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Comparative Analysis of the Relationship Between Cosmic Ray Intensity Variations and Flare-Associated Halo Coronal Mass Ejections During Solar Cycles 23 and 24

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Abstract

The modulation of galactic cosmic rays (GCRs) by solar activity is a fundamental aspect of heliospheric physics. In this study, we investigate the relationship between annual mean cosmic ray intensity variations recorded by the Thule Neutron Monitor and the occurrence of halo coronal mass ejections (CMEs), including X-class and M-class flare–associated halo CMEs, during Solar Cycles 23 and 24. Correlation analysis was performed using annual mean data to quantify the degree of association between cosmic ray intensity variations and solar eruptive phenomena.

The results reveal a significant inverse relationship between cosmic ray intensity and halo CME activity in both solar cycles. During Solar Cycle 23, a strong negative correlation ($r = -0.71$) was found between cosmic ray intensity variations and total halo CME occurrence. The relationship was moderately negative for X-class flare–associated halo CMEs ($r = -0.46$) and strongly negative for M-class flare–associated halo CMEs ($r = -0.86$), indicating a pronounced influence of these events on cosmic ray modulation. During Solar Cycle 24, moderate negative correlations were observed between cosmic ray intensity variations and total halo CMEs ($r = -0.51$), X-class flare–associated halo CMEs ($r = -0.44$), and M-class flare–associated halo CMEs ($r = -0.45$).

The consistently negative correlations demonstrate that increased solar eruptive activity is associated with reduced cosmic ray intensity near Earth, supporting the established concept of solar modulation of galactic cosmic rays. Furthermore, the stronger correlations observed during Solar Cycle 23 compared with Solar Cycle 24 suggest that the more intense solar and heliospheric conditions of Cycle 23 exerted a greater influence on cosmic ray transport and suppression. These findings contribute to a better understanding of the interplay between solar transients and cosmic ray variability and highlight the importance of halo CMEs as indicators of heliospheric disturbances affecting the near-Earth space environment.

1. Introduction

Galactic cosmic rays (GCRs) are highly energetic charged particles originating outside the solar system and propagating through the heliosphere before reaching Earth (Parker, 1965). Their intensity at Earth is modulated by solar activity through processes including diffusion, convection, adiabatic energy losses, and particle drifts within the heliospheric magnetic field (Jokipii, 1971; Potgieter, 2013).

Numerous investigations have established that cosmic ray intensity exhibits an inverse relationship with solar activity indicators such as sunspot number, solar radio flux, coronal mass ejections (CMEs), and solar flares (Forbush, 1958; Cane, 2000; Richardson & Cane, 2011). Halo CMEs are particularly important because they are generally Earth-directed and are associated with strong interplanetary disturbances capable of producing significant cosmic ray decreases known as Forbush decreases (Lockwood, 1971; Cane, 2000).Solar Cycle 23 was characterized by intense solar activity and numerous energetic eruptions, whereas Solar Cycle 24 was significantly weaker in terms of sunspot activity, CME occurrence, and heliospheric magnetic field strength (Gopalswamy et al., 2015). These differences provide an opportunity to examine how varying levels of solar activity influence long-term cosmic ray modulation. The objective of the present study is to investigate the relationship between annual mean cosmic ray intensity variations measured by the Thule Neutron Monitor and annual mean occurrences of halo CMEs, flare-associated halo CMEs, and solar activity indices during Solar Cycles 23 and the modulation of galactic cosmic rays (GCRs) within the heliosphere remains one of the most important manifestations of solar–terrestrial coupling. Variations in solar magnetic activity, heliospheric magnetic field strength, and transient disturbances such as coronal mass ejections (CMEs) significantly affect the transport of cosmic rays toward Earth (Potgieter, 2013). Recent investigations have shown that the unusually weak Solar Cycle 24 produced distinctive cosmic ray modulation characteristics compared with previous cycles, including reduced modulation strength and altered hysteresis behavior between solar activity and cosmic ray intensity.

2. Background

The anti-correlation between cosmic ray intensity and solar activity has been recognized for decades (Forbush, 1958). During solar maximum, enhanced solar wind turbulence and stronger heliospheric magnetic fields impede the penetration of galactic cosmic rays into the inner heliosphere, resulting in reduced cosmic ray intensity at Earth (Parker, 1965).

CMEs represent large-scale expulsions of plasma and magnetic fields from the solar corona (Webb & Howard, 2012). Halo CMEs are particularly geoeffective because they propagate along the Sun–Earth line and generate interplanetary shocks that modify cosmic ray transport conditions (Cane et al., 1996). Solar flares are categorized according to soft X-ray intensity into C-, M-, and X-class events. These flares are often associated with CMEs, and stronger flares generally produce larger heliospheric disturbances (Yashiro et al., 2005). Consequently, flare-associated halo CMEs may significantly contribute to cosmic ray modulation. Recent studies have demonstrated that Solar Cycle 24 exhibited weaker magnetic fields, reduced solar wind pressure, and lower CME kinetic energies compared with Solar Cycle 23, resulting in altered cosmic ray modulation patterns (Gopalswamy et al., 2015; Potgieter et al., 2014).

3. Literature Review

Recent analyses of neutron monitor observations during Solar Cycle 24 indicate that cosmic ray intensity remained strongly anti-correlated with solar activity indices despite the weaker heliospheric conditions of the cycle. Ross and Chaplin (2019) demonstrated that Solar Cycle 24 exhibited distinct lag characteristics and modulation patterns compared with earlier cycles.

Studies of rigidity spectrum variations using neutron monitor networks further revealed that heliospheric modulation processes during Solar Cycle 24 differed significantly from those observed during Solar Cycle 23, particularly near solar maximum and polarity reversal periods.

Yanke et al. (2023) reported that residual heliospheric modulation remains significant even after accounting for the conventional 11-year solar cycle, suggesting that long-term cosmic ray variations are influenced by additional heliospheric transport processes.

4. Data and Methodology

4.1 Cosmic Ray Data

Cosmic ray intensity data were obtained from the Thule Neutron Monitor located in Greenland. Neutron monitors provide continuous measurements of secondary particles generated when primary cosmic rays interact with Earth's atmosphere and are widely used for studies of long-term cosmic ray modulation (Simpson, 2000). Annual mean cosmic ray intensity variations were calculated for Solar Cycles 23 and 24.

4.2 Solar Activity Data

Solar activity parameters considered in this study include:

1-Halo CMEs2-X-class flare-associated halo CMEs3-M-class flare-associated halo CMEs4-C-class flare-associated halo CMEs5-Solar Activity Index
Halo CME and flare data were derived from standard solar event catalogs and space-based observations (Yashiro et al., 2004; Gopalswamy et al., 2009) also from SOHO /LASCO CME Catalogue.

4.3 Data Analysis

Pearson correlation coefficients were calculated between annual mean cosmic ray intensity variations and each solar activity parameter.
The Pearson coefficient is given by:

$$r = \Sigma[(Xi - \bar{X})(Yi - \bar{Y})] / \sqrt{[\Sigma(Xi - \bar{X})^2 \Sigma(Yi - \bar{Y})^2]}$$

where X and Y represent paired observations of cosmic ray intensity and solar activity parameters.

4.4 Cosmic Rays and Halo CMEs During Solar Cycle 23

A strong negative correlation (r = −0.71) was found between annual mean cosmic ray intensity and halo CME occurrence during Solar Cycle 23. This indicates that as the number of halo CMEs increased, cosmic ray intensity decreased significantly. The result supports the concept of solar modulation, where enhanced solar eruptive activity generates stronger interplanetary magnetic disturbances that hinder the propagation of galactic cosmic rays toward Earth. The relatively high correlation suggests that halo CMEs played an important role in the suppression of cosmic ray intensity during the more active conditions of Solar Cycle 23.

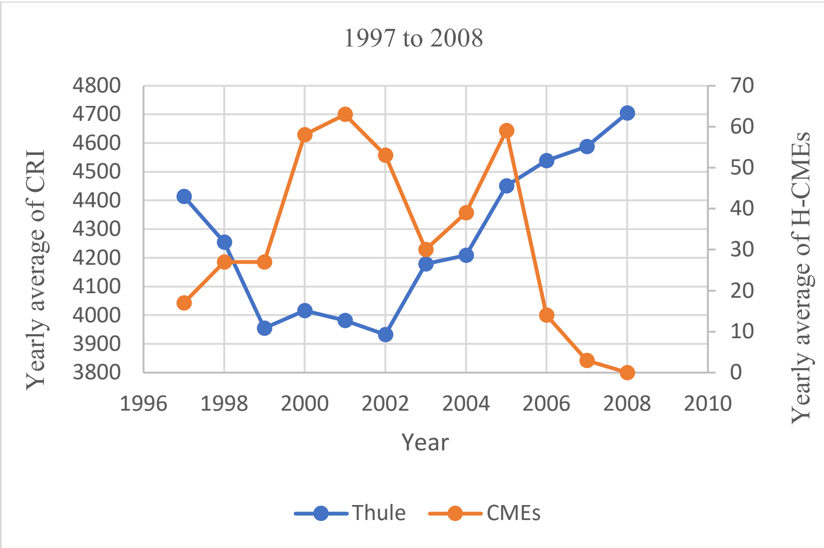

Fig.4.1 Shows the relationship between yearly average value of CRI (Thule) and H-CMEs, for the period of solar cycle 23.

4.5-Cosmic Rays and X-Class Flare–Associated Halo CMEs During Solar Cycle 23

A moderate negative correlation (r = −0.46) was observed between annual mean cosmic ray intensity variations and X-class flare–associated halo CMEs during Solar Cycle 23. This result indicates that increased occurrence of X-class flare–associated halo CMEs was generally accompanied by a decrease in cosmic ray intensity. The negative relationship supports the role of major solar eruptive events in enhancing heliospheric disturbances and reducing the flux of galactic cosmic rays reaching Earth. However, the moderate strength of the correlation suggests that, in addition to X-class flare–associated halo CMEs, other solar and interplanetary factors also contributed to cosmic ray modulation during Solar Cycle 23.

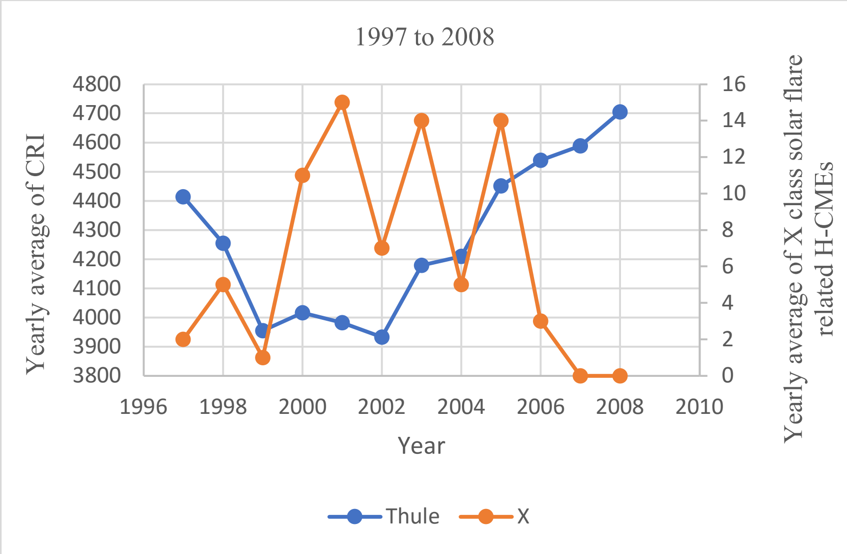

Fig.4.2 Shows the relationship between yearly average value of CRI (Thule) and X-Class solar flare related H-CMEs, for the period of solar cycle 23.

4.6 Cosmic Rays and M-Class Flare–Associated Halo CMEs During Solar Cycle 23

A strong negative correlation (r = −0.86) was observed between annual mean cosmic ray intensity variations and M-class flare–associated halo CMEs during Solar Cycle 23. This indicates that periods with a higher occurrence of M-class flare–associated halo CMEs were strongly associated with lower cosmic ray intensities. The result suggests that these solar eruptive events played a significant role in modulating galactic cosmic rays by enhancing heliospheric magnetic disturbances and reducing cosmic ray penetration into the inner heliosphere. The high correlation coefficient highlights the substantial influence of M-class flare–associated halo CMEs on cosmic ray suppression during the more active conditions of Solar Cycle 23.

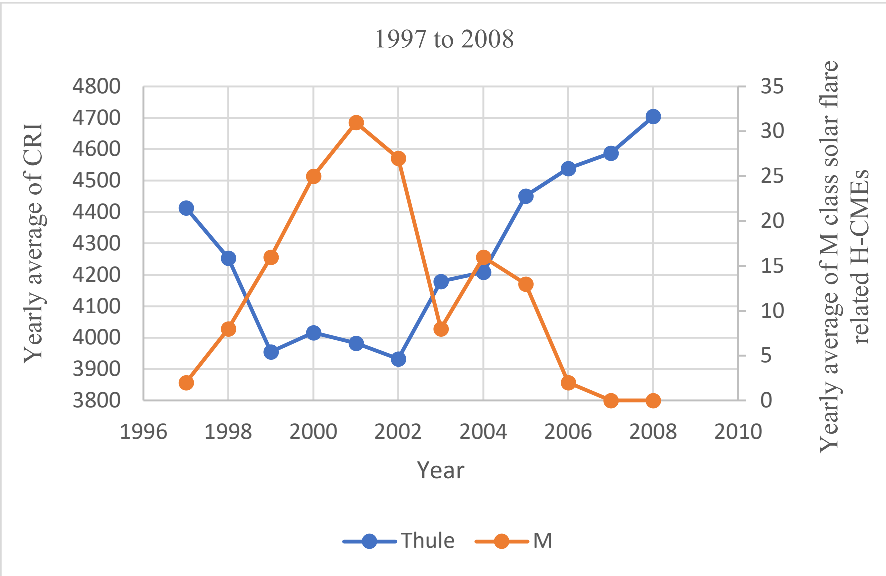

Fig.4.3 Shows the relationship between yearly average value of CRI (Thule) and M-Class solar flare related H-CMEs, for the period of solar cycle 23.

4.7 Cosmic Rays and Halo CMEs During Solar Cycle 24

A moderate negative correlation (r = −0.51) was observed between annual mean cosmic ray intensity variations and halo CME occurrence during Solar Cycle 24. This indicates that an increase in halo CME activity was generally associated with a decrease in cosmic ray intensity near Earth. The inverse relationship supports the role of solar eruptive events in modulating galactic cosmic rays through enhanced heliospheric magnetic disturbances. However, the weaker correlation compared with Solar Cycle 23 suggests that the relatively lower solar activity and weaker heliospheric conditions of Solar Cycle 24 had a reduced influence on cosmic ray suppression.

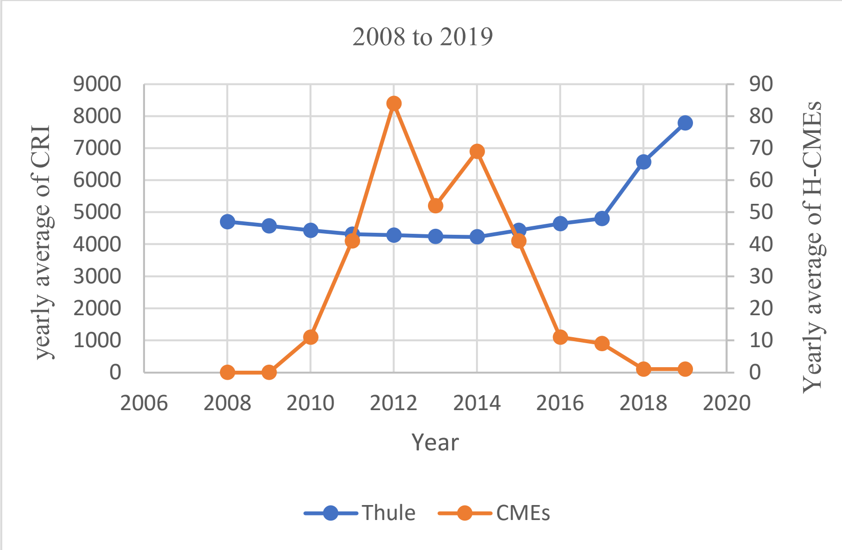

Fig.4.4 Shows the relationship between yearly average value of CRI (Thule) and H-CMEs, for the period of solar cycle 24.

4.8 Cosmic Rays and X-class flare–associated halo CMEs during Solar Cycle 24

A moderate negative correlation (r = −0.44) was observed between annual mean cosmic ray intensity variations and X-class flare–associated halo CMEs during Solar Cycle 24. This indicates that increased occurrence of X-class flare–associated halo CMEs was generally accompanied by a decrease in cosmic ray intensity. The result supports the role of major solar eruptive events in generating heliospheric disturbances that inhibit the propagation of galactic cosmic rays toward Earth. The moderate strength of the correlation suggests that X-class flare–associated halo CMEs contributed to cosmic ray modulation during Solar Cycle 24, although their influence was weaker than that observed during the more active Solar Cycle 23.

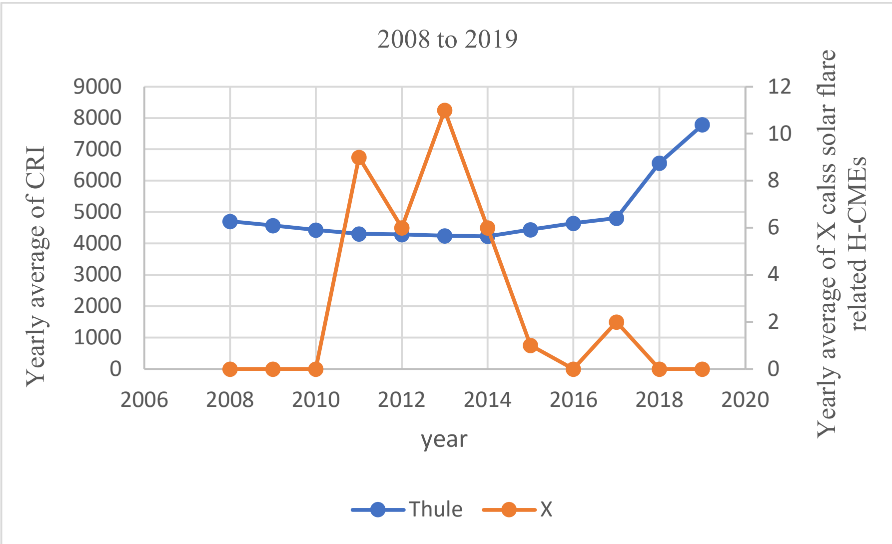

Fig.4.5 Shows the relationship between yearly average value of CRI (Thule) and X-Class solar flare related H-CMEs, for the period of solar cycle 24.

4.9 Cosmic Rays and M-class flare–associated halo CMEs during Solar Cycle 24

A moderate negative correlation (r = −0.45) was observed between cosmic ray intensity variations and M-class flare–associated halo CMEs during Solar Cycle 24. This indicates that increases in M-class flare–associated halo CME activity were generally linked with decreases in cosmic ray intensity. The result supports the idea that solar eruptive events contribute to heliospheric disturbances that modulate galactic cosmic ray flux reaching Earth. However, the moderate correlation also suggests that the effect was relatively weaker in Solar Cycle 24, likely due to its overall reduced solar activity compared to Solar Cycle 23.

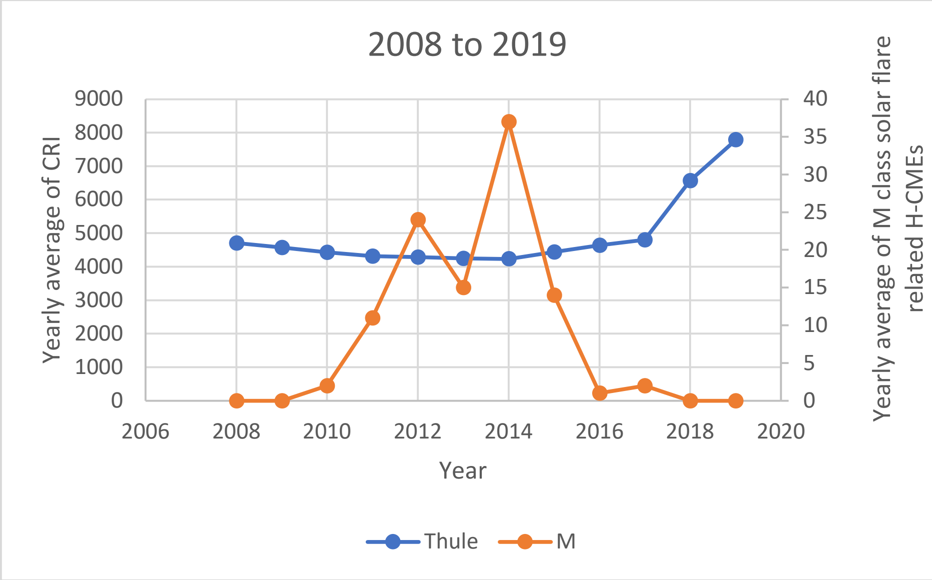

Fig.4.6 Shows the relationship between yearly average value of CRI (thule) and M-Class solar flare related H-CMEs, for the period of solar cycle 24.

5. Discussion

The present study examined the relationship between annual mean galactic cosmic ray (GCR) intensity variations observed by the Thule Neutron Monitor and the occurrence of halo coronal mass ejections (CMEs), including X-class and M-class flare–associated halo CMEs, during Solar Cycles 23 and 24. The results demonstrate a consistently negative correlation between cosmic ray intensity and solar eruptive activity, confirming the fundamental role of transient solar phenomena in the modulation of GCRs within the heliosphere.

The strong inverse correlation observed between cosmic ray intensity and total halo CME occurrence during Solar Cycle 23 (r = −0.71) indicates that periods of enhanced CME activity are associated with a substantial reduction in cosmic ray flux reaching Earth. Halo CMEs are generally associated with large-scale disturbances in the interplanetary medium, including enhanced magnetic fields, shock waves, and turbulent solar wind structures. These disturbances increase the scattering and diffusion of energetic charged particles, thereby reducing the penetration of galactic cosmic rays into the inner heliosphere. The observed relationship is consistent with the classical theory of solar modulation, which predicts a decrease in cosmic ray intensity during periods of elevated solar activity.

A particularly noteworthy result is the very strong negative correlation between cosmic ray intensity and M-class flare–associated halo CMEs during Solar Cycle 23 (r = −0.86). This finding suggests that M-class flare–associated eruptions may represent a major contributor to heliospheric disturbances influencing long-term cosmic ray transport. Although X-class flares are more energetic on an event-by-event basis, their lower occurrence frequency may reduce their overall contribution to annual-scale modulation. In contrast, the greater abundance of M-class flare–associated halo CMEs may produce a cumulative effect that significantly alters heliospheric magnetic conditions and enhances cosmic ray suppression.

The weaker but still significant negative correlations observed during Solar Cycle 24 (r = −0.51 for total halo CMEs, r = −0.44 for X-class flare–associated halo CMEs, and r = −0.45 for M-class flare–associated halo CMEs) reflect the comparatively lower solar activity characterizing this cycle. Solar Cycle 24 was widely recognized as one of the weakest solar cycles of the space-age era, exhibiting reduced sunspot numbers, lower CME kinetic energies, weaker heliospheric magnetic fields, and diminished solar wind pressure. Such conditions likely resulted in less efficient modulation of galactic cosmic rays, thereby reducing the strength of the observed correlations. The weaker relationships suggest that although halo CMEs remained important drivers of cosmic ray variability, their influence was moderated by the overall decline in heliospheric activity.

The contrast between Solar Cycles 23 and 24 highlights the importance of cycle-dependent heliospheric conditions in regulating cosmic ray transport. During the more active Solar Cycle 23, stronger magnetic field intensities and a higher frequency of geoeffective solar eruptions created a more turbulent heliosphere capable of effectively suppressing cosmic ray propagation. Conversely, the weaker magnetic environment of Solar Cycle 24 allowed greater penetration of cosmic rays into the inner heliosphere, leading to reduced modulation efficiency. These findings support previous studies indicating that the global heliospheric magnetic field strength and solar wind properties are critical factors controlling cosmic ray intensity variations.

From a space-weather perspective, the results emphasize the utility of halo CMEs as indicators of large-scale heliospheric disturbances that affect energetic particle transport near Earth. Since cosmic ray variations

influence atmospheric ionization, radiation exposure in aviation and space missions, and the near-Earth radiation environment, understanding the relationship between halo CME activity and cosmic ray modulation is essential for improving predictive models of space-weather effects.
While the present analysis provides valuable insight into long-term relationships between solar eruptive events and cosmic ray intensity, several limitations should be acknowledged. The use of annual mean values may smooth short-term variations such as Forbush decreases and transient recovery phases associated with individual CMEs. Future investigations employing monthly or event-based analyses, together with additional heliospheric parameters such as solar wind speed, interplanetary magnetic field strength, and heliospheric current sheet tilt angle, may provide a more comprehensive understanding of the mechanisms governing cosmic ray modulation. Furthermore, extending the analysis to multiple neutrons monitor stations with different geomagnetic cutoff rigidities would allow assessment of the rigidity dependence of the observed relationships.

6. Conclusion

This study investigated the association between galactic cosmic ray intensity variations measured by the Thule Neutron Monitor and halo CME activity, including X-class and M-class flare–associated halo CMEs, during Solar Cycles 23 and 24. The results revealed consistently negative correlations between cosmic ray intensity and solar eruptive activity, demonstrating that enhanced halo CME occurrence is associated with a reduction in cosmic ray flux near Earth.
The strongest relationship was observed during Solar Cycle 23, where cosmic ray intensity exhibited a strong inverse correlation with total halo CME occurrence ($r = -0.71$) and an exceptionally strong inverse correlation with M-class flare–associated halo CMEs ($r = -0.86$). In comparison, Solar Cycle 24 showed moderate negative correlations for all categories of halo CMEs, reflecting the reduced solar and heliospheric activity that characterized this weaker cycle. These findings indicate that the effectiveness of cosmic ray modulation depends not only on the occurrence of solar eruptive events but also on the overall strength of heliospheric conditions prevailing during a solar cycle.
The study provides further evidence that halo CMEs serve as important manifestations of heliospheric disturbances capable of modulating the transport of galactic cosmic rays. The stronger correlations observed during Solar Cycle 23 suggest that enhanced magnetic turbulence, stronger interplanetary magnetic fields, and more frequent solar eruptions create conditions that more effectively suppress cosmic ray propagation. Conversely, the weaker heliospheric environment of Solar Cycle 24 resulted in reduced modulation efficiency and higher cosmic ray penetration into the inner heliosphere.
Overall, the results contribute to a deeper understanding of the coupling between solar eruptive activity and cosmic ray variability and reinforce the significance of halo CMEs as key drivers of long-term heliospheric modulation processes. Future studies incorporating higher temporal resolution data, multiple neutrons monitor stations, and additional heliospheric parameters will further improve our understanding of cosmic ray transport and enhance the capability to forecast radiation conditions in near-Earth space.

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Conflict of Interest

Here by I declare that there is no conflict of Interest in the preparation of this research paper.

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Authors Contribution

Abstract, Introduction and data extraction done by the Ajay Kuamr Saket and proof reading and formatting have been contributed by Nand Kumar Patel.

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