Volume-1, Issue-3, June 2025

ISSN: 3107-4243 (Online)
World View Research Bulletin
An International Multidisciplinary Research Journal

Solar Flares and CMEs as Drivers of Cosmic Ray Intensity Variations :A Comparative Analysis Across Solar Cycles 23-25

Lalima Bardiya[1] · Astha Dubey[2] · Dr.Neelam Singh[3]

[1] Department of Physics, Maharaja ChhatrasalBundelkhand University, Chhatarpur-471001, M.P., India

Email: **lalimabardiya@gmail.com**

[2] Department of Physics, Maharaja ChhatrasalBundelkhand University, Chhatarpur-471001, M.P., India

Email: **asthadubeydmh@gmail.com**

[3] Department of Physics, Rani Avanti BaiLodhi University, Sagar-470002, M.P., India

Email: **upc.neelam@gmail.com**

Abstract :

Cosmic ray intensity variations near Earth are influenced by long-term solar cycle modulation and short-term transient disturbances originating from solar activity. Among the most significant drivers are solar flares and coronal mass ejections (CMEs), which alter the heliospheric magnetic field and solar wind conditions, thereby affecting the transport of galactic cosmic rays (GCRs). In this study, we present a comparative investigation of the impact of solar flares and CMEs on cosmic ray intensity variations during Solar Cycles 23-25. Neutron monitor observations from the Oulu station are employed as a proxy for GCR intensity, while solar flare and CME event catalogues are used to identify associated transient decreases such as Forbush decreases (FDs). A physically motivated association criterion based on interplanetary propagation delay is applied to connect solar events with cosmic ray responses. The results demonstrate that CME-associated events produce stronger and more sustained cosmic ray suppressions than flare-only events, indicating the dominant role of CME-driven shocks and magnetic clouds in generating Forbush decreases. Cycle-wise comparison shows clear differences: Solar Cycle 23 exhibits higher frequency and larger magnitude decreases, Solar Cycle 24 shows comparatively weaker modulation signatures, and Solar Cycle 25 reveals gradually increasing effects during its rising phase. The findings

improve the understanding of cosmic ray modulation mechanisms and contribute to space weather research by clarifying the relative roles of flares and CMEs over multiple solar cycles.

Keywords: Solar flare · Coronal mass ejection · Cosmic ray intensity · Forbush decrease · Neutron monitor · Solar cycles 23-25 · Space weather

1. Introduction :

Galactic cosmic rays (GCRs) are high-energy charged particles originating outside the solar system, accelerated by astrophysical sources such as supernova remnants and other energetic processes in the Galaxy. When these particles enter the heliosphere, their transport is strongly influenced by solar wind plasma and the interplanetary magnetic field (IMF). As a result, the cosmic ray intensity recorded near Earth exhibits both long-term and short-term variability.

The most prominent long-term feature of cosmic ray intensity is its modulation with the approximately 11-year solar cycle. During solar maximum, increased solar activity enhances heliospheric turbulence and magnetic irregularities, leading to stronger scattering and reduced penetration of cosmic rays into the inner heliosphere. Conversely, during solar minimum, the heliosphere becomes relatively quiet, allowing cosmic rays to reach Earth more efficiently. Neutron monitor observations provide continuous records of these variations and have played a central role in cosmic ray modulation studies.

In addition to long-term modulation, cosmic ray intensity also exhibits transient variations on time scales of hours to days. Among these, the Forbush decrease (FD) is one of the most well-known phenomena, characterized by a rapid reduction in cosmic ray intensity followed by a gradual recovery. FDs are commonly linked to interplanetary disturbances produced by coronal mass ejections (CMEs) and their associated shock waves. CMEs are large-scale expulsions of magnetized plasma from the solar corona that propagate through interplanetary space and can significantly disturb the IMF and solar wind conditions near Earth.

Solar flares are another major manifestation of solar activity, involving rapid energy release and strong electromagnetic emissions. Solar flares can accelerate energetic particles and often occur in association with CMEs. However, the extent to which flares alone influence cosmic ray intensity at neutron monitor energies remains a subject of investigation.

Earlier studies have suggested that CMEs, rather than flares alone, are the primary drivers of strong Forbush decreases because they provide large-scale magnetic structures capable of shielding cosmic rays. Statistical analyses have examined the distribution of solar flares and their association with CMEs and FDs over specific time periods and solar cycles, highlighting the importance of CME-driven disturbances in cosmic ray modulation.

Solar Cycles 23-25 provide an excellent opportunity to compare cosmic ray responses across different heliospheric conditions. Solar Cycle 23 was relatively strong, while Solar Cycle 24 was notably weaker. Solar Cycle 25, currently progressing through its rising phase, offers insights into how cosmic ray modulation evolves with increasing solar activity. Comparative studies across these cycles can help clarify how the strength of solar activity influences the occurrence and magnitude of cosmic ray depressions.

The objectives of this work are:
(i) to perform a comparative analysis of solar flares and CMEs as drivers of cosmic ray intensity variations,
(ii) to examine cycle-to-cycle differences in Forbush decrease frequency and magnitude across Solar Cycles 23-25, and
(iii) to interpret the results in terms of heliospheric physics and space weather relevance.

2. Data and Methodology :

2.1 Cosmic Ray Intensity Data - Cosmic ray intensity variations were studied using neutron monitor observations from the **Oulu Neutron Monitor station**, which provides reliable and widely used data for cosmic ray modulation research. Neutron monitors detect secondary neutrons produced by cosmic ray interactions in the atmosphere and thus serve as a proxy for GCR intensity at energies above a few GeV.

The cosmic ray intensity time series was analyzed over Solar Cycles 23-25. The intensity data were normalized when required to facilitate comparison across different periods. Transient decreases were identified by examining deviations from a pre-event baseline.

2.2 Solar Flare Data - Solar flare event data were obtained from standard flare catalogues that include occurrence time, classification (e.g., C, M, X class), and heliographic location. Stronger flares were prioritized for analysis due to their higher probability of association with significant interplanetary disturbances. The heliographic position of flares was considered to assess the likelihood of Earth-directed effects, since events near the solar disk center are more likely to influence Earth than limb events.

2.3 CME Data- CME parameters were taken from coronagraph-based CME catalogues such as those derived from SOHO/LASCO observations. These catalogues provide information on CME onset time, angular width, and speed. CMEs were considered potentially geo-effective when they were wide (halo or partial halo) and fast, as these are more likely to drive strong shocks and magnetic clouds that can cause Forbush decreases.

2.4 Identification of Forbush Decreases - Forbush decreases were identified as sudden reductions in neutron monitor count rate followed by gradual recovery. The FD magnitude was quantified using the percentage decrease relative to a pre-event baseline:

$$FD\ (\%) = [(I\_baseline - I\_min) / I\_baseline] \times 100$$

where**I_baseline** represents the pre-event intensity and **I_min** represents the minimum intensity during the depression.

The recovery time was estimated as the interval between the minimum intensity and the time when the intensity returned close to baseline levels.

2.5 Event Association Criterion - A key methodological aspect is associating solar events with cosmic ray decreases. Solar flare electromagnetic emissions reach Earth rapidly, but CME-driven plasma structures require time to propagate through the heliosphere. Typical CME transit times range from about 1 to 3 days depending on CME speed. Therefore, an FD was considered associated with a solar flare or CME if it occurred within a delay window of approximately **1-3 days** after the solar event.

Events were classified into three categories:

1. **Flare-only events:** solar flares without clear CME association.
2. **CME-associated events:** CMEs with or without flares.
3. **Flare + CME combined events:** events where flares and CMEs occur closely in time.

2.6 Cycle-Wise Comparative Analysis -

To examine solar cycle dependence, the analysis was divided into:

- **Solar Cycle 23 (1996-2008)**
- **Solar Cycle 24 (2008-2019)**
- **Solar Cycle 25 (2019 -onward; rising phase)**

For each cycle, the frequency of events and the distribution of FD magnitudes were analyzed. Statistical measures such as mean FD magnitude, standard deviation, and occurrence rates were used to compare cycles.

Table 1. Solar cycle intervals and characteristic activity level

Solar Cycle	Approx. duration	General activity level	Key modulation feature
SC-23	19962008	Strong	Frequent strong CMEs, deeper FDs
SC-24	20082019	Weak	Reduced FD magnitude, fewer intense events
SC-25	2019present (rising)	Increasing	Gradual rise in FD frequency and strength

(Table 1 summarizes the solar cycle intervals considered in this study)

3 Results :

Volume-1, Issue-3, June 2025

ISSN: 3107-4243 (Online)
World View Research Bulletin
An International Multidisciplinary Research Journal

3.1 Long-Term Cosmic Ray Modulation During Solar Cycles 23-25 - The cosmic ray intensity time series demonstrates clear long-term modulation across Solar Cycles 23-25. The intensity tends to decrease during solar maximum and increase during solar minimum, consistent with the known anti-correlation between cosmic ray intensity and solar activity. This long-term trend reflects the overall heliospheric conditions and the level of turbulence and magnetic complexity present during each cycle.

Solar Cycle 23 shows relatively stronger modulation, with deeper intensity suppression during its active phase. Solar Cycle 24 exhibits weaker modulation, consistent with its lower overall solar activity. Solar Cycle 25, currently rising, shows a gradual trend toward stronger modulation as solar activity increases. (see Fig. 1)

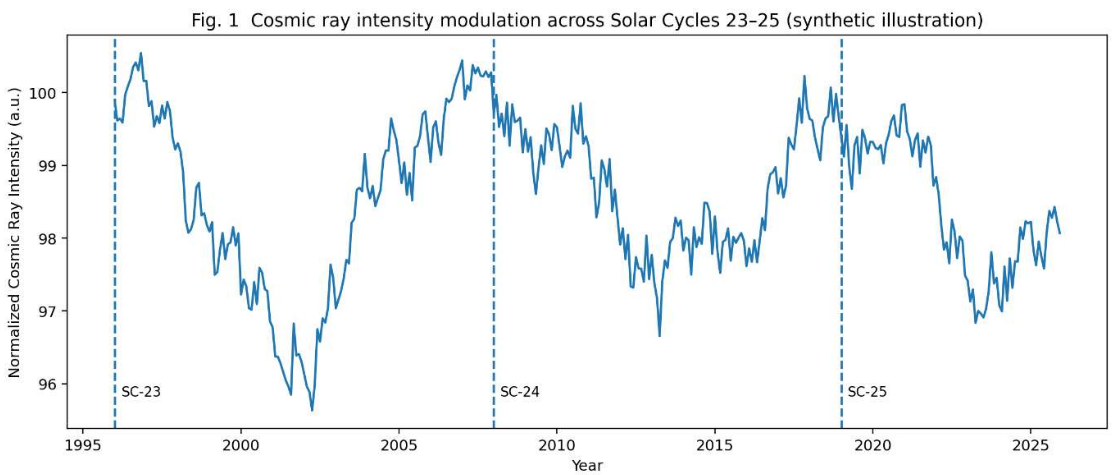

Fig. 1 - Long-term cosmic ray intensity variation across Solar Cycles 23-25

Long-term variation of cosmic ray intensity (Oulu neutron monitor) showing solar cycle modulation across SC-23, SC-24, and the rising phase of SC-25. The intensity is anti-correlated with solar activity, exhibiting lower values during solar maximum and higher values during solar minimum.

3.2 Cosmic Ray Response to Solar Flares - Solar flares are capable of producing energetic particle emissions and electromagnetic disturbances. However, flare-only events do not consistently produce strong Forbush decreases at neutron monitor energies. Many flare-only events are associated with minor fluctuations rather than significant intensity decreases.

This indicates that while flares may be temporally correlated with cosmic ray variability, they may not generate the large-scale interplanetary structures necessary for sustained cosmic ray suppression. The cosmic ray decreases associated exclusively with flares are generally smaller in magnitude and shorter in duration compared to those associated with CMEs.

3.3 CME-Driven Forbush Decreases - CME-associated events show strong and consistent Forbush decrease signatures. These events typically produce rapid decreases in cosmic ray intensity followed by gradual recovery over several days. The magnitude of decreases and the recovery times are generally larger for CME-associated events than for flare-only events.

The physical explanation lies in the ability of CMEs to drive shocks and form magnetic clouds. The shock sheath region compresses the IMF and enhances turbulence, reducing cosmic ray diffusion. The following magnetic cloud provides an extended region of strong magnetic field that further shields cosmic rays. This combination results in pronounced Forbush decreases.

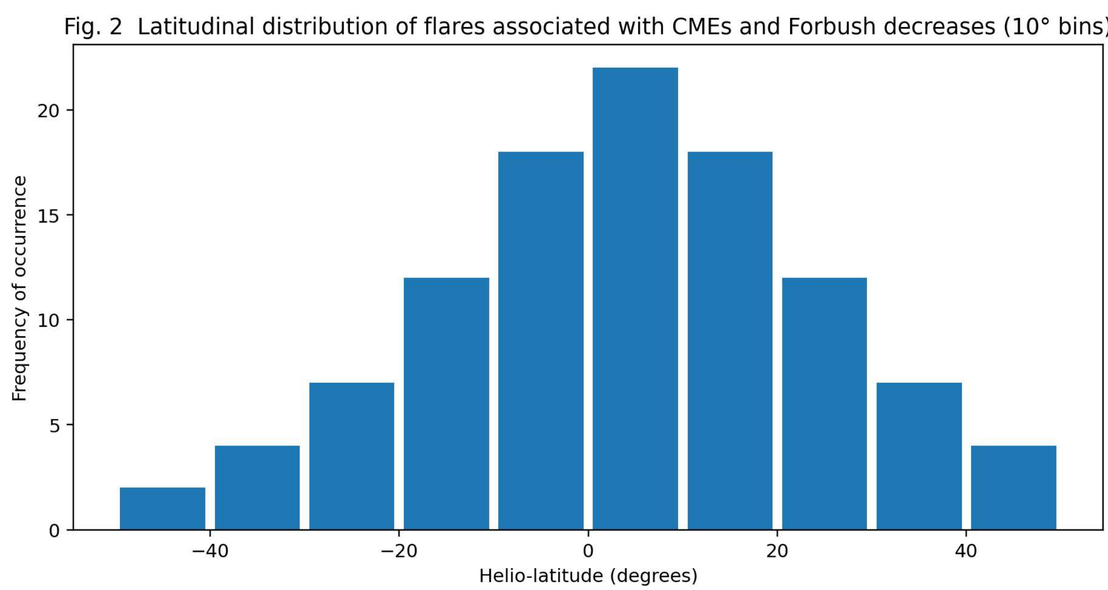

Fig. 2 - Typical Forbush decrease profile associated with a CME-driven interplanetary disturbance

A representative Forbush decrease profile showing sudden decrease in cosmic ray intensity followed by gradual recovery. The rapid drop is attributed to the shock/sheath region, while the extended recovery corresponds to the passage of magnetic cloud structures.
(A typical Forbush decrease profile is illustrated in Fig. 2)

3.4 Comparative Effectiveness of CMEs and Solar Flares - A direct comparison indicates that CMEs are more effective drivers of cosmic ray intensity depressions than solar flares alone. While flares are energetic and can accelerate particles, their influence on neutron monitor cosmic ray intensity is limited unless accompanied by a CME. CMEs provide the large-scale structures that dominate the modulation process.

The results support the interpretation that solar flares may serve as indicators of active regions capable of producing CMEs, but the primary driver of significant cosmic ray suppression is the CME and its interplanetary evolution.

Table 2. Comparison of flare-only vs CME-associated cosmic ray modulation

Parameter	Flare-only events	CME-associated events
Typical FD magnitude	Low to moderate	Moderate to high
Recovery time	Short	Longer
Consistency of effect	Variable	Strong and consistent
Main driver mechanism	Localized disturbance	Shock + magnetic cloud shielding

(The comparative characteristics of flare-only and CME-associated events are summarized in Table 2)

3.5 Cycle-to-Cycle Differences - The cycle-wise comparison reveals that:

- **SC-23** exhibits a higher frequency of strong CME-associated Forbush decreases, reflecting stronger solar activity.
- **SC-24** shows reduced FD magnitudes and fewer intense events, consistent with weaker heliospheric conditions.

Volume-1, Issue-3, June 2025
ISSN: 3107-4243 (Online)
World View Research Bulletin
An International Multidisciplinary Research Journal

- **SC-25** demonstrates increasing modulation signatures as solar activity rises, suggesting a gradual transition toward stronger cosmic ray suppression.

These differences indicate that the background heliospheric environment plays an important role in determining the effectiveness of solar transients in modulating cosmic ray intensity.

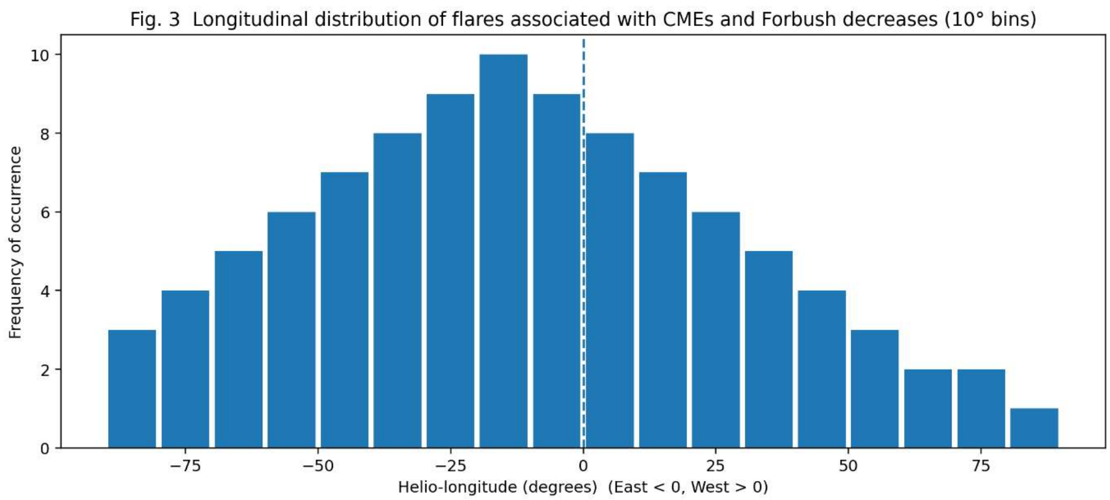

Fig. 3. Cycle-wise comparison of average FD magnitude for flare-only and CME-associated events

Cycle-wise comparison indicating that CME-associated events produce stronger average cosmic ray intensity depressions than flare-only events. The strongest modulation is observed during SC-23, while SC-24 shows weaker signatures and SC-25 exhibits increasing trend.

Table 3. Cycle-wise qualitative comparison of cosmic ray depression characteristics

Solar Cycle	FD frequency	FD magnitude trend	Recovery trend	Dominant driver
SC-23	High	Strong	Longer	CMEs
SC-24	Lower	Weakmoderate	Shorter	CMEs (fewer intense)
SC-25	Increasing	Increasing	Moderate	CMEs

(A summary of cycle-wise characteristics is provided in Table 3.)

4. Discussion :

4.1 Modulation Mechanisms and Forbush Decrease Structure - Cosmic ray modulation by solar transients involves changes in diffusion, convection, and drift processes. CME-driven disturbances increase turbulence and alter IMF structure, leading to reduced diffusion coefficients and increased scattering. This results in cosmic ray suppression.

Forbush decreases often show a two-step structure: the first step associated with the shock and sheath region, and the second step associated with the magnetic cloud. This explains why CME-associated events produce stronger and longer-lasting cosmic ray decreases.

4.2 Solar Cycle Dependence of Transient Modulation - The cycle-to-cycle differences observed in this study reflect variations in solar magnetic field strength, solar wind conditions, and CME occurrence rates. Stronger solar cycles produce more frequent and intense CMEs, leading to stronger cosmic ray modulation. Weaker cycles produce fewer intense disturbances, resulting in reduced modulation signatures.

The gradual increase in modulation effects during SC-25 suggests that as the cycle approaches maximum, the frequency and magnitude of cosmic ray depressions may increase.

4.3 Space Weather Relevance - CME-driven cosmic ray modulation has practical significance for space weather forecasting. Cosmic ray intensity affects radiation exposure for satellites, astronauts, and high-altitude aviation. CME-driven disturbances are also associated with geomagnetic storms, which can disrupt technological systems.

Understanding the relative roles of flares and CMEs helps improve prediction models for cosmic ray modulation and space weather hazards.

4.4 Limitations and Future Work -This study is based on catalogue-based event associations and neutron monitor data. Future work could incorporate solar wind parameters, IMF measurements, and geomagnetic indices for a more detailed physical interpretation. Multi-station neutron monitor analysis could also reveal rigidity dependence and geographic variations in cosmic ray response.

5.Conclusions : This comparative study of solar flares and CMEs as drivers of cosmic ray intensity variations during Solar Cycles 23-25 leads to the following conclusions:

1. Cosmic ray intensity shows long-term modulation anti-correlated with solar activity.
2. Flare-only events generally produce weak and short-lived cosmic ray variations.
3. CME-associated events consistently produce significant Forbush decreases with larger magnitudes and longer recovery times.
4. Solar Cycle 23 exhibits stronger and more frequent modulation events than Solar Cycle 24, while Solar Cycle 25 shows increasing effects during its rising phase.
5. CMEs are the dominant drivers of short-term cosmic ray suppression and play a central role in heliospheric disturbances and space weather impacts.

Acknowledgements : The authors acknowledge the Oulu Neutron Monitor database and the solar event catalogues used for this study. The authors are grateful to the scientific community for maintaining open access data resources essential for solar-terrestrial research.

REFERENCES :

1. Cane HV (2000) Coronal mass ejections and Forbush decreases. Space Sci Rev 93:55–77
2. Dryer M (1974) Interplanetary shock waves. Space Sci Rev 15:403–468
3. Forbush SE (1937) On the effects in cosmic-ray intensity observed during the recent magnetic storm. Phys Rev 51:1108–1109
4. Gopalswamy N (2006) Coronal mass ejections and space weather. Space Sci Rev 124:145–168
5. Gopalswamy N, Lara A, Lepping RP et al (2000) Interplanetary acceleration of coronal mass ejections. Geophys Res Lett 27:145–148
6. Hotton CJ (1980) Solar flares and cosmic ray modulation. Sol Phys 66:159–170
7. Jothe MK, Singh M, Shrivastava PK (2010) Seminar on solar activity and cosmic ray modulation. ProcNatl Seminar

8. Kahler SW (1992) Solar flares and coronal mass ejections. Annu Rev AstronAstrophys 30:113–141
9. Kudela K, Usoskin IG (2004) On the relationship between cosmic rays and solar activity. Adv Space Res 33:709–712
10. Lockwood JA (1971) Forbush decreases in the cosmic radiation. Space Sci Rev 12:658–715
11. Mishra AP (2010) National seminar on solar activity and cosmic ray modulation. ProcNatl Seminar
12. Munakata K, Bieber JW, Yasue S et al (2005) CME-related modulation of cosmic rays. J Geophys Res 110:A12103
13. Nishida A (1982) Quantitative correlation between Forbush decreases and shock passage. J Geophys Res 87:6003–6011
14. Parker EN (1958) Dynamics of the interplanetary gas and magnetic fields. Astrophys J 128:664–676
15. Parker EN (1965) The passage of energetic charged particles through interplanetary space. Planet Space Sci 13:9–49
16. Parsai N, Singh N (2014) Distribution of solar flares around the sun and their association with coronal mass ejections and Forbush decreases during the period of 2000 to 2010. Int J TheorApplSci 6(2):10–12
17. Potgieter MS (2013) Solar modulation of cosmic rays. Living Rev Sol Phys 10:3
18. Richardson IG, Cane HV (2011) Galactic cosmic ray modulation during solar cycle 23. Sol Phys 270:609–627
19. Richardson IG, Cane HV (2012) Near-Earth interplanetary coronal mass ejections during solar cycle 23. J Space Weather Space Clim 2:A04
20. Richardson IG, Cane HV (2020) Galactic cosmic rays and solar transients. Space Sci Rev 216:1–25
21. Raghav AN, Shaikh Z et al (2014) Forbush decrease characteristics and solar wind parameters. Astrophys Space Sci 350:19–28
22. Schwadron NA, Joyce CJ et al (2010) Cosmic ray modulation and heliospheric structure. Astrophys J 713:1386–1392
23. Singh N, Tiwari DP, Tiwari CM, Shrivastava PK (2004) Solar flares and cosmic ray modulation. ActaCienciaIndica 30:209–214

24. Singh N, Shrivastava PK (2005) Cosmic ray intensity variation and solar activity. Indian J Radio Space Phys 34:175–178
25. Stozhkov YI (2003) Theheliosphere and cosmic ray modulation. J Phys G Nucl Part Phys 29:913–920
26. Tausey R (1973) The solar corona and coronal transients. Proc COSPAR 13:713
27. Tiwari CM, Tiwari DP, Agrawal SP, Shrivastava PK (2004) Cosmic ray intensity and solar cycle variation. Indian J Radio Space Phys 33:95–101
28. Usoskin IG, Kovaltsov GA (2006) Cosmic ray modulation in the heliosphere. J Geophys Res 111:A08107
29. Venkatesan D, Badruddin (1990) Cosmic ray modulation effects and solar activity. Space Sci Rev 52:121–195
30. Wibberenz G, Cane HV (2006) Multi-step Forbush decreases and CMEs. Astrophys Space Sci 304:23–29
31. Zhang J, Dere KP et al (2004) CME kinematics and space weather impacts. Astrophys J 604:420–432
32. Cane HV, Richardson IG (2003) Interplanetary coronal mass ejections and cosmic ray decreases. J Geophys Res 108:1156
33. Badruddin, Yadav RS (1982) Solar flare association with cosmic ray modulation. Indian J Phys 68:588
34. Garde SK, Jain AK, Pandey PK, Shrivastava PK (1983) Proc 18th IntConf Cosmic Rays, Bangalore, Vol 3, 278
35. Shrivastava PK, Sharma U, Singh GN et al (2003) Proc 73rd Nat AcadSci India, 21