



# Long-Term Association of Cosmic Ray Intensity in Relationship with Solar Activity during Solar Cycle 24

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**ABSTRACT:** The present study investigates the long-term relationship between cosmic ray intensity (CRI) and major solar activity indices during Solar Cycle 24 (2008–2019). Pressure-corrected CRI data from the Mexico, Moscow, and Thule neutron monitor stations were analyzed in conjunction with Sunspot Number (Rz), Flare Index (FI), and Solar Radio Flux F10.7 (SRF). Temporal variation and regression analyses were employed to examine the dependence of CRI on solar activity. The results reveal a significant inverse relationship between CRI and all solar activity parameters. The strongest anti-correlation was observed between CRI and F10.7 at Moscow ( $r \approx -0.96$ ), while moderate to strong correlations were found for SSN and FI. The modulation effect was most pronounced at high-latitude stations due to lower geomagnetic cutoff rigidity. These findings confirm that solar activity plays a dominant role in governing long-term cosmic ray modulation during Solar Cycle 24.

**KEYWORDS:** Cosmic Ray Intensity, Solar Cycle 24, Sunspot Number, Flare Index, Solar Radio Flux, Solar Modulation, Neutron Monitor.

## I. INTRODUCTION

Galactic Cosmic Rays (GCRs) are highly energetic charged particles originating primarily from supernova remnants and other energetic astrophysical sources within the Milky Way galaxy. Before reaching Earth, these particles propagate through the heliosphere where they experience modulation by solar wind plasma and the interplanetary magnetic field (IMF) carried by the solar wind (Parker, 1965; Potgieter, 2013).

Solar activity varies approximately every 11 years and is commonly represented by indices such as Sunspot Number (SSN), Flare Index (FI), and Solar Radio Flux (F10.7). During periods of enhanced solar activity, stronger heliospheric magnetic fields and increased solar wind turbulence reduce the penetration of GCRs into the inner heliosphere, resulting in decreased cosmic ray intensity (Forbush, 1954; Hathaway, 2015).

Several investigators have reported an inverse relationship between CRI and solar activity indicators (Ahluwalia, 2013; Tiwari et al., 2011; Parsai and Singh, 2016). However, the strength of this relationship depends on solar cycle phase and geomagnetic latitude. Therefore, the present work examines the long-term association between CRI and major solar activity indices during Solar Cycle 24 using observations from neutron monitor stations with different cutoff rigidities.

## II. DATA SOURCE

The present study utilizes pressure-corrected daily mean Cosmic Ray Intensity (CRI) data obtained from the Neutron Monitor Database (NMDB). Three neutron monitor stations representing different geomagnetic cutoff rigidities and latitudinal regions were selected, namely Thule (0.3 GV), Moscow (2.43 GV), and Mexico (8.2 GV). These stations provide an opportunity to investigate the latitude-dependent response of cosmic rays to solar activity. Solar activity parameters, including Sunspot Number (SSN), Flare Index (FI), and Solar Radio Flux (F10.7), were collected from internationally recognized databases. Monthly and daily SSN data were obtained from the Solar

Influences Data Analysis Center (SILSO), while FI data were acquired from the National Geophysical Data Center (NGDC/NOAA). The F10.7 solar radio flux data were obtained from the National Research Council of Canada and NOAA archives. The study covers the period from January 2008 to December 2019, encompassing the entire Solar Cycle 24, including the solar minimum, ascending phase, solar maximum, and declining phase. This period provides a complete representation of solar activity variations and their influence on cosmic ray modulation.

### III. METHODOLOGY

To investigate the long-term association between cosmic ray intensity and solar activity, daily mean values of CRI, SSN, FI, and F10.7 were analyzed. Initially, temporal variation plots were constructed to examine the evolution of CRI and solar activity indices throughout Solar Cycle 24 and to identify similarities or differences in their long-term behavior. Subsequently, statistical analyses were performed to quantify the relationships between CRI and the selected solar activity parameters. Pearson's correlation coefficient ( $r$ ) was calculated to determine the strength and direction of the association between CRI and each solar activity index. Furthermore, linear regression analysis was employed to evaluate the degree of dependence of CRI on solar activity parameters and to estimate the corresponding regression coefficients. To examine possible nonlinear modulation effects, second-order polynomial regression models were also applied. The goodness of fit of each model was assessed using the coefficient of determination ( $R^2$ ), adjusted  $R^2$ , and statistical significance levels ( $p$ -values). Comparative analyses among the three neutron monitor stations were conducted to assess the influence of geomagnetic cutoff rigidity and latitude on cosmic ray modulation. All graphical representations and statistical analyses were performed using Microsoft Excel and Origin software packages. The adopted methodology provides a comprehensive framework for understanding the role of solar activity in modulating galactic cosmic ray intensity during Solar Cycle 24.

### IV. EXPERIMENTAL RESULTS AND DISCUSSION

**CRI versus Sunspot Number ( $R_z$ )-** Fig 1. shows the temporal analysis demonstrates a clear anti-phase variation between CRI and SSN throughout Solar Cycle 24. During the solar minimum (2008–2009), SSN remained close to zero while CRI reached maximum values at all stations. As solar activity increased toward the solar maximum around 2014, CRI decreased significantly.

The regression analysis reveals a significant inverse relationship between CRI and SSN at all three stations (fig. 2). The strongest anti-correlation was observed at Moscow ( $r = -0.95$ ), followed by Mexico ( $r = -0.90$ ), whereas Thule exhibited a comparatively weaker relationship ( $r = -0.58$ ).

For Thule, the linear regression model yielded  $R^2 \approx 0.33$  with  $p \approx 0.0489$ , indicating that nearly 33% of the observed CRI variability can be explained by changes in SSN. Although statistically significant at the 95% confidence level, the relatively low  $R^2$  suggests the influence of additional heliospheric factors.

At Moscow, the relationship was exceptionally strong, with  $R^2 \approx 0.90$  and  $p < 0.0001$ . This indicates that approximately 90% of the variation in CRI is associated with changes in SSN. The polynomial model provided only a marginal improvement ( $R^2 \approx 0.91$ ), confirming that the relationship is predominantly linear.

Similarly, Mexico showed a strong negative correlation ( $r = -0.90$ ) with  $R^2 \approx 0.80$  and  $p < 0.0001$ . The polynomial fit slightly increased  $R^2$  to about 0.83; however, the improvement was not substantial, suggesting that the modulation process remains largely linear.

These results confirm that sunspot number is an effective indicator of long-term cosmic ray modulation and that enhanced solar activity significantly suppresses CRI. These observations are consistent with the classical solar modulation theory proposed by Parker (1965) and supported by previous investigations (Tiwari et al., 2011; Parsai and Singh, 2016).

**[1] Physical Interpretation-** Increased  $R_z$  corresponds to:

- Stronger heliospheric magnetic field.
- Enhanced solar wind turbulence.
- Increased scattering of GCRs.

Consequently, fewer cosmic rays reach Earth, leading to lower CRI.

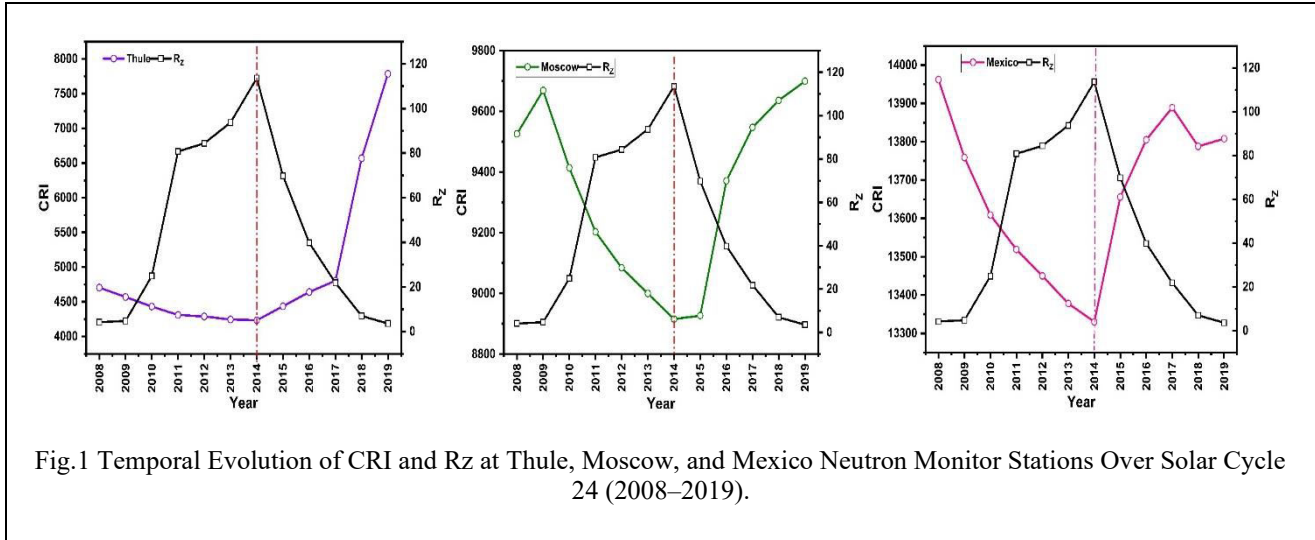


Fig.1 Temporal Evolution of CRI and Rz at Thule, Moscow, and Mexico Neutron Monitor Stations Over Solar Cycle 24 (2008–2019).

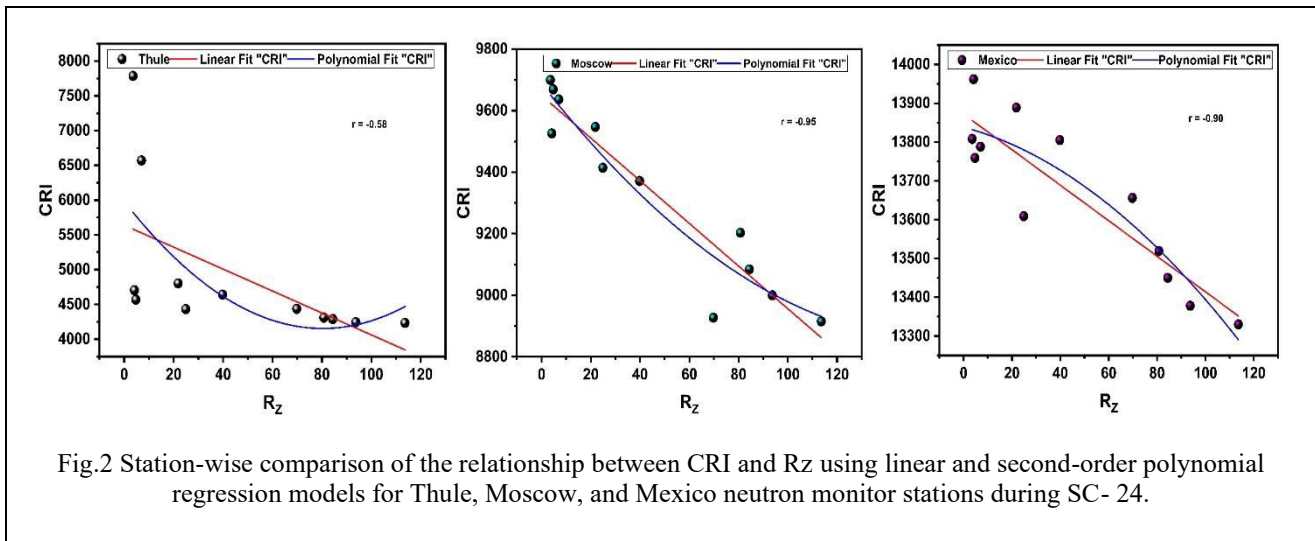


Fig.2 Station-wise comparison of the relationship between CRI and Rz using linear and second-order polynomial regression models for Thule, Moscow, and Mexico neutron monitor stations during SC- 24.

**CRI versus Flare Index (FI)**- The relationship between CRI and FI (fig.3 & fig. 4) was generally weaker than that observed for Rz but remained predominantly negative.

At Thule, the correlation coefficient was  $r = -0.46$  with  $R^2 \approx 0.22$  and  $p \approx 0.128$ . The polynomial model increased  $R^2$  to approximately 0.32; however, the corresponding p-value remained statistically insignificant ( $p \approx 0.17$ ). These findings indicate that flare activity alone explains only a limited fraction of CRI variability at high latitudes.

The Moscow station exhibited the strongest response to FI, with  $r = -0.85$  and  $R^2 \approx 0.72$ . The linear model was highly significant ( $p \approx 4.81 \times 10^{-4}$ ), while the polynomial model improved the fit considerably ( $R^2 \approx 0.86$ ;  $p \approx 1.38 \times 10^{-4}$ ). The significant quadratic term suggests the presence of nonlinear modulation effects.

For Mexico, the correlation coefficient was  $r = -0.77$ , with  $R^2 \approx 0.59$  and  $p \approx 0.0036$ . The polynomial model slightly improved the fit ( $R^2 \approx 0.62$ ;  $p \approx 0.0126$ ), indicating that the relationship remains primarily linear with a modest nonlinear contribution.

The Moscow station exhibited the strongest statistical relationship, suggesting that solar flare activity contributes significantly to long-term cosmic ray modulation.

Solar flares are frequently associated with CMEs and enhanced heliospheric disturbances, which strengthen the modulation of GCRs (Gonzalez et al., 1994).

[1] Physical Interpretation- High FI indicates:

- Increased flare occurrence.
- Enhanced CME activity.
- Greater heliospheric magnetic disturbances.

These conditions increase cosmic ray scattering and reduce CRI.

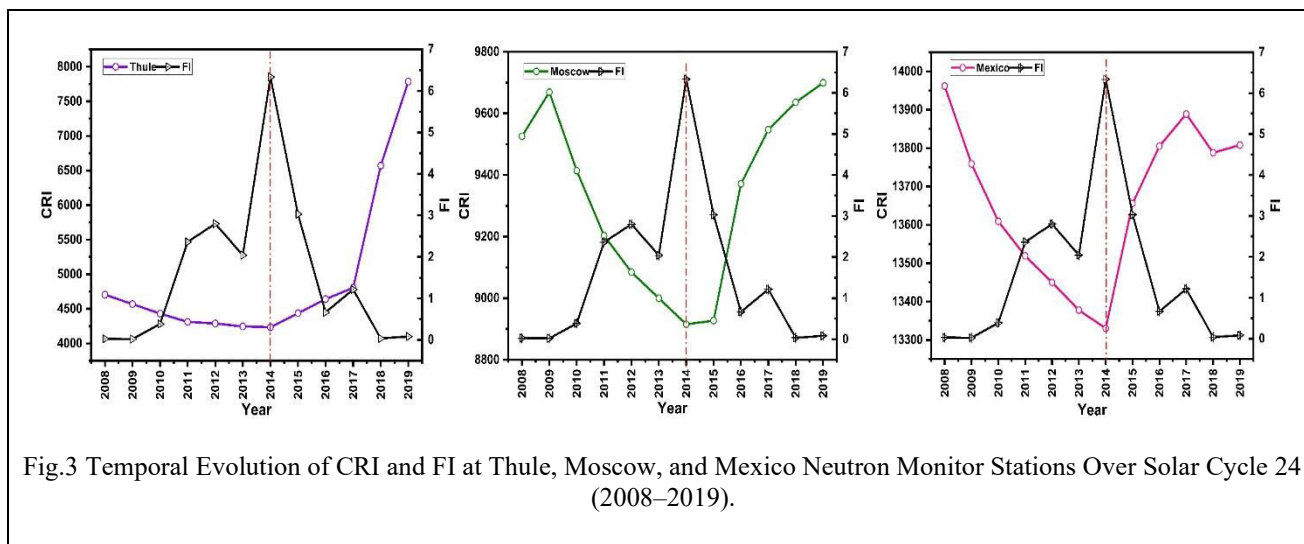


Fig.3 Temporal Evolution of CRI and FI at Thule, Moscow, and Mexico Neutron Monitor Stations Over Solar Cycle 24 (2008–2019).

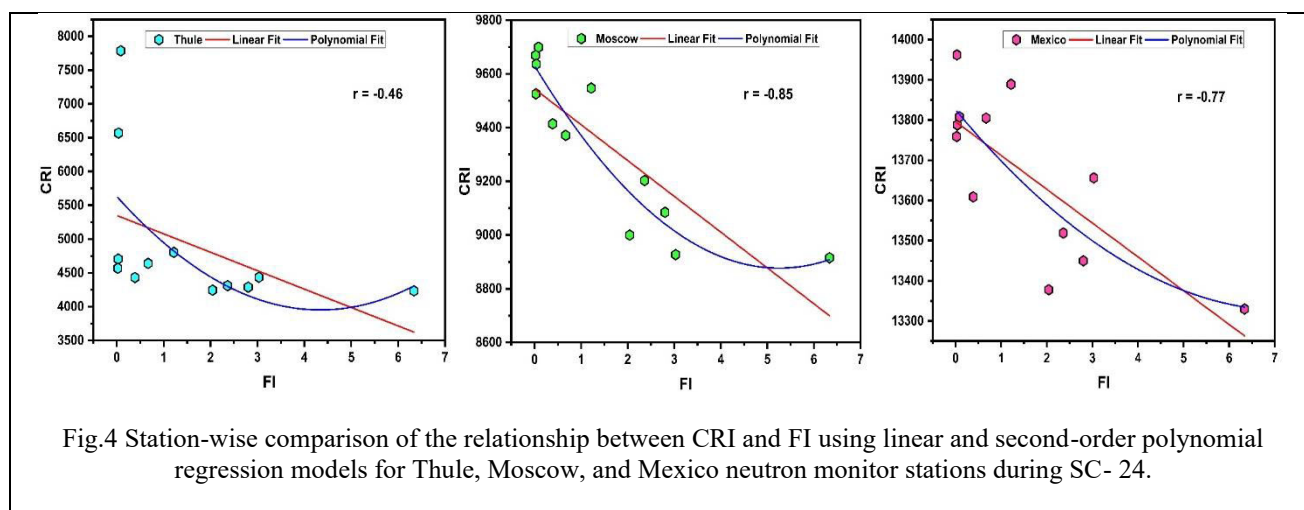


Fig.4 Station-wise comparison of the relationship between CRI and FI using linear and second-order polynomial regression models for Thule, Moscow, and Mexico neutron monitor stations during SC- 24.

**CRI versus Solar Radio Flux (F10.7)** – Among all investigated parameters, Solar Radio Flux (F10.7) demonstrated the strongest association with CRI.

At Thule, the correlation coefficient was  $r \approx -0.57$ , with  $R^2 \approx 0.32$ . The regression slope was negative, indicating an inverse relationship; however, the statistical significance was relatively weak ( $p > 0.05$ ). The polynomial model produced only a minor improvement, suggesting that F10.7 alone cannot fully explain CRI variability at this station. The Moscow station displayed the strongest correlation observed in the present study, with  $r \approx -0.96$  and  $R^2 \approx 0.93$ . The linear regression model was highly significant ( $p \ll 0.001$ ), indicating that more than 90% of the observed CRI variation can be explained by changes in F10.7. The polynomial model further improved the fit ( $R^2 \approx 0.95$ ), suggesting the existence of nonlinear modulation effects during periods of intense solar activity.

For Mexico, a strong inverse correlation was also found ( $r \approx -0.87$ ), with  $R^2 \approx 0.76$  and  $p < 0.001$ . The polynomial fit significantly increased the explanatory power of the model ( $R^2 \approx 0.95$ ), indicating a nonlinear response of CRI to solar radio flux variations.

The high  $R^2$  values and extremely small p-values obtained for Moscow and Mexico clearly establish F10.7 as the most reliable solar activity proxy for describing long-term cosmic ray modulation during Solar Cycle 24.

The regression analysis revealed highly significant negative relationships at Moscow and Mexico. Polynomial fitting further improved the coefficient of determination, indicating the presence of nonlinear modulation effects.

F10.7 is considered an excellent proxy for solar EUV emission and global solar activity (Tapping, 2013). Therefore, its strong correlation with CRI confirms its importance in describing long-term solar modulation.

**Physical Interpretation-** Higher F10.7 values correspond to:

- Enhanced solar magnetic activity.
- Stronger solar wind conditions.
- Greater heliospheric shielding.

This results in reduced penetration of galactic cosmic rays into the inner heliosphere.

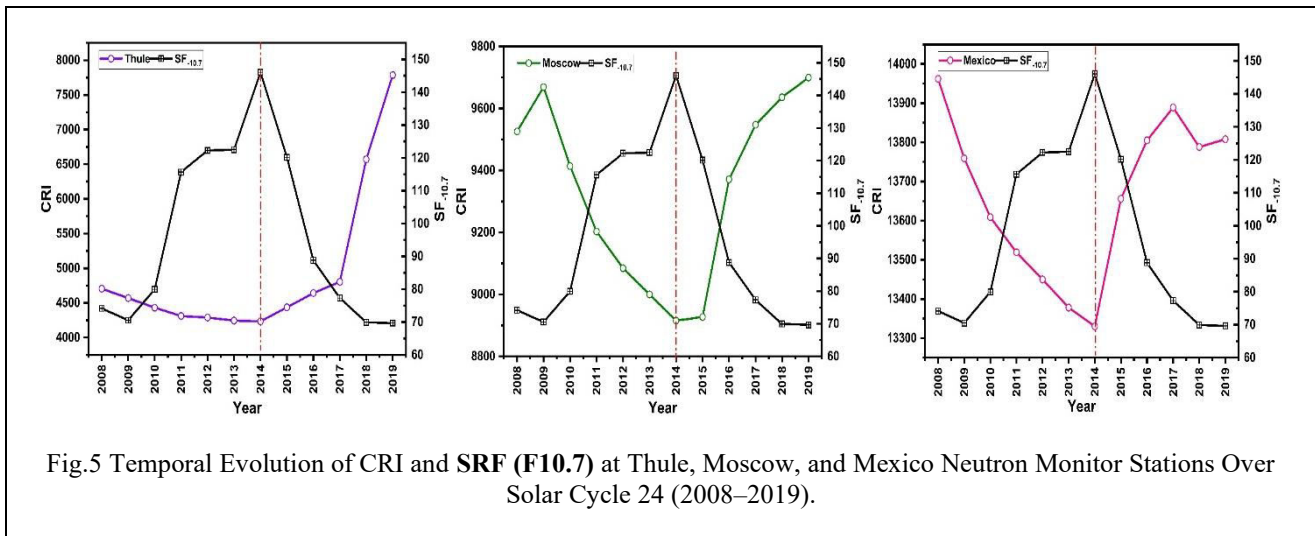


Fig.5 Temporal Evolution of CRI and SRF (F10.7) at Thule, Moscow, and Mexico Neutron Monitor Stations Over Solar Cycle 24 (2008–2019).

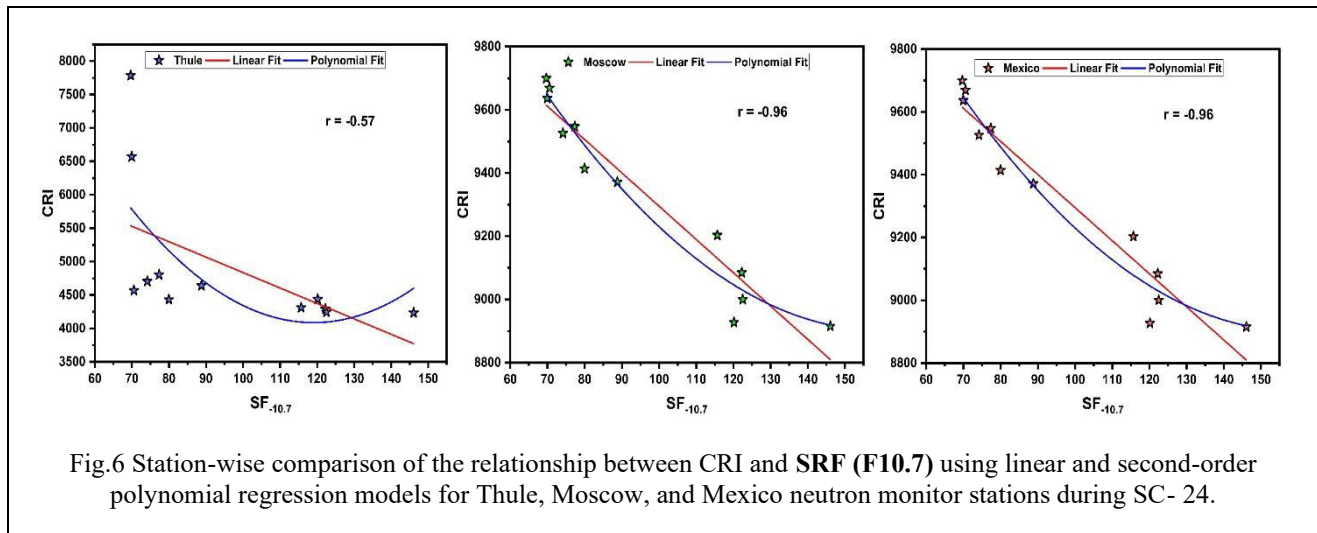


Fig.6 Station-wise comparison of the relationship between CRI and SRF (F10.7) using linear and second-order polynomial regression models for Thule, Moscow, and Mexico neutron monitor stations during SC- 24.

#### I. LATITUDE AND RIGIDITY DEPENDENCE

The analysis demonstrates a clear dependence of cosmic ray modulation on geomagnetic cutoff rigidity.

##### Thule (0.3 GV) -

- Largest amplitude variation.
- Highest sensitivity to solar modulation.
- Greater access of low-energy cosmic rays.

##### Moscow (2.43 GV) -

- Strongest statistical correlations.
- Best representation of global solar modulation.

##### Mexico (8.2 GV) -

- Reduced modulation amplitude.
- Strong geomagnetic shielding effect.

These findings agree with previous studies indicating that lower rigidity stations are more sensitive to heliospheric changes (Ahluwalia, 2013).

#### V. OVERALL STATISTICAL INTERPRETATION

A comparative examination of all regression results indicates that:

1. All solar activity parameters exhibit statistically significant inverse relationships with CRI.
2. Solar Radio Flux (F10.7) produces the strongest correlations and highest R<sup>2</sup> values, demonstrating its superior capability to represent solar modulation effects.
3. Sunspot Number (SSN) also shows strong and highly significant associations with CRI.
4. Flare Index (FI) exhibits comparatively weaker correlations, particularly at high latitudes.
5. Polynomial regression generally provides slightly better fits than linear regression, suggesting the presence of nonlinear modulation processes during periods of elevated solar activity.
6. Moscow consistently exhibits the strongest statistical relationships, while Thule shows larger variability but weaker statistical significance.
7. The very low p-values ( $p < 0.05$  and often  $p < 0.001$ ) confirm that the observed correlations are statistically significant and unlikely to have occurred by chance.

These findings strongly support the concept that solar activity governs the long-term modulation of galactic cosmic rays in the heliosphere through changes in the solar wind and heliospheric magnetic field.

## VI. CONCLUSION

The present investigation provides a comprehensive assessment of the long-term relationship between cosmic ray intensity and solar activity during Solar Cycle 24.

The major conclusions are:

- CRI exhibits a significant inverse relationship with all investigated solar activity indices.
- Solar maximum conditions around 2014 correspond to minimum CRI levels at all neutron monitor stations.
- F10.7 shows the strongest correlation with CRI, followed by SSN and FI.
- Moscow exhibits the strongest statistical relationships, whereas Thule displays the largest modulation amplitude.
- The results confirm that enhanced solar activity strengthens heliospheric shielding and reduces the flux of galactic cosmic rays reaching Earth.
- Geomagnetic cutoff rigidity plays an important role in determining the magnitude of observed cosmic ray modulation.

Overall, the study confirms that solar activity remains the dominant driver of long-term cosmic ray modulation during Solar Cycle 24.

## REFERENCES

- [1] Ahluwalia, H. S. (2013). Cosmic ray modulation studies during recent solar cycles. *Advances in Space Research*, 52, 211–221.
- [2] Forbush, S. E. (1954). Worldwide cosmic-ray variations, 1937–1952. *Journal of Geophysical Research*, 59, 525–542.
- [3] Gonzalez, W. D., Joselyn, J. A., Kamide, Y., et al. (1994). What is a geomagnetic storm? *Journal of Geophysical Research*, 99(A4), 5771–5792.
- [4] Hathaway, D. H. (2015). The Solar Cycle. *Living Reviews in Solar Physics*, 12, 4.
- [5] Parker, E. N. (1965). The passage of energetic charged particles through interplanetary space. *Planetary and Space Science*, 13, 9–49.
- [6] Parsai, M., & Singh, Y. P. (2016). Solar cycle dependence of cosmic ray intensity variations. *Solar Physics*, 291, 2565–2578.
- [7] Potgieter, M. S. (2013). Solar modulation of cosmic rays. *Living Reviews in Solar Physics*, 10, 3.
- [8] Singh, P.R. et al. (2021). *Indian Journal of Radio and Space Physics* Vol. 50, pp 156-162
- [9] Tapping, K. F. (2013). The 10.7 cm solar radio flux. *Space Weather*, 11, 394–406.
- [10] Tiwari, C. M., Tiwari, A. K., & Singh, Y. P. (2011). Relationship between cosmic ray intensity and solar activity parameters. *Indian Journal of Radio & Space Physics*, 40, 223–229



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