

Analysis of Cosmic Ray Variations with Solar Activity and Geomagnetic Parameters during Solar Cycles 2009–2025



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Abstract

The present study investigates the long-term variation of Cosmic Ray Intensity (CRI) in relation to Sunspot Number (SSN), Interplanetary Magnetic Field (IMF) and Kp Index during the period 2009–2025, covering Solar Cycles 24 and the beginning of Solar Cycle 25. Cosmic rays are energetic charged particles originating from outer space and their intensity near Earth is significantly influenced by solar activity and heliospheric magnetic conditions. The analysis of annual average values of CRI, SSN, IMF and Kp Index was carried out to examine their correlation and mutual dependence.

The results reveal a strong inverse correlation between CRI and SSN ($r = -0.90$), indicating that cosmic ray intensity decreases with increasing solar activity. Similarly, CRI shows a significant negative correlation with IMF ($r = -0.77$) and Kp Index ($r = -0.61$), suggesting that stronger interplanetary magnetic fields and geomagnetic disturbances act as barriers to the penetration of galactic cosmic rays into Earth's atmosphere.

The study confirms that solar and geomagnetic parameters play an important role in the modulation of cosmic rays. These findings contribute to a better understanding of solar-terrestrial interactions, space weather processes, and the behavior of cosmic ray intensity during different phases of solar cycles.

1. Introduction

Variations in cosmic ray intensity (CRI) are strongly influenced by modifications in the structure of solar wind (SW) and the interplanetary magnetic field (IMF), which arise due to solar source variability. These variations are closely associated with the movement of solar wind plasma in the interplanetary medium (Prithvi Raj Singh et al., 2017). It is well established that sunspot number (SSN) and galactic cosmic ray intensity (CRI) are inversely correlated (Mavromichalaki, 1988; Kane, 2005). The galactic cosmic ray curve follows an approximate 22-year cycle, characterized by alternate flat-topped and peaked maxima. The intensity reaches its maximum during the minimum phase of the 11-year solar cycle and varies inversely with SSN (Forbush, 1954, 1958).

During short intervals such as Forbush decreases (Cane, 1993) and in the distant heliosphere (Burlaga et al., 2000), a strong relationship has been observed between CRI variations and IMF intensity. This relationship highlights the importance of IMF structures in producing Forbush decreases (FDs) and demonstrates that IMF plays a significant role in cosmic ray modulation. Therefore, IMF cannot be ignored while studying cosmic ray variations. Moreover, the tilt of the heliospheric current sheet (HCS) along with other solar-heliospheric parameters has been found effective in explaining long-term cosmic ray variations over recent solar cycles, especially during solar maximum phases (Belov et al., 2001).

According to Nielsen and Kjeldsen (2011) and McDonald et al. (2010), the minimum phase between solar cycles 23 and 24 was unique compared to earlier solar minima. Sarver Khan et al. (2019) carried out a correlational study of long-term cosmic ray variations with interplanetary magnetic field parameters. Similarly, Chandrasekhar Bhoj et al. (2019) analyzed the behavior of CRI during geomagnetic storms by considering the southward component of IMF, total IMF (B), $|B_z|$, and solar wind speed (V) during two consecutive odd solar cycles 21 and 23.

Disturbances in Earth's magnetic field are strongly connected with solar outputs and interplanetary parameters such as IMF, solar wind velocity (SWV), and solar wind density. Variations in CRI are caused by changes in these solar outputs, which regulate the overall structure of the heliosphere (Singh S.G. et al., 2013; Tiwari & Ghormare, 2014). Through correlative analysis of long-term cosmic ray modulation with solar activity indices, Singh R.P. et al. (2011) found evidence of an anti-correlation between CRI and parameters such as solar wind speed, sunspot number, and the odd-even solar cycle hypothesis.

2. Data Analysis

The Moscow Neutron Monitor (<http://cro.izmiran.rssi.ru/mosc/main.htm>) provided the pressure-corrected data (yearly mean) for the study of cosmic rays, while the Omni web data-center (<http://omniweb.gsfc.nasa.gov/cgi/nx1.cgi>) provided the data for sunspot numbers, interplanetary magnetic fields (IMF) and Kp Index. Using the "minimizing correlation coefficient method," the correlation coefficient between CRI and SSN, IMF, Kp Index has been determined. To avoid ambiguity, the term "minimizing correlation coefficient method" refers to the use of the standard Pearson linear correlation coefficient. In this study, Pearson's correlation coefficient was calculated to quantify the linear relationship between the observed and estimated variables. The optimization procedure aimed to minimize the absolute value of the Pearson correlation coefficient, thereby reducing the linear dependence between the selected variables.

3. Results and Discussion

3.1. Correlative Study of Cosmic Ray Intensity with Sunspot Numbers

This study investigates the relationship between the annual average values of Cosmic Ray Intensity (CRI) and Sunspot Numbers (SSN) for the period 2009–2025. Figure (3.1) presents the linear graph plotted between the annual average values of CRI and SSN. The graph clearly indicates an inverse relationship between cosmic ray intensity and sunspot numbers.

It is observed that during periods of lower sunspot numbers, the cosmic ray intensity tends to be higher, whereas during periods of higher sunspot numbers, the cosmic ray intensity becomes lower. This variation suggests that solar activity strongly influences the intensity of cosmic rays reaching the Earth.

Furthermore, a scatter plot was drawn between the yearly average values of CRI and SSN for the same period, as shown in Figure (3.2). The scatter diagram also confirms the inverse relationship between the two parameters. The plotted points show that higher CRI values are associated with lower SSN values, and lower CRI values are associated with higher SSN values.

The calculated correlation coefficient ($r = -0.90$) indicates a strong negative correlation between CRI and SSN during the study period. This result confirms that as solar activity increases, the cosmic ray intensity decreases significantly, and vice versa. Such behavior is consistent with the modulation effect of solar magnetic activity on cosmic rays.

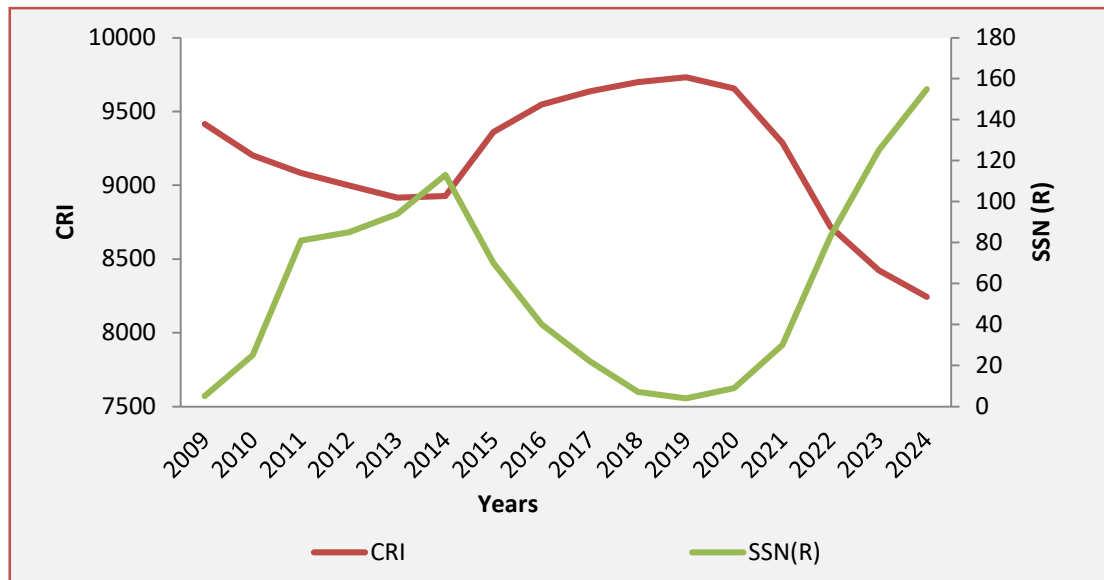


Fig.3.1 The linear relationship between the annual average CRI and SSN values from 2009 to 2025 is displayed.

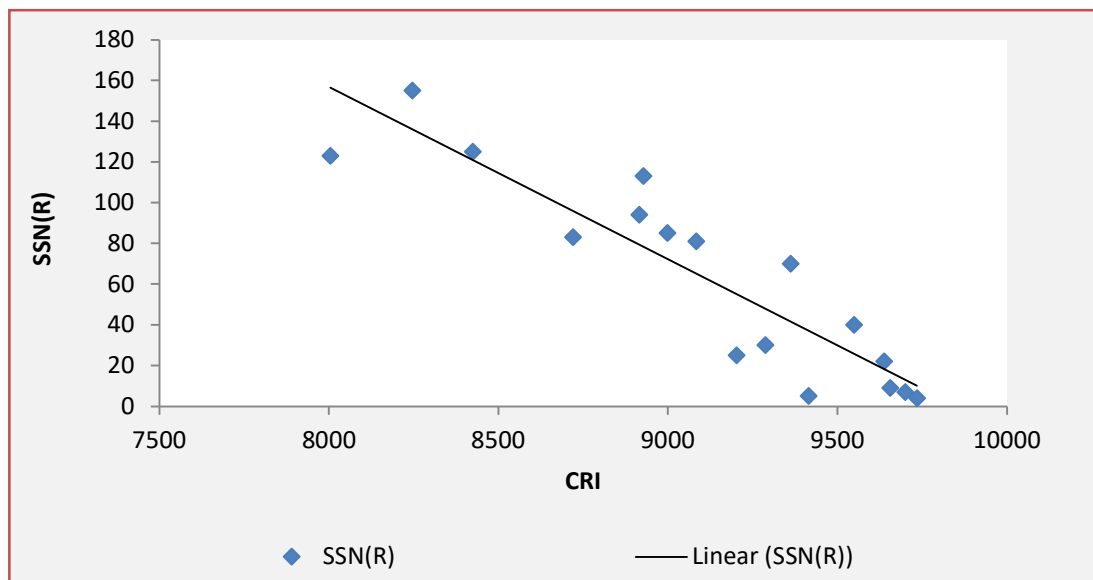


Fig.3.2 Displays the scatter plot of the annual average CRI and SSN data from 2009 to 2025 with a correlation coefficient of -0.90.

3.2. Correlative Study of Cosmic Ray Intensity with IMF

This study investigates the correlation between the annual average values of Cosmic Ray Intensity (CRI) and Interplanetary Magnetic Field (IMF) for the period 2009–2025. Figure (3.3) presents the linear graph plotted using the annual average values of CRI and IMF. The graphical analysis clearly indicates an inverse relationship between these two parameters. It is observed that higher values of CRI correspond to lower values of IMF, whereas lower values of CRI correspond to higher values of IMF.

To further examine this relationship, a scatter plot was constructed between the annual average values of IMF and CRI for the same period, as shown in Figure (3.4). The scatter diagram also confirms the inverse nature of their relationship. The distribution of data points demonstrates that an increase in IMF is associated with a decrease in CRI, while a decrease in IMF is associated with an increase in CRI.

The statistical analysis reveals a significant negative correlation coefficient of -0.77 between IMF and CRI during 2009–2025. This strong negative correlation suggests that variations in the interplanetary magnetic field play an important role in modulating cosmic ray intensity. The result supports the concept that stronger magnetic fields act as an effective barrier to cosmic rays, reducing their intensity near Earth.

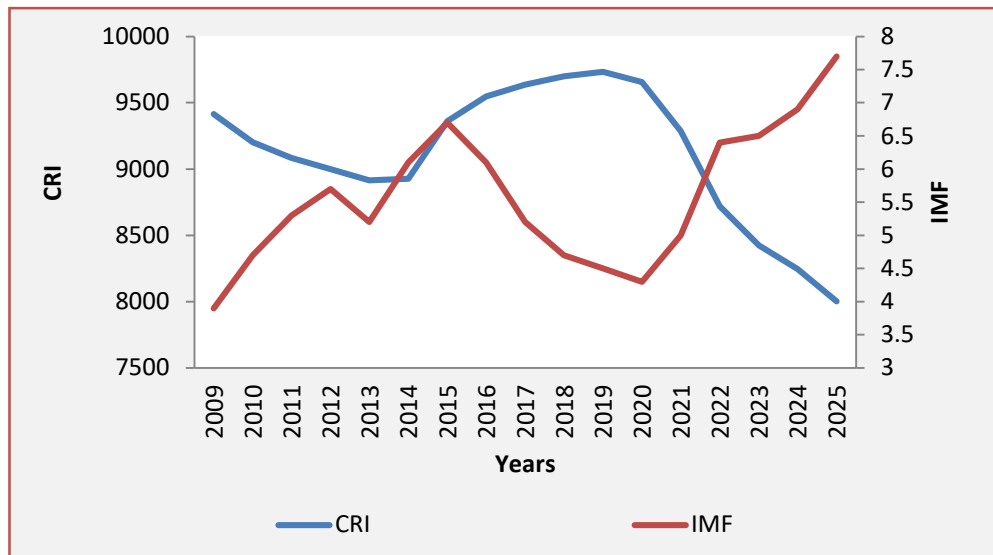


Fig. 3.3 Showing the linear relationship between the annual average CRI and IMF values from 2009 to 2025.

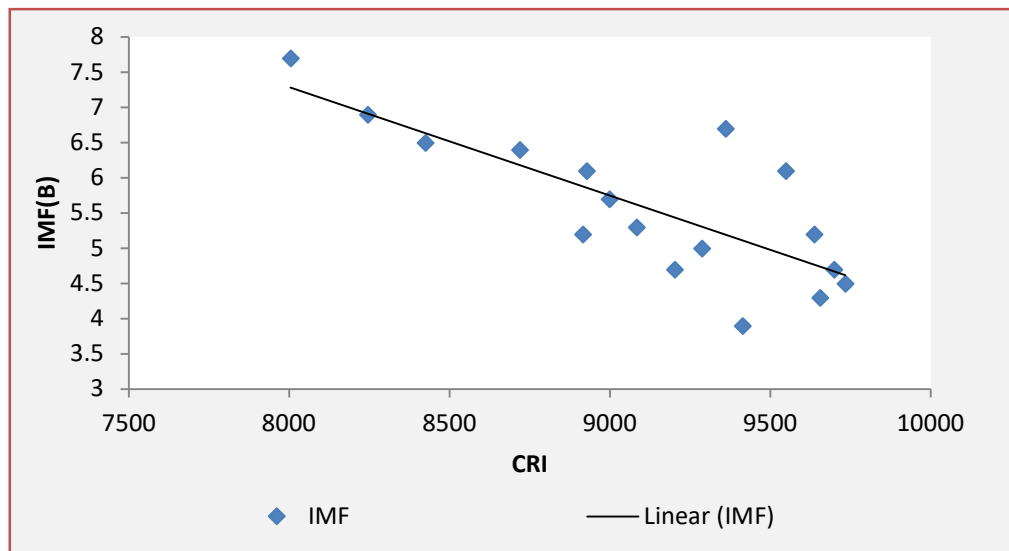


Fig.3.4 Displays a scatter plot with a correlation coefficient of -0.77 between the annual mean values of the CRI and IMF for the years 2009 to 2025.

3.3. Correlative Study of Cosmic Ray Intensity with Kp Index

This study investigates the relationship between the annual average values of Cosmic Ray Intensity (CRI) and the Kp index during the period 2009–2025. Figure (3.5) illustrates the linear graph plotted using the annual average values of CRI and the Kp index. The graph clearly indicates an inverse relationship between these two parameters. It is observed that higher values of CRI correspond to lower values of the Kp index, whereas lower values of CRI correspond to higher values of the Kp index.

To further analyze this relationship, a scatter plot was also prepared between the annual average values of CRI and the Kp index for the same period, as shown in Figure (3.6). The scatter diagram supports the inverse trend observed in the linear graph, showing that an increase in CRI is associated with a decrease in the Kp index, and vice versa.

The statistical analysis of the data reveals a significant negative correlation between CRI and the Kp index, with a correlation coefficient of -0.61 during 2009–2025. This negative correlation suggests that geomagnetic disturbances represented by the Kp index have a considerable influence on cosmic ray intensity. As geomagnetic activity increases, the intensity of cosmic rays tends to decrease.

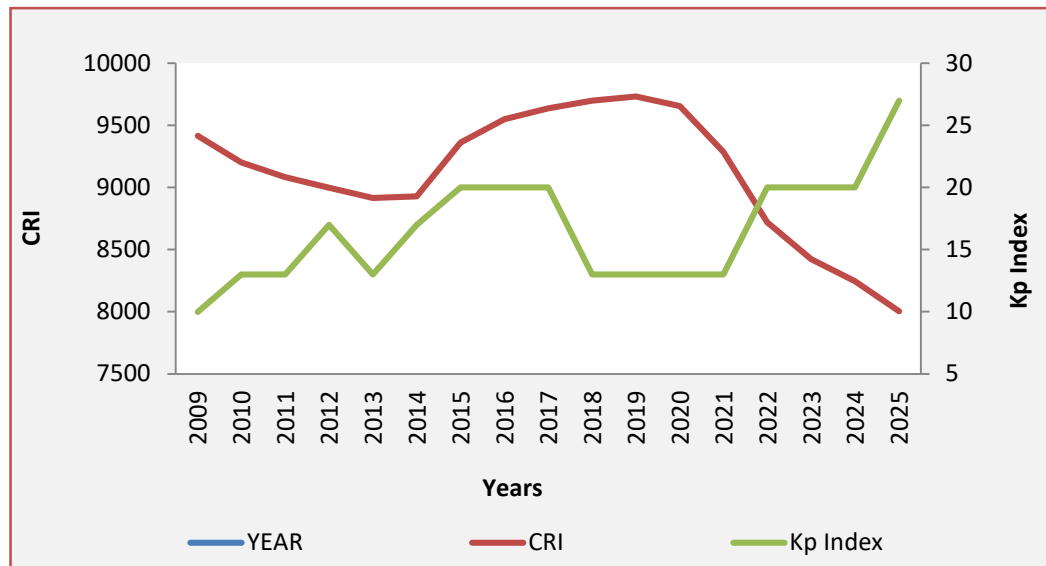


Fig.3.5 Showing the linear relationship between the annual average CRI and Kp index values from 2009 to 2025.

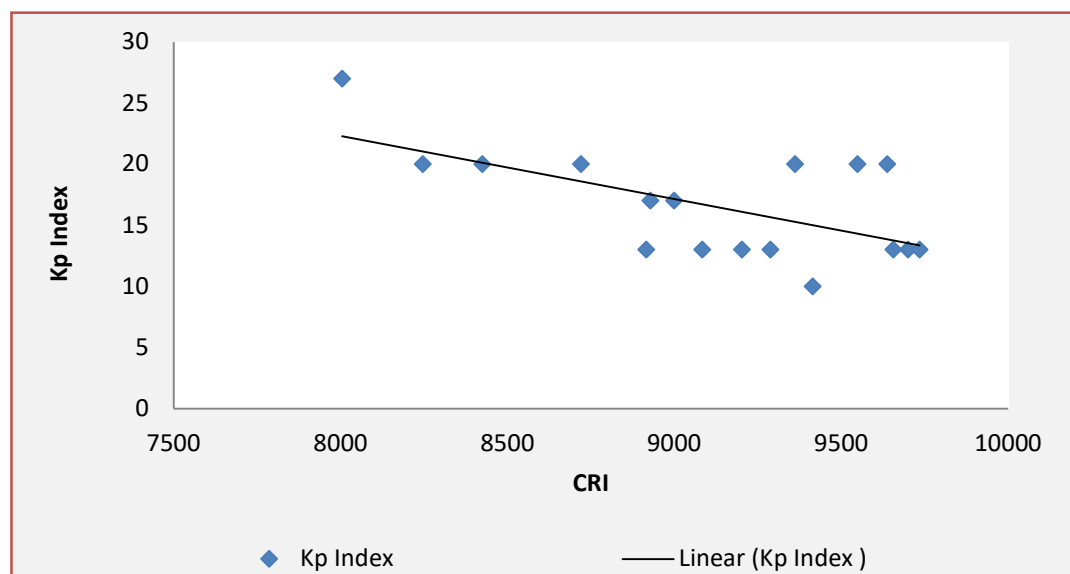


Fig.3.6 Displays a scatter plot with a correlation coefficient of -0.61 between the annual mean values of the CRI and Kp index for the years 2009 to 2025.

4. Conclusions

The present study provides important insights into the long-term modulation of cosmic ray intensity with solar and geomagnetic parameters during Solar Cycles 24 and 25.

The major conclusions are as follows:

1. Cosmic Ray Intensity (CRI) shows a clear inverse relationship with Sunspot Number, IMF, and Kp Index.
2. The strongest anti-correlation was observed between CRI and SSN ($r = -0.90$), confirming solar activity as the primary modulation factor.
3. A significant inverse correlation exists between CRI and IMF ($r = -0.77$), indicating the important role of heliospheric magnetic field strength.
4. A moderate inverse correlation was found between CRI and Kp Index ($r = -0.61$), showing the effect of geomagnetic disturbances.
5. Solar and geomagnetic parameters together regulate the penetration of galactic cosmic rays into Earth's atmosphere.
6. The comparative study of Solar Cycles 24 and 25 helps in understanding space weather behavior and heliospheric conditions.

Future work may include the analysis of Solar Wind Speed (SWS), Solar Flare Index (SFI), Coronal Mass Ejections (CMEs), and Heliospheric Current Sheet Tilt for deeper understanding.

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Conflict of Interest

The Authors declares that in this manuscript there is no potential conflict of interest.

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Authors Contribution

Pusparaj Singh prepare the manuscript, Nand Kumar Patel curated the desired datasets and Preetam Singh Gour analyze the data and review the manuscript.

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