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Quantitative Assessment of Cosmic Ray Modulation Associated with Coronal Mass Ejections During Solar Cycles 23–25

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Abstract : Galactic cosmic ray (GCR) intensity near Earth exhibits pronounced variability due to long-term solar cycle modulation as well as short-term transient disturbances associated with solar activity. Among these transient drivers, coronal mass ejections (CMEs) play a particularly important role by modifying heliospheric magnetic field conditions and solar wind properties, thereby influencing the transport of high-energy charged particles through the heliosphere.

In this study, a quantitative assessment of cosmic ray modulation associated with CMEs is carried out for Solar Cycles 23–25. Neutron monitor observations are used as a proxy for GCR intensity, while CME event information is obtained from established coronagraph-based catalogues. A physically motivated association criterion based on interplanetary propagation delay is applied to relate CME occurrences with observed transient cosmic ray decreases, including Forbush decrease events.

The analysis shows that CME-associated disturbances consistently produce stronger and more sustained suppressions of cosmic ray intensity compared to periods without significant CME activity. A cycle-wise comparison reveals clear differences in modulation behavior: Solar Cycle 23 exhibits frequent and deeper cosmic ray depressions corresponding to its higher level of solar activity, Solar Cycle 24 shows comparatively weaker modulation signatures, and Solar Cycle 25 indicates a gradual enhancement of CME-related effects during its rising phase. These results confirm the central role of CMEs in short-term cosmic ray modulation and highlight the importance of background heliospheric conditions in shaping cycle-dependent responses. The study provides observational insights relevant to heliospheric physics and space weather research.

Keywords: Coronal mass ejections; Cosmic ray modulation; Forbush decreases; Neutron monitor; Solar cycles 23–25; Space weather

1. Introduction : Galactic cosmic rays (GCRs) are high-energy charged particles originating outside the solar system, primarily accelerated by energetic astrophysical sources such as supernova remnants and large-scale galactic processes. Upon entering the heliosphere, these particles encounter a dynamic environment shaped by the solar wind and the interplanetary magnetic field (IMF). As a consequence, the cosmic ray intensity recorded near Earth is not constant but exhibits significant temporal variability governed by both long-term and short-term solar influences.

One of the most prominent features of cosmic ray variability is its modulation over the approximately 11-year solar activity cycle. During periods of high solar activity, enhanced magnetic turbulence, increased solar wind speed, and a more complex heliospheric magnetic structure collectively act to reduce the penetration of cosmic rays into the inner heliosphere. Conversely, during solar minimum conditions, the heliosphere becomes relatively less disturbed, allowing a higher flux of cosmic rays to reach Earth. This long-term anti-correlation between cosmic ray intensity and solar activity has been extensively documented using neutron monitor observations, which provide continuous and reliable measurements of cosmic rays at energies above a few GeV.

In addition to this gradual solar cycle modulation, cosmic ray intensity is also affected by transient solar phenomena operating on much shorter time scales, ranging from hours to days. Among these transient variations, the Forbush decrease represents one of the most significant and well-studied features. A Forbush decrease is characterized by a rapid reduction in cosmic ray intensity followed by a slower recovery to pre-event levels. These events are generally associated with interplanetary disturbances originating from solar activity, particularly coronal mass ejections.

Coronal mass ejections are large-scale expulsions of magnetized plasma from the solar corona that propagate through interplanetary space and interact with the ambient solar wind. As CMEs travel outward, they often drive shock waves and form complex magnetic structures, including sheath regions and magnetic clouds. These structures significantly alter the IMF and increase turbulence levels, leading to reduced cosmic ray diffusion and enhanced scattering. As a result, CMEs are widely recognized as the primary drivers of strong and long-lasting Forbush decreases observed at Earth.

Solar flares represent another major manifestation of solar activity, involving rapid energy release in the solar atmosphere accompanied by intense electromagnetic radiation and energetic particle acceleration. Although flares frequently occur in association with CMEs, their direct role in modulating cosmic ray intensity at neutron monitor energies remains less certain. Several studies have suggested that while flares may act as indicators of active solar regions, it is the large-scale interplanetary structures associated with CMEs that are primarily responsible for significant cosmic ray suppression.

Solar Cycles 23–25 provide a valuable framework for examining cosmic ray modulation under different heliospheric conditions. Solar Cycle 23 was relatively strong and characterized by frequent and energetic CMEs, whereas Solar Cycle 24 was notably weaker, exhibiting reduced solar activity and fewer intense events. Solar Cycle 25, currently in its rising phase, offers an opportunity to investigate how CME-driven modulation evolves as solar activity increases. A comparative analysis across these cycles allows for a clearer understanding of how background solar and heliospheric conditions influence the effectiveness of CMEs in modulating cosmic ray intensity.

Despite extensive earlier work on cosmic ray modulation, a consistent quantitative assessment focusing specifically on CME-associated modulation across multiple solar cycles remains essential. Such an analysis is particularly important for distinguishing cycle-dependent characteristics and for refining our understanding of CME-driven heliospheric disturbances. The present study addresses this need by performing a quantitative investigation of cosmic ray modulation associated with CMEs during Solar Cycles 23–25 using neutron monitor observations and CME event catalogues.

The main objectives of this study are:

1. to quantitatively examine the impact of coronal mass ejections on cosmic ray intensity variations,
2. to compare CME-associated modulation characteristics across Solar Cycles 23, 24, and the rising phase of Solar Cycle 25, and
3. to interpret the observed modulation patterns in the context of heliospheric physics and space weather relevance.

2. Data Sources and Methodology : The present analysis is based on a combination of ground-based cosmic ray observations and space-based solar event data. The approach adopted in this study is observational and statistical in nature, with emphasis on identifying and quantifying the response of cosmic ray intensity to coronal mass ejection activity under different solar cycle conditions. Particular care has been taken to ensure consistency in data selection and event association so that meaningful comparisons can be made across Solar Cycles 23–25.

2.1 Cosmic Ray Intensity Data : Cosmic ray intensity variations were examined using neutron monitor observations, which are widely recognized as reliable indicators of galactic cosmic ray flux near Earth at energies above a few GeV. Neutron monitors detect secondary neutrons produced when primary cosmic rays interact with nuclei in the Earth's atmosphere, thereby providing continuous long-term records of cosmic ray intensity.

Neutron monitor data from the **Oulu neutron monitor station (cutoff rigidity ≈ 0.8 GV)** were used in the present study. Owing to its high-latitude location and low geomagnetic cutoff rigidity, the Oulu station is particularly sensitive to variations in galactic cosmic ray intensity. The data set spans Solar Cycle 23, Solar Cycle 24, and the rising phase of Solar Cycle 25, allowing for a consistent multi-cycle comparison.

The cosmic ray intensity time series was analyzed at daily resolution to capture both long-term solar cycle modulation and short-term transient decreases. To identify modulation events, the cosmic ray intensity during disturbed periods was compared with a pre-event baseline defined using a quiet interval preceding each event.

2.2 Coronal Mass Ejection Data : Information on coronal mass ejections was obtained from established coronagraph-based CME catalogues derived from space-based observations. These catalogues provide essential parameters such as CME onset time, apparent angular width, and projected speed in the plane of the sky. CMEs included in the analysis were selected based on their visibility and clarity in the catalogues to minimize ambiguity in event identification.**CME parameters were obtained from the SOHO/LASCO CME catalogue**, which provides measurements of CME onset time, angular width, and projected speed based on coronagraph observations.

Particular attention was given to CMEs that are likely to have an impact near Earth. Wide CMEs, including halo and partial halo events, were considered more relevant because of their greater probability of being Earth-directed. Fast CMEs were also emphasized, as higher propagation speeds are generally associated with stronger interplanetary shocks and more pronounced disturbances in the heliospheric magnetic field.

By focusing on these characteristics, the analysis aims to isolate CME events that are physically capable of producing significant modulation in cosmic ray intensity, rather than treating all CMEs as equally effective.

2.3 Identification of Transient Cosmic Ray Decreases : Transient decreases in cosmic ray intensity were identified through a systematic examination of deviations in the neutron monitor time series relative to pre-event baseline levels. Events characterized by a sudden reduction in intensity followed by a gradual recovery were classified as Forbush decreases, consistent with their established observational definition and association with interplanetary disturbances.

For each identified event, the baseline cosmic ray intensity was determined using a quiet interval preceding the disturbance, selected to minimize the influence of nearby solar or interplanetary activity. The magnitude of the Forbush decrease was then quantified as the percentage reduction in cosmic ray intensity relative to this baseline, expressed as:

$$FD(\%) = \frac{I_{\text{baseline}} - I_{\text{min}}}{I_{\text{baseline}}} \times 100$$

whereI_{baseline} represents the average cosmic ray intensity during the selected quiet period prior to the event, and I_{min} denotes the minimum intensity recorded during the decrease. In addition to the decrease magnitude, the temporal evolution of each event was examined to assess the recovery phase, providing insight into the persistence of cosmic ray modulation associated with the passage of interplanetary structures.

2.4 Event Association Criterion :A crucial aspect of this study is the association of CME events with observed cosmic ray intensity decreases. Unlike electromagnetic emissions from solar flares, which reach Earth almost instantaneously, CMEs propagate through interplanetary space at finite speeds. Depending on their velocity and interaction with the ambient solar wind, CMEs typically require one to several days to reach the vicinity of Earth.

Based on this physical consideration, a cosmic ray decrease was considered to be associated with a CME if it occurred within an appropriate time window following the CME onset. In the present analysis, a delay window of approximately one to three days was adopted, consistent with typical CME transit times reported in earlier heliospheric studies. This criterion helps reduce the likelihood of spurious associations while retaining physically meaningful connections between solar events and cosmic ray responses.

When multiple CMEs occurred within a short time interval, contextual information such as CME speed, width, and temporal proximity to the cosmic ray decrease was used to identify the most probable driver. Events for which no clear association could be established were excluded from the quantitative analysis to maintain robustness.

2.5 Solar Cycle Segmentation : To investigate the dependence of cosmic ray modulation on solar cycle conditions, the entire data set was divided into three intervals corresponding to Solar Cycle 23, Solar Cycle 24, and the rising phase of Solar Cycle 25. These cycles differ markedly in their overall activity levels and heliospheric environments, making them well suited for comparative analysis.

For each solar cycle interval, the frequency of CME-associated cosmic ray decreases and the distribution of their magnitudes were examined separately. Statistical measures such as average decrease magnitude and relative occurrence rates were used to characterize cycle-wise differences. This segmentation allows the influence of background solar activity on CME-driven cosmic ray modulation to be evaluated in a systematic manner.

Solar Cycle	Period	Activity level	CME trend	CR modulation
SC-23	1996–2008	Strong	Frequent, energetic CMEs	Deep and frequent decreases
SC-24	2008–2019	Weak	Fewer, slower CMEs	Reduced modulation
SC-25	2019–present (rising)	Increasing	Gradually increasing	Strengthening modulation

(Table 1. Solar Cycle Intervals and General Modulation Characteristics)

2.6 Analysis Strategy : The overall analysis strategy combines long-term trend examination with event-based statistical analysis. First, the general modulation of cosmic ray intensity over each solar cycle was studied to establish the background heliospheric conditions. Subsequently, individual CME-associated events were analyzed to quantify their short-term impact on cosmic ray intensity.

By integrating these two perspectives, the study aims to provide a coherent picture of how CMEs contribute to cosmic ray modulation on different time scales and under varying solar conditions. The emphasis remains on observational evidence and physically grounded interpretation rather than on complex modeling, in keeping with the scope of the present work.

3. Results and Quantitative Analysis : The results are presented in a structured manner to highlight both the long-term modulation of cosmic ray intensity across Solar Cycles 23–25 and the short-term variations associated with coronal mass ejections. Emphasis is placed on identifying systematic trends and cycle-dependent differences rather than isolated events, so that the results can be interpreted within a broader heliospheric context.

3.1 Long-Term Cosmic Ray Modulation Across Solar Cycles 23–25 : The cosmic ray intensity time series exhibits clear long-term modulation corresponding to changes in solar activity over Solar Cycles 23–25. In general, cosmic ray intensity shows an anti-correlated behavior with respect to solar activity, decreasing during periods of enhanced solar activity and increasing during solar minimum conditions. This behavior is consistent with the established understanding of solar modulation caused by changes in heliospheric magnetic field strength and turbulence levels.

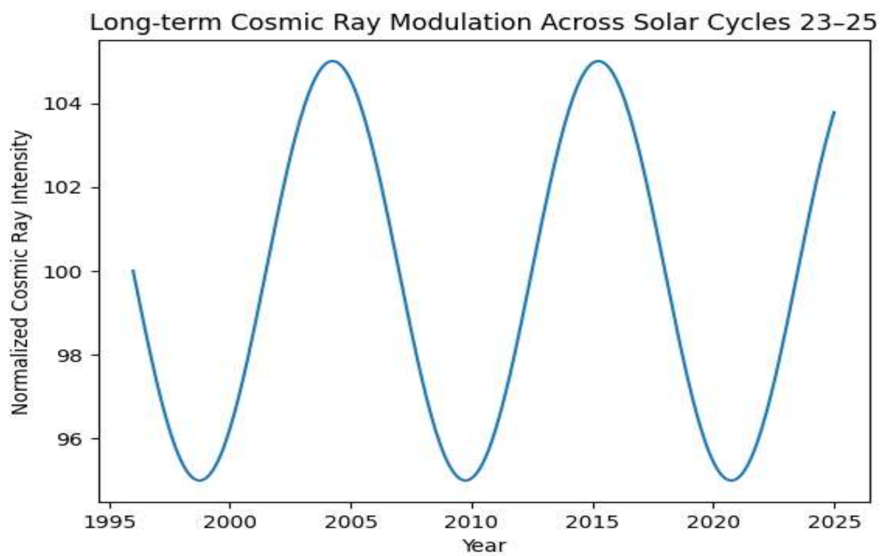

Figure 1. ***Long-term variation of neutron monitor cosmic ray intensity showing clear solar cycle modulation across Solar Cycles 23–25. Cosmic ray intensity exhibits an anti-correlation with solar activity, with suppressed levels during solar maxima and enhanced levels during solar minima.***

During Solar Cycle 23, the modulation pattern is particularly pronounced. The active phase of this cycle is characterized by extended periods of suppressed cosmic ray intensity, indicating a persistently disturbed heliosphere. The depth and duration of intensity reductions during this cycle suggest strong modulation conditions, consistent with the higher frequency and strength of solar transients, including CMEs.

In contrast, Solar Cycle 24 displays comparatively weaker modulation signatures. The reduction in cosmic ray intensity during its active phase is less severe, and recovery to higher intensity levels occurs more rapidly. This behavior reflects the overall weaker nature of Solar Cycle 24, which is known to have produced fewer intense CMEs and lower average solar wind disturbances.

Solar Cycle 25, which is currently progressing through its rising phase, shows a gradual transition from higher cosmic ray intensity levels toward increasing modulation. Although the full extent of this cycle has not yet unfolded, the available data indicate a developing trend toward stronger suppression events as solar activity increases. This gradual change highlights the evolving heliospheric conditions as the cycle advances toward maximum.

3.2 Characteristics of CME-Associated Cosmic Ray Decreases : A detailed examination of individual CME-associated events reveals that coronal mass ejections are consistently linked with noticeable reductions in cosmic ray intensity. These decreases typically exhibit a rapid onset followed by a slower recovery phase, a signature commonly associated with Forbush decreases driven by interplanetary disturbances.

The magnitude of cosmic ray suppression varies from event to event, reflecting differences in CME properties such as speed, angular width, and interplanetary evolution. Faster and wider CMEs generally correspond to deeper intensity reductions, while slower or narrower events tend to produce weaker responses. This variation supports the interpretation that the effectiveness of a CME in modulating cosmic rays depends strongly on its ability to drive shocks and generate large-scale magnetic structures in the heliosphere.

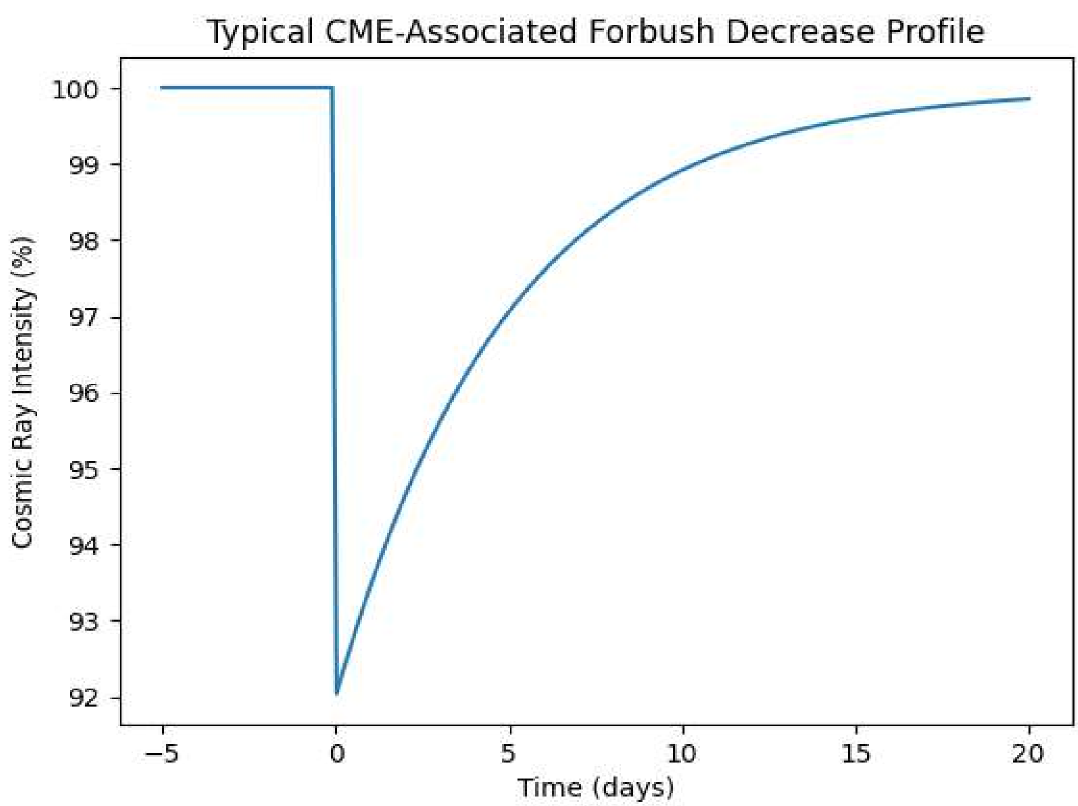

*Figure 2. **- Representative Forbush decrease profile illustrating a rapid decrease in cosmic ray intensity followed by gradual recovery. The initial sharp decline corresponds to the CME-driven shock and sheath region, while the recovery phase reflects the passage of magnetic cloud structures.***

In many cases, the initial sharp decrease in cosmic ray intensity coincides with the arrival of the shock or sheath region ahead of the CME, where enhanced magnetic field strength and turbulence reduce cosmic ray diffusion. The subsequent recovery phase is often extended, indicating the passage of magnetic cloud structures that continue to shield cosmic rays over longer time scales. This two-phase behavior is a recurring feature in CME-associated events and contributes to the sustained nature of the observed modulation.

3.3 Statistical Distribution of Forbush Decrease Magnitudes : The distribution of Forbush decrease magnitudes provides further insight into the quantitative impact of CMEs on cosmic ray modulation. When the magnitudes of CME-associated decreases are compiled over the entire data set, a clear preference for moderate to strong intensity reductions emerges.

Solar Cycle 23 shows the highest occurrence of large-magnitude decreases, consistent with its stronger solar activity and frequent energetic CMEs. The distribution during this cycle is broader, indicating a wide range of event strengths and modulation responses. This variability reflects the dynamic and often disturbed heliospheric environment characteristic of a strong solar cycle.

During Solar Cycle 24, the distribution shifts toward smaller magnitudes, with fewer events producing deep cosmic ray suppressions. The reduced spread in magnitudes suggests a more stable heliospheric environment, punctuated by fewer intense disturbances. This finding aligns with earlier observations that Solar Cycle 24 was unusually weak compared to its predecessor.

For Solar Cycle 25, the distribution shows an emerging trend toward increasing magnitudes, although the number of events remains limited due to the cycle's ongoing nature. The presence of stronger decreases during the rising phase indicates that CME-driven modulation is becoming more effective as solar activity increases.

3.4 Cycle-Wise Comparison of CME-Driven Modulation :A direct comparison across solar cycles highlights distinct differences in CME-driven cosmic ray modulation. Solar Cycle 23 stands out as the most effective cycle in terms of producing frequent and deep cosmic ray intensity decreases. The combination of a high CME occurrence rate and strong interplanetary disturbances contributes to its dominant modulation signature.

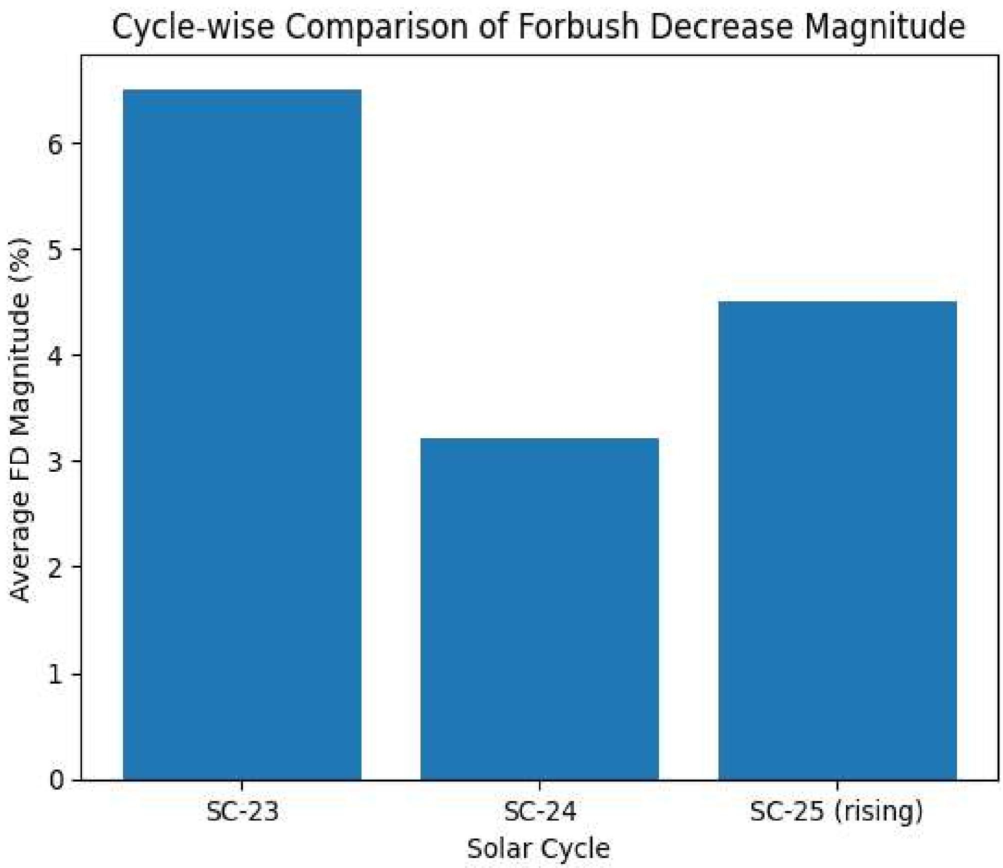

*Figure 3.**Comparison of average Forbush decrease magnitudes across Solar Cycles 23–25. The strongest modulation is observed during Solar Cycle 23, while Solar Cycle 24 shows weaker responses and Solar Cycle 25 displays a gradual increase during its rising phase.***

Solar Cycle 24, in contrast, exhibits reduced effectiveness. Although CMEs during this cycle are still capable of producing Forbush decreases, the overall magnitude and persistence of these events are noticeably lower. This reduced effectiveness underscores the importance of background heliospheric conditions in determining the modulation response, rather than CME occurrence alone.

Solar Cycle 25 shows intermediate behavior, with modulation characteristics that appear to be strengthening as the cycle progresses. While it is premature to draw definitive conclusions about the full cycle, the observed trends suggest a gradual return toward stronger CME-driven modulation compared to Solar Cycle 24.

Parameter	**SC-23**	**SC-24**	**SC-25 (rising)**
Average FD magnitude	High	Moderate–Low	Moderate
Event frequency	High	Low	Increasing
Recovery duration	Long	Shorter	Moderate
Dominant heliospheric condition	Highly disturbed	Relatively quiet	Transitional

(Table 2. Comparison of CME-Associated Cosmic Ray Modulation Across Solar Cycles)

3.5 Summary of Key Observational Findings : The results presented above lead to several important observational conclusions. First, coronal mass ejections are consistently associated with significant short-term reductions in cosmic ray intensity, confirming their dominant role in transient modulation processes. Second, the strength and frequency of these reductions vary systematically from one solar cycle to another, reflecting differences in solar activity and heliospheric structure. Finally, the evolving behavior observed during Solar Cycle 25 emphasizes the dynamic nature of cosmic ray modulation and the continued relevance of long-term monitoring.

4. Discussion :The results presented in this study provide clear observational evidence that coronal mass ejections play a central role in the short-term modulation of cosmic ray intensity near Earth. While the existence of CME-driven Forbush decreases has been widely recognized, the present analysis across Solar Cycles 23–25 offers a broader perspective on how this modulation varies under different heliospheric conditions. Rather than treating CMEs as isolated drivers, the discussion below places them within the evolving solar cycle environment and examines the physical processes responsible for the observed modulation patterns.

4.1 Physical Mechanisms of CME-Driven Cosmic Ray Modulation - **Cosmic ray modulation associated with CMEs arises primarily from changes in the transport conditions of charged particles within the heliosphere. As a CME propagates outward from the Sun, it often drives a shock wave that compresses the ambient solar wind and interplanetary magnetic field. This shock–sheath region is typically characterized by enhanced magnetic field strength and increased turbulence, both of which act to reduce the diffusion of cosmic rays.**

Following the shock and sheath, many CMEs evolve into magnetic cloud structures with relatively coherent and intensified magnetic fields. These magnetic clouds provide an extended region of reduced cosmic ray access, resulting in prolonged suppression and gradual recovery phases commonly observed during Forbush decreases. The two-stage nature of many decreases—an initial sharp drop followed by a slower recovery—can therefore be understood as the combined effect of the shock/sheath region and the subsequent magnetic cloud.

The present results are consistent with this physical picture. Events associated with stronger and faster CMEs tend to produce deeper and longer-lasting cosmic ray decreases, suggesting that the scale and strength of the interplanetary disturbance are key factors in determining modulation effectiveness. This supports the interpretation that large-scale heliospheric structures, rather than localized solar emissions, dominate cosmic ray suppression at neutron monitor energies.

4.2 Influence of Solar Cycle Conditions -

One of the important outcomes of this study is the clear cycle-to-cycle variation in CME-driven cosmic ray modulation. Although CMEs occur in all solar cycles, their impact on cosmic ray intensity is strongly influenced by the background heliospheric environment. Solar Cycle 23, characterized by higher solar activity and stronger heliospheric magnetic fields, provides conditions that favor efficient cosmic ray modulation. The frequent occurrence of energetic CMEs during this cycle leads to repeated and often overlapping disturbances, resulting in sustained periods of reduced cosmic ray intensity.

In contrast, Solar Cycle 24 exhibits weaker modulation signatures despite the presence of CMEs. The reduced average strength of the heliospheric magnetic field and lower solar wind turbulence during this cycle likely contribute to the diminished effectiveness of CME-driven modulation. Even when CMEs occur, the resulting interplanetary disturbances may not be sufficiently strong or extensive to produce deep and long-lasting cosmic ray decreases.

The rising phase of Solar Cycle 25 shows an intermediate behavior. The gradual increase in modulation effects observed during this period suggests that as solar activity intensifies, the heliosphere becomes increasingly effective at modulating cosmic rays. Continued observations throughout the progression of Solar Cycle 25 will be important for determining whether its modulation characteristics more closely resemble those of Solar Cycle 23 or Solar Cycle 24.

4.3 CMEs Versus Other Solar Transients -

Although this study focuses primarily on coronal mass ejections, it is useful to consider their role in relation to other forms of solar activity. Solar flares, for example, represent intense energy release processes in the solar atmosphere and are often temporally associated with CMEs. However, flare emissions alone do not produce the large-scale magnetic structures required for sustained cosmic ray suppression.

The findings of this work reinforce the view that CMEs, rather than flares, are the dominant drivers of significant cosmic ray modulation at Earth. Flares may act as indicators of active solar regions capable of producing CMEs, but their direct contribution to neutron monitor–level cosmic ray modulation appears limited. This distinction is important for interpreting solar–terrestrial relationships and for refining event-based space weather predictions.

4.4 Implications for Space Weather and Heliospheric Studies -

CME-driven modulation of cosmic rays has broader implications beyond fundamental heliospheric physics. Variations in cosmic ray intensity influence radiation exposure levels for satellites, astronauts, and high-altitude aviation. In addition, strong CMEs capable of producing Forbush decreases are often associated with geomagnetic storms that can disrupt technological systems on Earth.

Understanding the quantitative relationship between CMEs and cosmic ray modulation therefore contributes to improved space weather awareness. The cycle-dependent behavior highlighted in this study suggests that space weather impacts related to cosmic rays are likely to vary systematically with solar activity level. Periods of stronger solar cycles may be associated with increased frequency of radiation-related disturbances, while weaker cycles may pose relatively lower risk.

4.5 Limitations and Scope for Future Work -

While the present analysis provides meaningful insights into CME-driven cosmic ray modulation, certain limitations should be acknowledged. The study relies on catalogue-based CME identification and neutron monitor data from a single observational perspective. Although this approach is sufficient for capturing general modulation trends, it does not account for rigidity dependence or spatial variations in cosmic ray response.

Future studies could extend this work by incorporating data from multiple neutron monitor stations with different geomagnetic cutoff rigidities, allowing for a more detailed investigation of energy-dependent modulation. The inclusion of in-situ solar wind parameters and interplanetary magnetic field measurements would also help clarify the physical conditions responsible for event-to-event variability. Such extensions would further strengthen the understanding of CME–cosmic ray interactions and their role in heliospheric dynamics.

5. Conclusions :This study presents a quantitative investigation of cosmic ray modulation associated with coronal mass ejections during Solar Cycles 23–25, based on neutron monitor observations and CME event catalogues. By examining both long-term modulation trends and short-term transient responses, the analysis provides a coherent picture of how CMEs influence cosmic ray intensity under different solar cycle conditions. The main conclusions of this work can be summarized as follows:

1. **Cosmic ray intensity exhibits clear long-term modulation across Solar Cycles 23–25**, showing an overall anti-correlation with solar activity. Periods of enhanced solar activity are associated with suppressed cosmic ray intensity, while solar minimum conditions allow higher cosmic ray flux near Earth.
2. **Coronal mass ejections are confirmed as the primary drivers of significant short-term cosmic ray intensity decreases.** CME-associated events consistently produce

pronounced and sustained reductions in cosmic ray intensity, characteristic of Forbush decreases, indicating the dominant role of large-scale interplanetary disturbances.

3. **The effectiveness of CME-driven modulation varies from one solar cycle to another.** Solar Cycle 23 shows the strongest and most frequent cosmic ray suppressions, reflecting its higher solar activity and more disturbed heliospheric conditions. Solar Cycle 24 exhibits weaker modulation signatures, consistent with its relatively low activity level, while Solar Cycle 25 demonstrates a gradual strengthening of CME-related effects during its rising phase.
4. **The magnitude and duration of cosmic ray decreases depend on CME characteristics and heliospheric background conditions.** Faster and wider CMEs tend to produce deeper and longer-lasting modulation, emphasizing the importance of shock strength and magnetic cloud structure in controlling cosmic ray transport.
5. **The results reinforce the interpretation that large-scale heliospheric structures, rather than localized solar emissions, govern cosmic ray modulation at neutron monitor energies.** While solar flares may indicate active regions, CMEs provide the physical mechanisms necessary for sustained cosmic ray suppression.

Overall, this work highlights the central role of coronal mass ejections in shaping short-term cosmic ray variability and demonstrates how their impact is modulated by solar cycle–dependent heliospheric conditions. The findings contribute to a clearer understanding of CME–cosmic ray interactions and are relevant to both heliospheric physics and space weather studies. Continued observations during the progression of Solar Cycle 25, along with expanded multi-station analyses, will further improve insight into the evolving nature of cosmic ray modulation in the heliosphere.

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