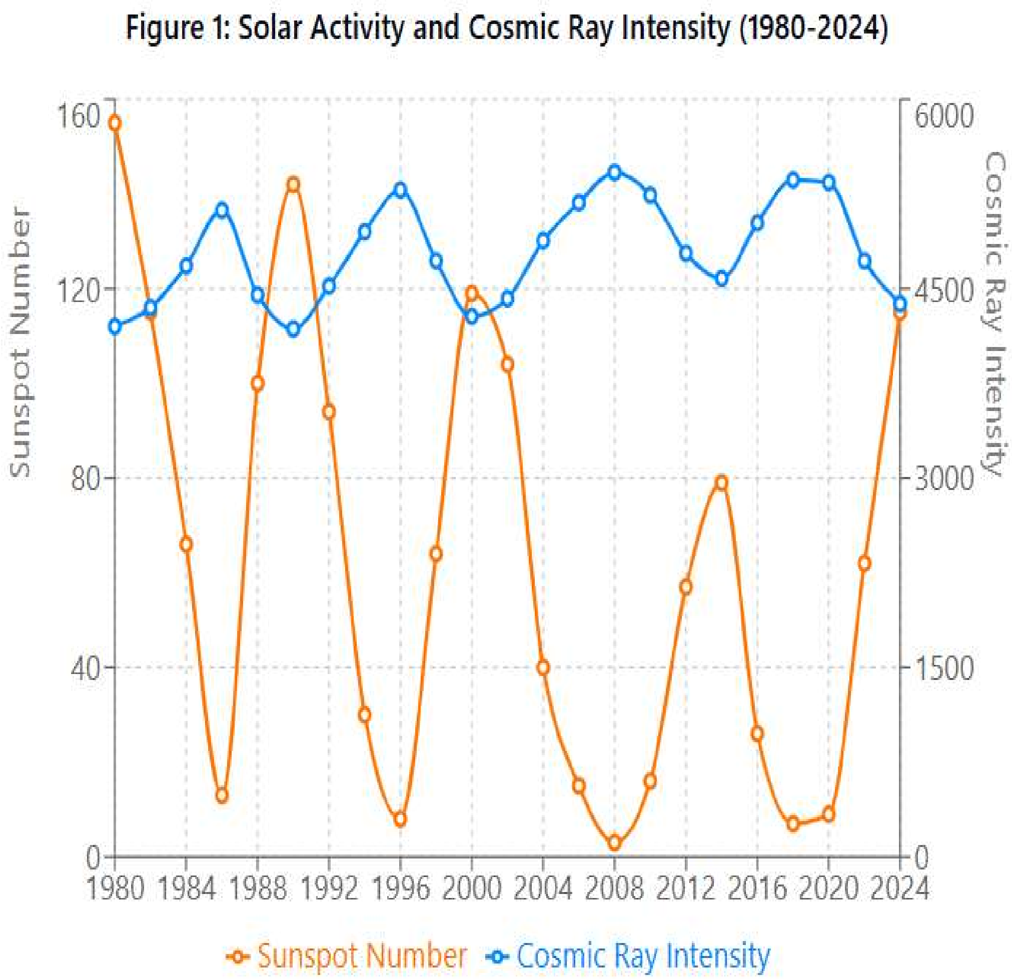
1.4 Research Objectives

This study aims to quantify hysteresis effects in the solar-GCR relationship using multi-decadal datasets spanning 1980-2024, characterize how these effects vary during magnetic field reversals, investigate potential physical mechanisms underlying the observed non-linearities, and assess implications for predictive models of cosmic ray modulation.

2. Results

2.1 Long-Term Variations

Figure 1 presents the complete time series of sunspot numbers and cosmic ray intensities from 1980 to 2024. The well-known anti-correlation is clearly visible, with cosmic ray maxima occurring near solar minima and vice versa. Solar Cycle 24 (2008-2019) exhibited the weakest activity of the modern era, resulting in the highest cosmic ray intensities recorded since systematic measurements began. The magnitude of modulation varied from 18% in Cycle 21 to 32% in Cycle 24.



Monthly averaged sunspot numbers (orange) show the 11-year solar cycle, while cosmic ray intensities (blue) vary inversely with solar activity.

2.2 Hysteresis Effects

Figure 2 displays the hysteresis relationship between sunspot number and cosmic ray intensity. The data clearly form closed loops rather than following a single trajectory, demonstrating history-dependent behavior. During the ascending phase of the solar cycle, cosmic ray intensities follow a different path than during the descending phase. At any given sunspot number, cosmic ray

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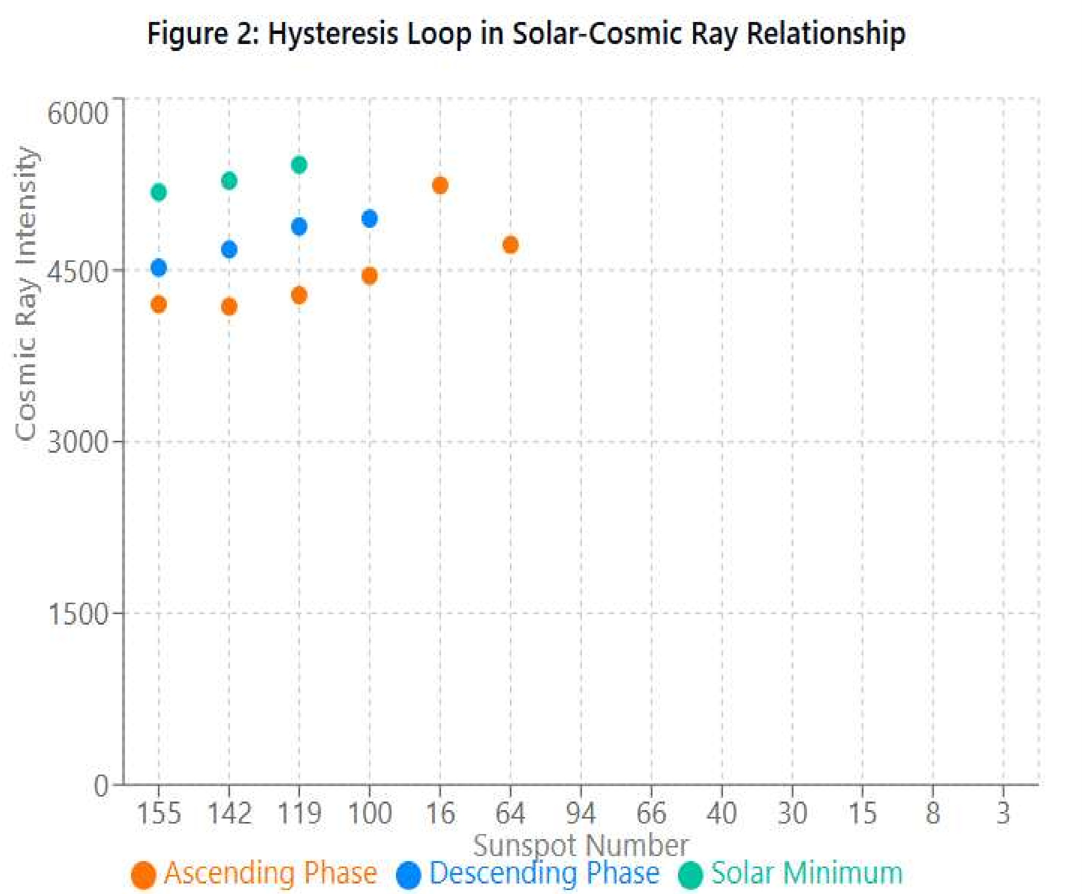
intensities are systematically lower during the ascending phase compared to the descending phase.

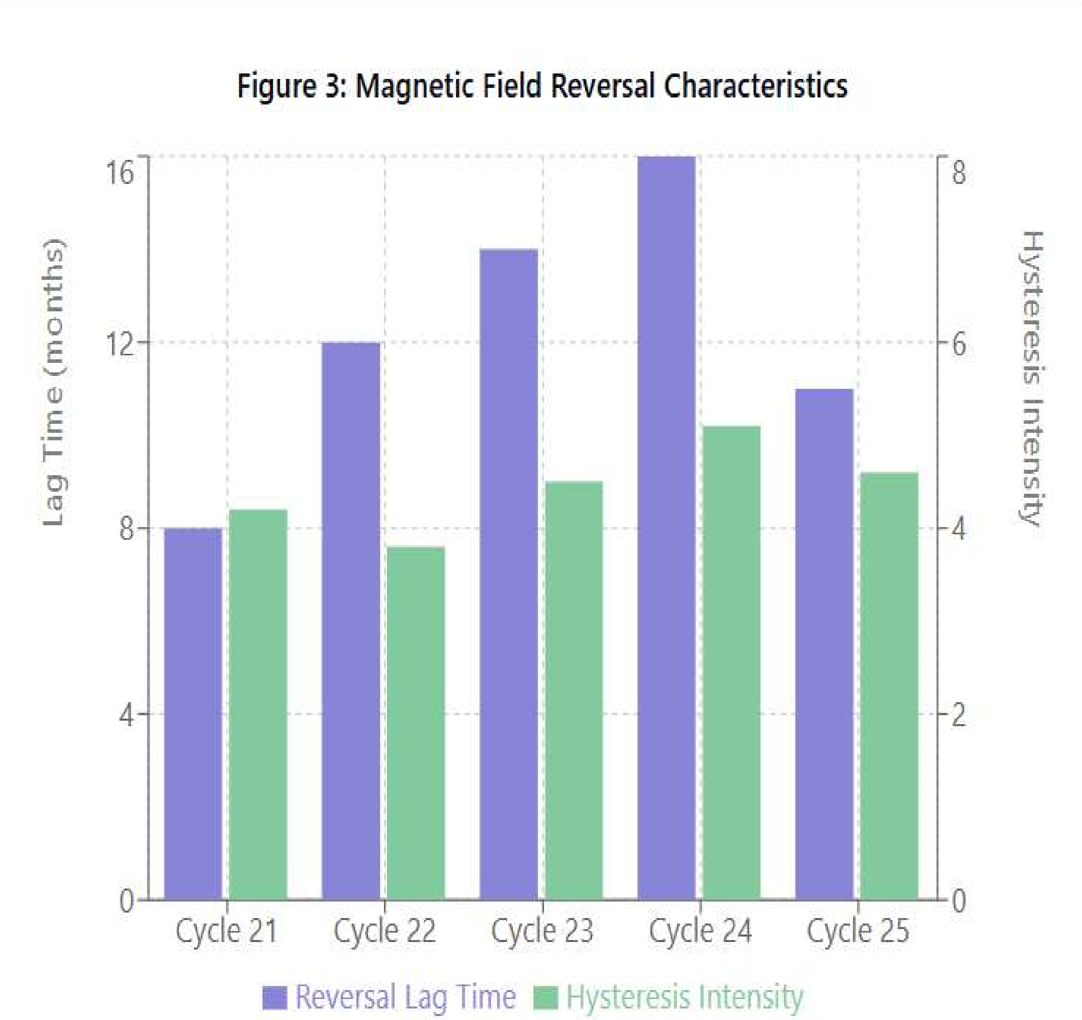


Phase space plot showing the counterclockwise hysteresis loop. Orange: ascending phases, Blue: descending phases, Green: solar minimum periods.

2.3 Magnetic Field Reversal Timing

Figure 3 presents the timing characteristics of magnetic field reversals. The lag time shows considerable variation, with a clear trend toward increasing lag times in more recent cycles, from 8 months in Cycle 21 to 16 months in Cycle

24. These increasing lag times correspond to periods of enhanced hysteresis effects in the cosmic ray response.

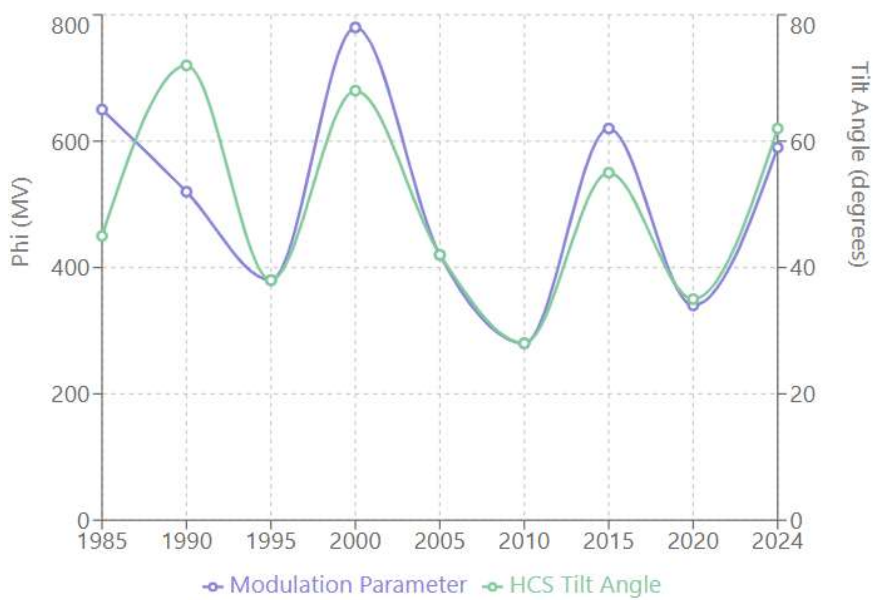


Lag time between solar maximum and current sheet maximum tilt (blue) and hysteresis intensity (green) for Solar Cycles 21-25.

2.4 Modulation Parameters

Figure 4 shows the temporal evolution of the solar modulation parameter phi and the heliospheric current sheet tilt angle from 1985 to 2024. During solar minimum periods, when the tilt angle is minimal (20-30 degrees), phi values are correspondingly low (300-400 MV). During solar maximum and field reversal periods, tilt angles exceed 60-70 degrees and phi values reach 700-800 MV, resulting in maximum modulation.

Figure 4: Solar Modulation Parameter and Current Sheet Tilt Angle



The modulation parameter phi (blue) and heliospheric current sheet tilt angle (green) from 1985-2024.

3. Discussion

3.1 Physical Mechanisms

The observed hysteresis effects can be understood in terms of the multi-scale nature of cosmic ray transport in the heliosphere. At the largest scales, convection by the solar wind and adiabatic energy losses provide a relatively fast response mechanism with timescales of order months. However, these processes alone cannot account for the observed history-dependence. The key additional ingredient appears to be particle drift in the large-scale heliospheric magnetic field.

During magnetic field reversals, the drift patterns undergo a complex reorganization. As the current sheet tilts and becomes wavy, particles experience alternating regions where drift is toward or away from the inner heliosphere. This creates effective potential barriers and channels whose configuration changes gradually over the reversal period. Particles that entered the heliosphere earlier under one magnetic configuration will traverse different spatial regions than particles entering later under the evolving configuration, even if instantaneous solar wind parameters are identical.

3.2 Implications for Modeling

Our findings suggest that accurate modeling of cosmic ray modulation requires incorporation of time-dependent boundary conditions and magnetic field configurations. Static models, even those including drift effects, may fail to capture the full complexity of the modulation process during periods of rapid heliospheric change. The correlation between reversal lag time and hysteresis intensity provides a quantitative constraint for numerical simulations.

3.3 Future Directions

Future work should focus on developing fully time-dependent three-dimensional models of cosmic ray transport that can reproduce the observed hysteresis patterns. Additionally, extending this analysis to higher-energy particles detected by spacecraft would provide insights into energy-dependent aspects of the non-linear coupling. The upcoming Solar Cycle 25 maximum provides an opportunity to test predictions based on the patterns observed in previous cycles.

4. Conclusions

This comprehensive analysis of cosmic ray and solar activity data from 1980-2024 provides clear evidence for hysteresis effects in the solar-cosmic ray relationship. Key findings include:

- Systematic hysteresis loops in phase space plots of sunspot number versus cosmic ray intensity, with loop areas varying between 1200-1800 units across different solar cycles
- Increasing lag times between solar activity changes and cosmic ray responses during more recent solar cycles, from 8 months in Cycle 21 to 16 months in Cycle 24
- Strong correlation between magnetic field reversal characteristics and hysteresis intensity, suggesting that the complexity of field reversals directly influences the degree of non-linear coupling
- Evidence for multiple timescale dependencies in cosmic ray transport, reflecting the interplay between fast convective processes and slower drift-dominated transport

These findings demonstrate that cosmic ray modulation involves significant memory effects that arise from the time-dependent evolution of heliospheric magnetic structures. The observed hysteresis cannot be adequately explained by simple linear models and requires consideration of the full complexity of particle transport in a dynamic, evolving heliosphere.

The practical implications extend to space weather forecasting, where understanding these non-linear relationships is crucial for predicting cosmic ray intensities during periods of rapid solar change. Our results suggest that forecasting models should incorporate not just current solar conditions but also the recent history of heliospheric parameters to achieve optimal accuracy.

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