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Variation of Cosmic Ray Intensity Profiles at Different Phases of Solar Cycle 24

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ABSTRACT: Based on the daily average data of Sunspot Number (SSN), Cosmic Ray Intensity (CRI), and the Solar Flux Index (SFI), a comprehensive correlative analysis was carried out to examine the interrelationship between cosmic ray modulation and solar activity throughout the different phases of Solar Cycle 24. The results demonstrate a strong inverse correlation between CRI and both SSN and SFI, reaffirming the well-established concept that heightened solar activity reduces cosmic ray intensity due to enhanced heliospheric shielding. Furthermore, a strong positive correlation is observed between SSN and SFI, highlighting their mutual consistency as solar activity indicators. Significantly, the negative correlation between CRI and solar parameters (SSN and SFI) is found to be more prominent during the descending phase of the solar cycle compared to the ascending phase. This observation implies that cosmic ray modulation becomes more sensitive to solar activity fluctuations in the latter half of the cycle, possibly due to changes in heliospheric conditions and solar wind structure during the declining activity period.

KEYWORDS: Cosmic ray intensity, sunspot number, solar flux index, solar cycle 24.

I. INTRODUCTION

The effects of solar activity on cosmic ray intensity (CRI) variation have been previously studied using data from ground-based detectors (mainly the global grid of ultra neutron monitors) in combination with other solar geophysical factors (Ables et al. 1965, Agrawal et al. 1965, Usoskin et al 1998, Jaroslav et al 2021). The interrelationship between these factors is called the Sun-Earth relationship. Both long term as well as short-term variations in CRI, remain an open problem in cosmic ray research. Multiple investigations reveal that the 11-year solar cycle of sunspot activity modulates the cosmic rays, which reaches a minimum near to the solar cycle's peak and a maximum during the stationary phase. It is well known that galactic cosmic ray (GCR) intensity and solar activity levels exhibit an inverse relationship over the 11-year solar cycle, often with a possible time delay (Forbush, 1958; Parker, 1965; Usoskin et al., 1998; Van Allen, 2000). This inverse correlation between GCRs and sunspot number (SSN) is clearly illustrated in Figure 1.

GCRs observed at Earth are influenced by solar modulation processes occurring within the heliosphere, driven by the outward-moving solar wind (SW). This modulation is controlled by several factors: the convection caused by the solar wind, the inward diffusion of GCRs through irregularities in the heliospheric magnetic field (HMF), drift along the structured HMF, and the adiabatic cooling of GCR particles due to solar wind expansion. The GCR intensity measured near Earth exhibits a range of quasi-periodic variations over both long and short timescales (see, for example, Kudela and Sabbah, 2016; Chowdhury, Kudela, and Moon, 2016; Bazilevskaya et al., 2014). Notable periodic patterns include cycles of approximately 22 years, 11 years, 27 days, and the solar diurnal variation (~24 hours). Superimposed on the long-term solar modulation—linked to the 22-year and 11-year cycles of the global HMF and solar activity (SA), respectively—are short-term variations, which include both sporadic events (e.g., Forbush decreases) and recurrent effects occurring roughly every 27 days.

The solar magnetic field is responsible for the solar wind's perpetual movement from the sun into interplanetary space. The charged cosmic ray particles are greatly impacted by this flow, which causes the field to fluctuate both in space and time. As a result, the notable long-term variation in their intensity has been attributed to the 22-year solar magnetic

polarity cycle and the 11-year solar activity as indicated by the sunspot numbers (Parker, 1965). It has been investigated by a number of authors that the intensities of cosmic ray are modulated by solar activity parameter (Hatton, 1980; Petropoulos, 1987; Bhattacharya & Roy, 2014). The long-term correlation between solar parameters and cosmic ray intensity has been the subject of extensive research in the past. Flares and sunspots are the most visible signs of solar activity. The only readily available and trustworthy metric for assessing solar activity is the sunspot number (Singh et al., 2011). This paper aims to investigate the correlation between solar activity parameters and cosmic ray intensity during the ascending and descending phases of solar cycles.

II. DATA SOURCE AND METHOD

In this analysis, pressure-corrected cosmic ray intensity (CRI) data from the Oulu Neutron Monitor (cut-off rigidity: 0.8 GV; latitude: 65.05°N; longitude: 24.47°E) have been utilized. The dataset, obtained from <http://cosmicrays.oulu.fi>, spans the period 2008 to 2018, effectively covering the entirety of Solar Cycle 24. These CRI measurements are correlated with key solar activity parameters, such as the Sunspot Number (SSN) and the 10.7 cm Solar Radio Flux (F10.7 index), retrieved from <http://www.ngdc.noaa.gov>.

This study aims to investigate the long-term variation of cosmic ray intensity in association with these solar indices. A variety of graphs, charts, scatter plots, and correlation analyses are employed to explore the trends and relationships over time. To quantitatively evaluate the degree of association, statistical techniques have been applied, including the computation of the correlation coefficient (r) between CRI and solar parameters. This comprehensive approach facilitates a deeper understanding of the modulation of cosmic rays in response to varying levels of solar activity throughout Solar Cycle 24.

III. RESULT AND DISCUSSION

ASCENDING PHASE OF SOLAR CYCLE 24- Figure 1 illustrates the yearly variation of Cosmic Ray Intensity (CRI) and Sunspot Number (SSN) from 2008 to 2014. The plot reveals a clear inverse relationship between CRI and SSN. CRI reaches its peak in 2009, which corresponds to a period of solar minimum, when sunspot numbers are lowest. As solar activity begins to rise after 2009, indicated by a steady increase in SSN, the CRI shows a consistent decline, reaching its lowest point around 2014, which is the solar maximum period.

This pattern supports the well-known concept of solar modulation of cosmic rays, where high solar activity (increased sunspots) leads to stronger solar winds and magnetic fields, which deflect incoming galactic cosmic rays and reduce their intensity at Earth (Dorman, 2004; Usoskin et al., 2011). The figure thus provides strong visual evidence of the anti-correlation between CRI and SSN during the ascending phase of Solar Cycle 24, consistent with earlier studies using neutron monitor data (Mavromichalaki et al., 2007).

Figure 2 shows the yearly association of Cosmic Ray Intensity (CRI) with the Solar Flux Index (SFI, F10.7-index) during the same ascending phase. The F10.7-index peaked in 2014 and reached its minimum in 2009. Similar to the previous observation, CRI was highest in 2009 and lowest in 2014, further confirming the inverse correlation between CRI and the solar flux index. In general, a pattern emerges where the maximum (minimum) of solar activity indicators coincides with the minimum (maximum) of CRI. This relationship aligns with the well-known mechanism of solar modulation of cosmic rays, in which increased solar activity leads to enhanced heliospheric magnetic shielding that reduces the flux of cosmic rays reaching Earth (Dorman, 2004; Tapping, 2013; Usoskin et al., 2011).

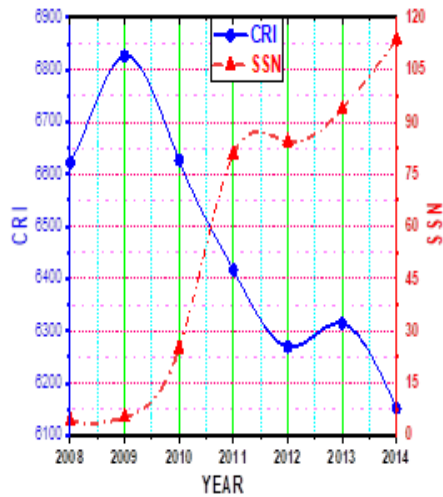


Fig 1 Association of CRI with SSN during ascending phase of solar cycle 24

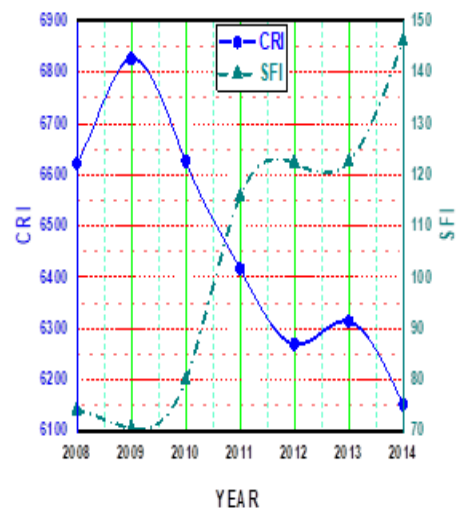


Fig 2 Association of CRI with SFI during ascending phase of solar cycle 24

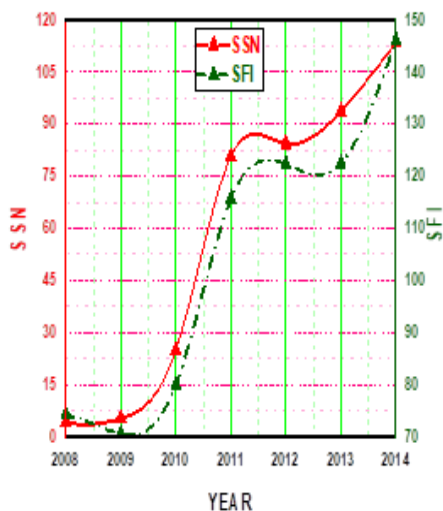


Fig 3 Association of SSN with SFI during ascending phase of solar cycle 24

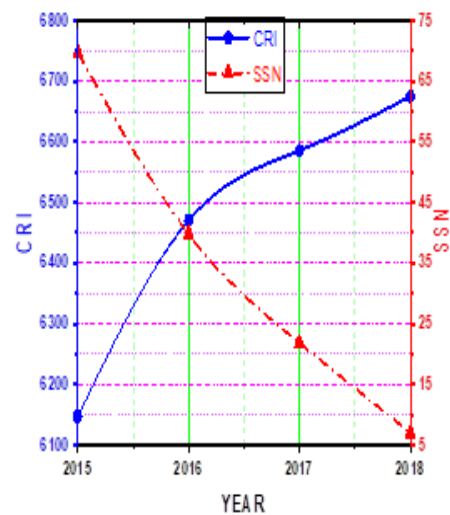


Fig 4 Association of CRI with SSN during descending phase of solar cycle 24

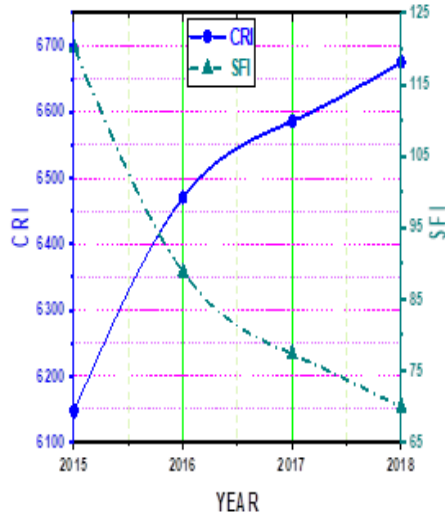


Fig 5 Association of CRI with SFI during descending phase of solar cycle 24

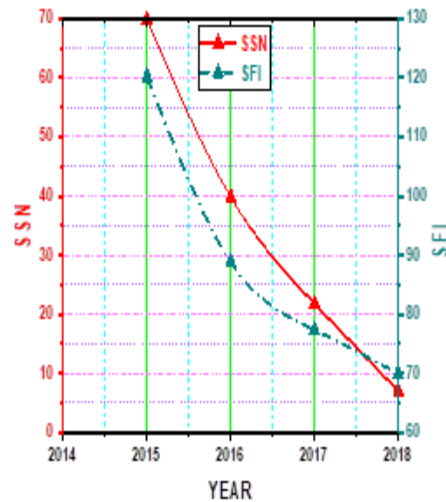


Fig 6 Association of SSN with SFI during descending phase of solar cycle 24

Figure 3 depicts the yearly variation of Sunspot Number (SSN) and F10.7-index, revealing a strong positive correlation between these two solar parameters. The F10.7-index reached its minimum in 2009 and maximum in 2014, while SSN followed a similar pattern from 2008 to 2014. This synchronization reflects the well-established direct relationship between solar radio flux and sunspot activity (Tapping, 2013; Svalgaard & Hudson, 2010; NOAA, 2023).

Descending Phase of Solar Cycle 24- Figure 4 shows the yearly association of Cosmic Ray Intensity (CRI) with Sunspot Number (SSN) during the descending phase of Solar Cycle 24 (2015–2018). The maximum SSN occurred in 2015 and the minimum in 2018, while CRI was highest in 2018 and lowest in 2015, again indicating a strong inverse correlation. Unlike the ascending phase, in this period, the maximum and minimum of CRI and SSN are more closely aligned, highlighting a tighter coupling during the descending phase (Usoskin et al., 2011; Mavromichalaki et al., 2007).

Figure 5 presents the association of CRI with the F10.7-index. Here, CRI reached a maximum in 2018 and a minimum in 2015, while the F10.7-index showed an opposite trend—highest in 2015 and lowest in 2018. This consistent inverse pattern mirrors that of CRI and SSN, reaffirming the influence of solar modulation (Dorman, 2004; Tapping, 2013).

Figure 6 displays the relationship between SSN and the F10.7-index, again demonstrating a strong positive correlation, with both parameters reaching their maximum in 2015 and minimum in 2018 (Svalgaard & Hudson, 2010).

We also computed the correlation coefficients among these parameters. The results are presented in the table below.

Table 1: - Correlation coefficient between CRI and solar parameters during different phase of solar cycle- 24

Parameters	Correlation Ascending phase	Correlation Descending phase
CRI vs SSN	-0.94	-0.93
CRI vs SFI	-0.95	-0.99
SSN vs SFI	+0.99	+0.99

A detailed correlative analysis is done between solar activity parameters and cosmic ray intensity. It is apparent from the analysis that the variation of cosmic ray intensity under different parameters has distinct difference for solar cycle 24. Correlation coefficient is different for the ascending and descending phase. We know that the number of sunspots is

inversely proportional to the variation in cosmic ray intensity over 11 years. Sunspot maxima and minima, however, frequently differ from cosmic-ray intensity maxima and minima. A detailed analysis taking into account data such as CRI and SSN was reported by Popielawska (1992) in order to illustrate the relation between CRI and SSN. During solar cycle 22–24, she computed the correlation coefficient between the monthly mean values of these two parameters in order to examine the relationship between the SSN and CRI. At solar cycle 23, her SSN value peaked in September 2001 at 150.7 and fell to 0.9 in October 2007. With a 23-month SSN of 81.8, solar cycle 24 reached its zenith in April 2014, whereas cycle 23 peaking in September 2001, started in May 1996. In contrast to other recent solar cycles, this maximum was much lower. R. Bhattacharya and M. Roy examined the relationship between Cosmic Ray Intensity (CRI) and solar activity across different phases of solar cycles. Their study suggested that, for long-term modulation of CRI, both the sunspot number (SSN) and the F10.7 solar radio flux (SFI) are reliable indicators of solar activity. They also observed that the correlation coefficients between CRI and these indices vary not only from one solar cycle to another but also between the ascending and descending phases within each cycle. In general, they found that during odd-numbered solar cycles, the correlation is stronger in the ascending phase compared to the descending phase. In contrast, for even-numbered cycles, the descending phase shows a stronger correlation than the ascending phase. The reported correlation coefficients between CRI and SSN/SFI are as follows:

Solar Cycle 22- 0.98 (SSN) and 1 (SFI) for both ascending and descending phases. Solar Cycle 23- 0.98 (SSN) and 1.00 (SFI) in the ascending phase, and 0.97 (SSN) and 1.00 (SFI) in the descending phase. Solar Cycle 24- 0.99 (SSN) and 1.00 (SFI) during the ascending phase.

Our findings are in strong agreement with these results, further validating the observed phase-dependent correlation between CRI and solar activity indicators.

IV. CONCLUSION

These results strongly confirm the inverse correlation between cosmic ray intensity (CRI) and solar activity indices (SSN, SFI) during both the rising and declining phases of the solar cycle. The behavior is symmetrical across the cycle: CRI is maximum during solar minima and minimum during solar maxima. This relationship is vital in understanding space weather effects and Earth's atmospheric interactions with galactic cosmic rays.

These findings are consistent with theoretical expectations in solar-terrestrial physics and useful for modeling space weather effects. Interestingly, the cross-correlation patterns observed during the ascending phase deviate from earlier findings, implying possible variability in the behavior of solar and interplanetary parameters during different solar cycles or sub-phases. These results emphasize the dynamic nature of solar modulation of cosmic rays and highlight the importance of phase-wise analysis in understanding the complex interactions between solar and cosmic phenomena.

These results reinforce the understanding that cosmic ray modulation is largely governed by solar activity, especially solar flux, which reflects the output of solar electromagnetic radiation.

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