

Study of Correlation between Sunspot Number and Galactic Cosmic-Ray Intensity during Solar Cycle 23, 24 and ascending phase of Solar Cycle 25

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Abstract: Galactic cosmic rays (GCRs) reaching the Earth's atmosphere are strongly modulated by solar activity. Cosmic rays intensity measured through ground based neutron monitor have a strong correlation with the sunspots number (SSN) on the solar photosphere. This study investigates the relationship between sunspot number (SSN) and cosmic-ray intensity (CRI) during Solar Cycle 23 (1996 –2008), 24(2009 –2020) and current phase of Solar Cycle 25 (2021 – August 2026). The analysis is based on the supplied time-series plot containing sunspot count and corrected neutron-monitor count rates to examine long-term variations, the strength of their correlation, and the temporal lag between the two parameters. The results reveal a clear anti-phase relationship between SSN and CRI. Sunspot numbers generally increase from solar minimum toward solar maximum and subsequently decline, whereas cosmic-ray intensity exhibits an approximately opposite pattern, decreasing during periods of enhanced solar activity and increasing during relatively quiet solar conditions. Cross-correlation analysis yields an optimal correlation coefficient of -0.8919 at a time lag of 10 months, indicating a strong inverse association between solar activity and cosmic-ray intensity at the selected lag. This temporal offset suggests that the relationship between solar activity and cosmic-ray modulation may involve delayed responses to evolving heliospheric conditions. The findings demonstrate the significance of long-term neutron-monitor observations and time-lag analysis in understanding the modulation of galactic cosmic rays across multiple solar cycles.

Keywords: Sunspot number, cosmic ray intensity, Solar Cycle 23–25, solar modulation, neutron monitor, cross-correlation analysis, time lag.

I. INTRODUCTION

The Sun is the foremost variable source of electromagnetic radiation and charged-particle activity throughout the heliosphere. The solar cycle is one of the most fundamental periodic phenomena observed in astrophysics characterized by an approximately 11-year variation in solar magnetic activity that regulates the occurrence of sunspots, coronal mass ejections (CMEs), solar energetic particles, solar flares, and variations in solar irradiance. The solar cycle is generated by the solar dynamo, a mechanism involving the interplay of plasma motion, differential rotation and magnetic fields in the interior and convection zone of the Sun. Since the discovery of the sunspot cycle by Samuel Heinrich Schwabe in 1844, extensive observational and theoretical studies have enriched understanding of solar variability. [1] Modern space missions and ground-based observatories provide continuous observations of the Sun across multiple wavelengths, enabling detailed investigations of solar magnetic activity and improvements in space-weather monitoring. Solar activity can significantly influence the heliosphere, near-Earth space environment, satellite operations, radio communication, power transmission systems, navigation technologies.



Sunspots are dark regions observed on the solar photosphere that appear darker than their surroundings because their temperatures are lower than those of the surrounding photosphere. They are associated with intense magnetic fields that inhibit the transport of heat to the solar surface [1, 2]. The sunspot number (SSN) is a well-known index of solar activity. It generally increases during the ascending phase of the solar cycle, reaches a maximum and decreases during the declining phase. Although SSN is a useful indicator of solar activity, it does not fully represent all aspects of solar and heliospheric conditions [1, 8].

Cosmic rays consist of high-energy relativistic charged particles, including protons, α -particles, and heavier nuclei. [3] Cosmic rays (CRs) travel through space at nearly the speed of light. They originate from various sources, including the Sun, distant supernovae, and other energetic astrophysical phenomena. Cosmic rays are categorized according to their energy levels, ranging from a few MeV to more than 10^{20} eV. When cosmic rays enter Earth's atmosphere, they interact with atmospheric nuclei and produce cascades of secondary particles that can be detected by ground-based instruments, including neutron monitors.[4, 5]

Before reaching the Earth's atmosphere, these particles propagate through the heliosphere and interact with the solar magnetic field and solar wind. Consequently, as a result, the intensity of cosmic rays observed near Earth fluctuates in accordance with solar activity. The dominant long-term variation in cosmic-ray intensity has an approximately 11-year periodicity and is generally anti-correlated with solar activity.

Cosmic-ray intensity exhibits both long-term and short-term variations. Long-term variations include, for example, the approximately 11-year solar-cycle modulation and the effect of the approximately 22-year solar magnetic polarity cycle. Forbush decreases are relatively rapid reductions in cosmic-ray intensity that are typically associated with interplanetary disturbances and coronal mass ejections. Short-term variations include Forbush decreases. Investigating these variations provides information about the response of galactic cosmic rays to changing heliospheric conditions [3, 4, 5, 6, 7]. Previous studies have shown that the relationship between cosmic-ray intensity and solar activity can differ among solar cycles. Time-lag analysis and hysteresis plots are therefore useful for investigating the temporal response of cosmic rays to solar activity and for comparing the behaviour of different cycles [2, 4, 9].

The study considered the correlation between sunspot number and cosmic-ray intensity, as measured by the corrected neutron-monitor count rates, in Solar Cycles 23 and 24 and the ascending phase of Solar Cycle 25. The analysis focuses on temporal variations in the correlation between SSN and GCR intensity, possible time delays in their relationship, and hysteresis behaviour over the selected study intervals. The aim of the study is to determine whether the strength and temporal characteristics of the relationship SSN-GCR are different for the three intervals. This comparison may help improve the observational understanding of solar modulation and the role of changing heliospheric conditions in governing cosmic-ray intensity near Earth. The interpretation of Solar Cycle 25 is limited to the period covered in the dataset and the choice of the dates and the identification of this period as the ascending phase should be clearly stated in the Methods section.

II. DATA AND METHODOLOGY

Neutron monitors detect secondary particles generated when primary cosmic rays interact with nuclei in the Earth's atmosphere and provide continuous observations suitable for studying long-term cosmic-ray modulation. Pressure-corrected hourly cosmic-ray count-rate data were taken from the Oulu neutron monitor (cutoff rigidity 0.8 GV; latitude $\approx 65.1^\circ$ N) operated by Sodankyla Geophysical Observatory of the University of Oulu Finland.

Sunspots are relatively dark regions of the photosphere associated with strong magnetic fields. The total sunspot number is one of the longest-running quantitative indicators of solar activity. We have taken data of solar parameter SSN from the World Data Center SILSO at the Royal Observatory of Belgium Brussels which provides daily, monthly, smoothed and yearly sunspot-number series. The current official series is Version 2.0. [8]



III. RESULTS AND DISCUSSION

We have analysed data obtained from Oulu neutron monitor station for the period from 1996 to August 2026, covering Solar Cycle 23, Solar Cycle 24, and the selected ascending and early declining interval of Solar Cycle 25. The temporal variations in sunspot number (SSN) and corrected neutron-monitor count rate were examined, followed by time-lagged cross-correlation analysis to determine the lag corresponding to the strongest negative Pearson correlation.

Solar Cycle 23

Figure 1 illustrates the temporal relationship between sunspot activity and corrected neutron-monitor count rate during approximately 1996–2009, corresponding to Solar Cycle 23. A pronounced inverse variation is evident. The corrected count rate was relatively high during the solar minimum around 1996–1997, decreased progressively during the rising phase of solar activity, and reached relatively low values near the solar maximum around 2000–2002. Subsequently, as sunspot activity declined, the corrected count rate progressively recovered and reached relatively high levels toward the end of the investigated interval nearly 2008.

For Solar Cycle 23, the strong negative cross-correlation coefficient, (r_{opt}), is determined - 0.8882. Figure 2 shows the time-lagged cross-correlation between sunspot number and corrected cosmic-ray count rate for the period 1996–2009. For this period optimal time lag is found to be 14 months. According to the lag convention used in the figure, a positive lag indicates that the cosmic-ray response follows the sunspot variation. The result indicates a strong inverse association between the two parameters, consistent with the expected solar modulation of galactic cosmic rays.

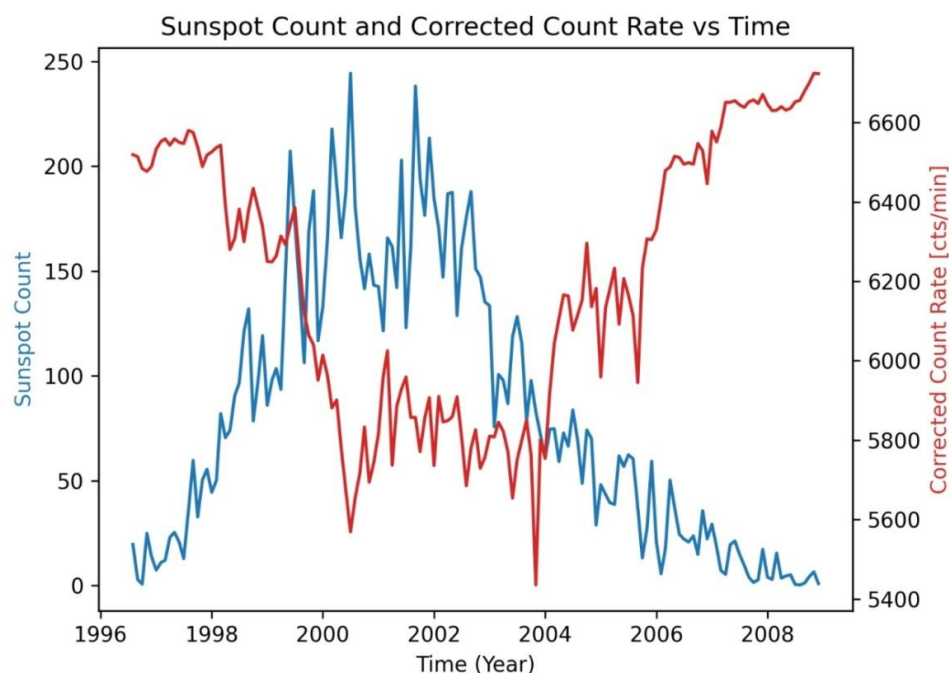


Figure 1. Temporal variation of sunspot number and pressure corrected neutron-monitor count rate during Solar Cycle 23.



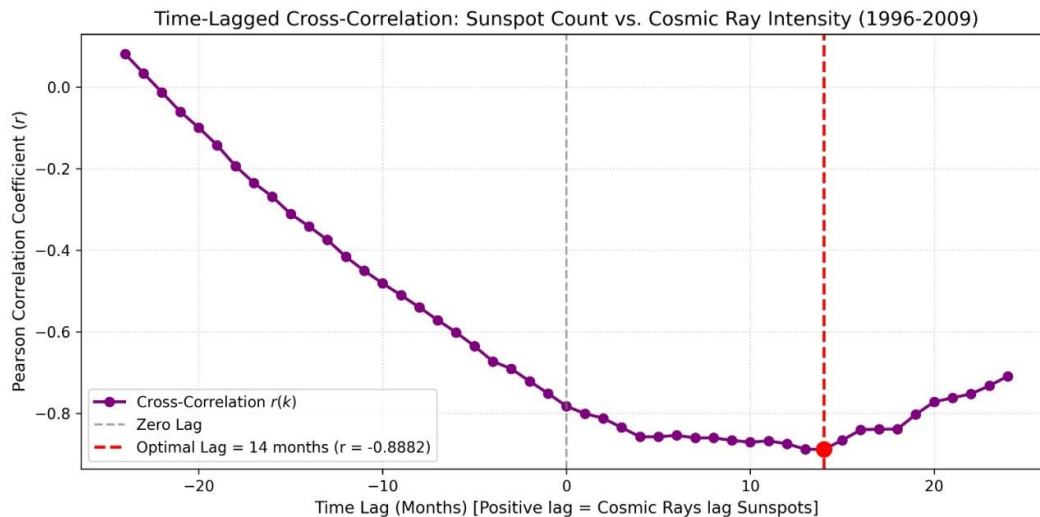


Figure 2. Time-lagged cross-correlation between sunspot number and pressure corrected cosmic-ray intensity during Solar Cycle 23. The red dashed line indicates the lag corresponding to the strongest negative correlation ($r = -0.8882$) at 14 months.

Solar Cycle 24

Figure 3 demonstrate the sequential relationship between sunspot activity and corrected detector count rate during approximately 2009–2020, corresponding to Solar Cycle 24. In this cycle initially corrected count rate remained relatively elevated during the solar minimum phase occurring around 2009–2010, declined steadily throughout the ascending phase of solar activity, and attained relatively low values near the solar maximum occurring around 2015. Following the subsequent decrease in sunspot activity, the adjusted count rate gradually increased and attained its highest levels near the end of the cycle nearly 2020.

For this Solar Cycle Peak Anti-Correlation (r_{opt}) is determined to be -0.9082 . Figure 4 present a graphical representation of the Time- Lagged Cross- Correlation analysis between Sunspot count and cosmic ray intensity for the period spanning 2009-2020. For this temporal interval, optimal time lag is found to be only 4 months. The magnitude of the strongest negative correlation is greater than that obtained for Solar Cycle 23, while the estimated lag is considerably shorter. This difference suggests that the observed temporal relationship between solar activity and cosmic-ray intensity was not identical in the two cycles.



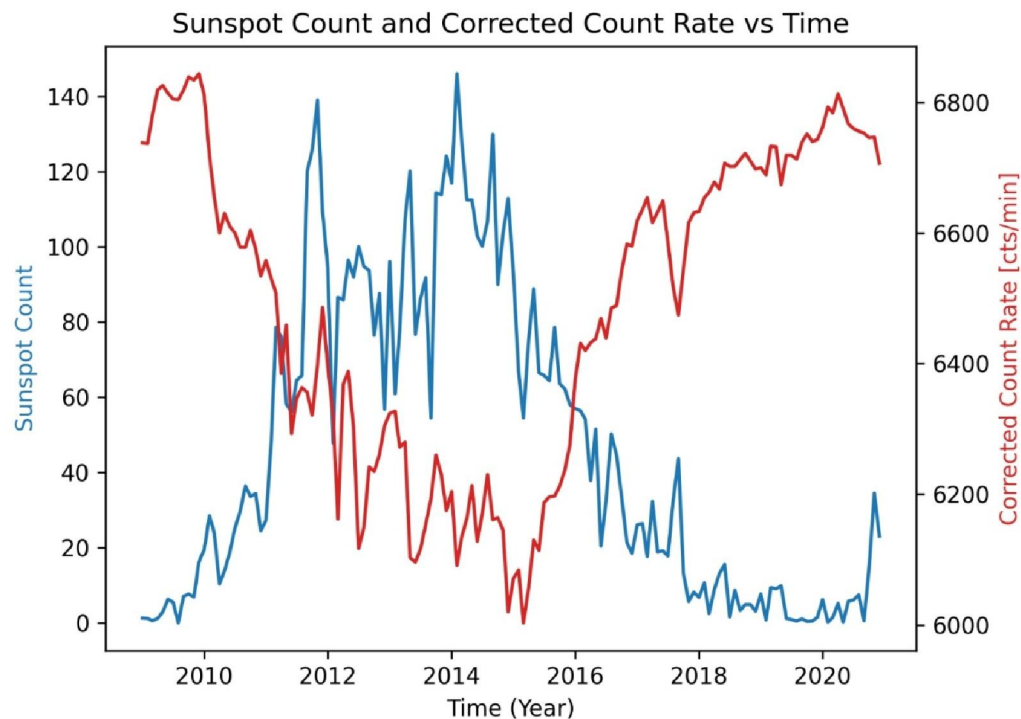


Figure 3. Temporal variation of sunspot number and corrected neutron-monitor count rate during Solar Cycle 24.

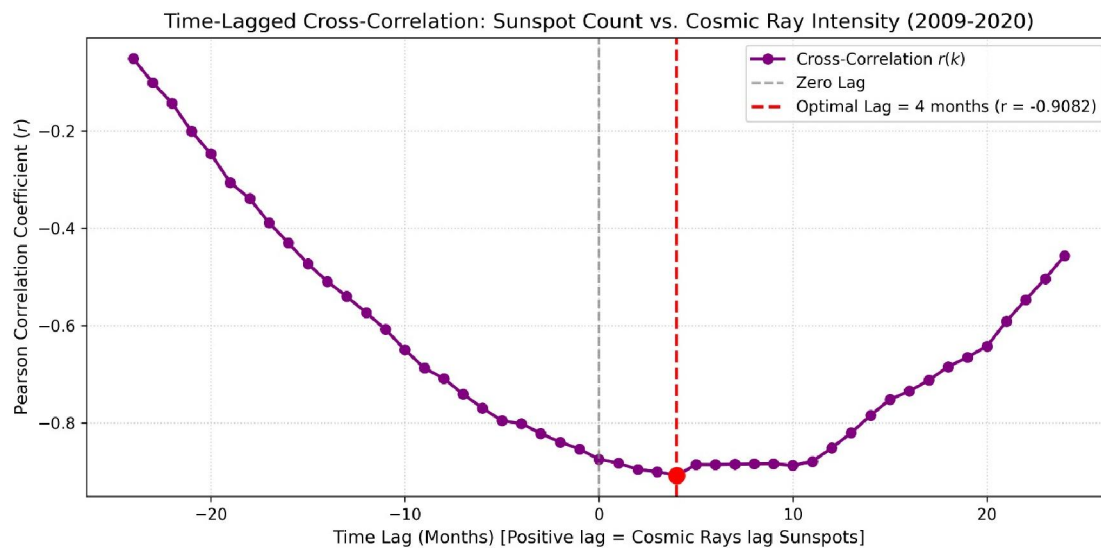


Figure 4. Time-lagged cross-correlation between sunspot number and corrected cosmic-ray intensity during Solar Cycle 24. The red dashed line indicates the lag corresponding to the strongest negative correlation ($r = -0.9082$) at 4 months.



Solar Cycle 25

Figure 5 shows the temporal association between sunspot activity and corrected detector count rate spanning throughout the period approximately 2021–August 2026. The interval includes the rise toward the maximum of Solar Cycle 25 and the subsequent evolution of solar activity. During the Initial phase of this Solar cycle corrected count rate was relatively high during the solar minimum around 2020, declined progressively during the rising phase of solar activity, and attained relatively low values near the solar maximum around 2026. As sunspot activity declined, the corrected count rate progressively commenced to recover.

For the selected Solar Cycle 25 interval, Peak Anti-Correlation (r_{opt}) is determined -0.8805 . Figure 6 presents a graphical representation of the Time- Lagged Cross- Correlation: Sunspot count v/s cosmic ray intensity for the ascending phase of Solar Cycle 25. For this period optimal time lag is found to be nearly 11 months.

The result indicates a strong inverse relationship, with an estimated lag longer than that obtained for Solar Cycle 24 but shorter than that obtained for Solar Cycle 23. Since the study interval does not represent a complete solar cycle, this lag should be interpreted as a result for the selected interval rather than as a definitive lag for the entire cycle.

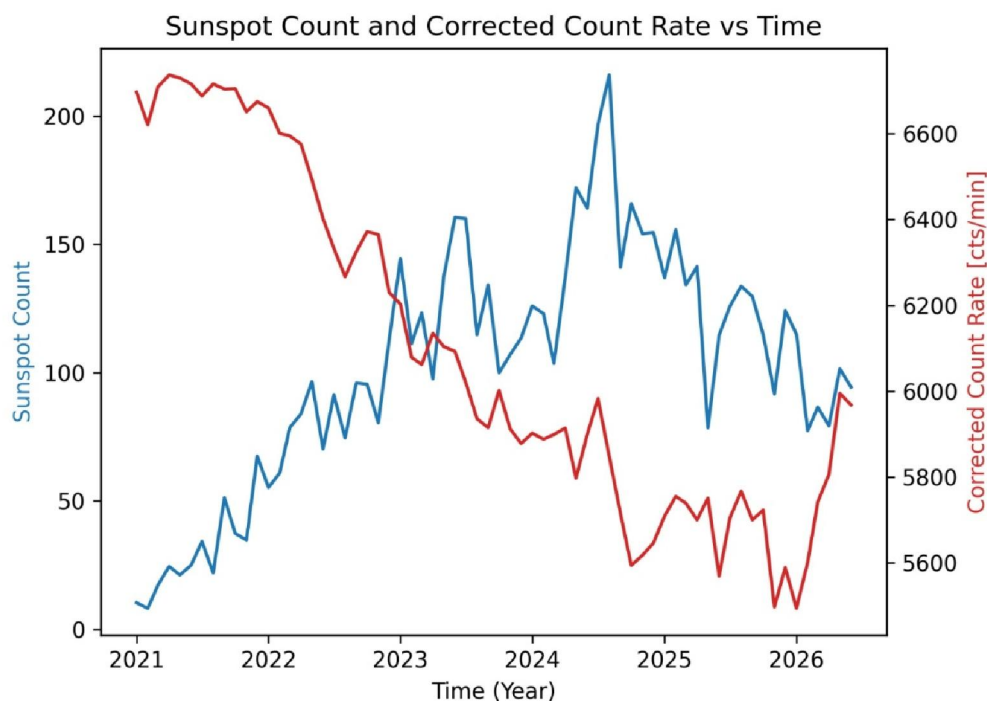


Figure 5. Temporal variation of sunspot number and corrected neutron-monitor count rate during the selected interval of Solar Cycle 25.



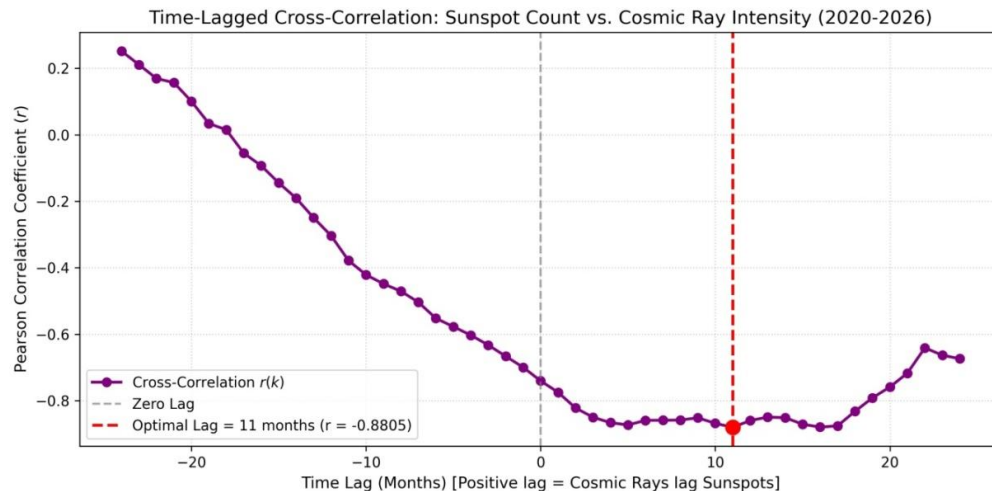


Figure 6. Time-lagged cross-correlation between sunspot number and corrected cosmic-ray intensity during the selected interval of Solar Cycle 25. The red dashed line indicates the lag corresponding to the strongest negative correlation ($r = -0.8805$) at 11 months.

Long-term variation during 1996–August 2026

Figure 7 shows the long-term temporal variations in sunspot number and corrected neutron-monitor count rate over the full study period, covering Solar Cycles 23 and 24 and the selected interval of Solar Cycle 25. A clear inverse relationship is apparent over much of the record: the corrected count rate generally decreases as solar activity increases and recovers as solar activity declines. This behaviour is consistent with the long-term modulation of galactic cosmic rays by changing heliospheric conditions.

For the full study period, the strongest negative cross-correlation coefficient was ($r_{\text{opt}} = -0.8919$), at an optimal lag of 10 months. Figure 8 shows the corresponding time-lagged cross-correlation. This result indicates a strong overall inverse association between sunspot number and corrected cosmic-ray count rate, with an estimated lag of approximately 10 months. [9] The full-period estimate should not be interpreted as a single physical response time applicable to all three cycles, because the individual cycles exhibit different optimal lags.

Mahendra Singh et al. [10] also reported time lags of approximately 2–10 months in the long-term variation of cosmic-ray intensity with solar activity. The present estimates are broadly comparable with that reported range for Solar Cycle 24 (4 months) and the full study period (10 months), whereas the estimates for Solar Cycle 23 (14 months) and the selected Solar Cycle 25 interval (11 months) are longer. Such differences may reflect variations in heliospheric conditions, the selected study intervals, and the methods used to estimate the lag.

Overall, the analysis indicates that the relationship between sunspot number and corrected cosmic-ray count rate is strongly negative, but the optimal lag varies among the investigated intervals. This suggests that the relationship is not perfectly instantaneous and that the observed modulation may be influenced by changes in solar-wind conditions, heliospheric magnetic-field structure, coronal mass ejections, cosmic-ray diffusion, particle drifts, and the 22-year solar magnetic-polarity cycle. These mechanisms provide a physical context for the observed variations; however, the correlation and lag estimate alone cannot establish the contribution of any individual mechanism.



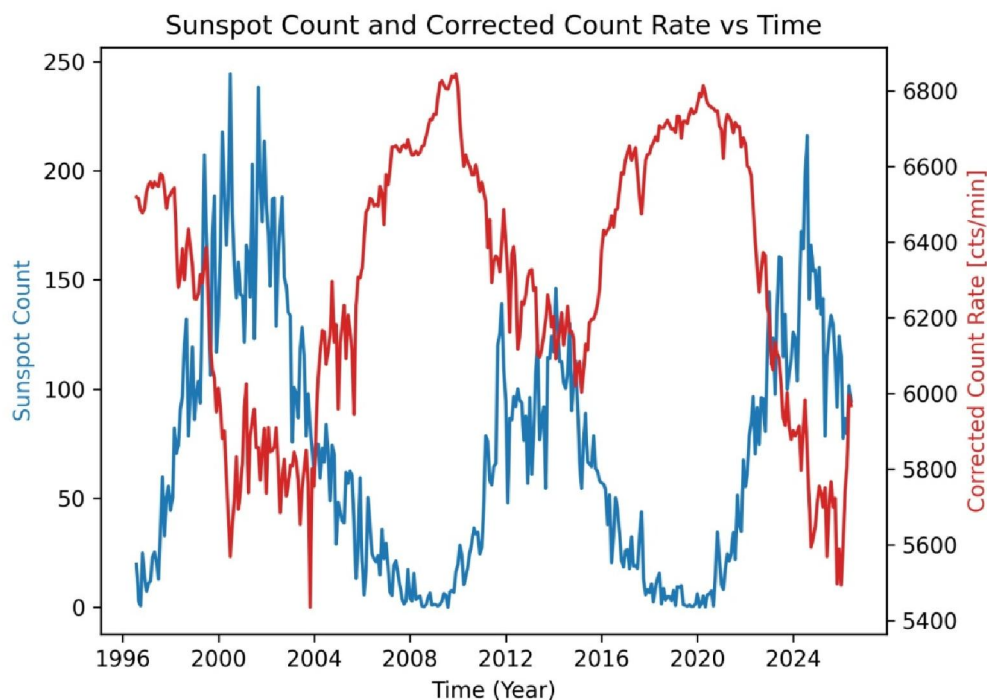


Figure 7. Long-term temporal variation of sunspot number and corrected neutron-monitor count rate from 1996 to August 2026, covering Solar Cycles 23 and 24 and the selected interval of Solar Cycle 25.

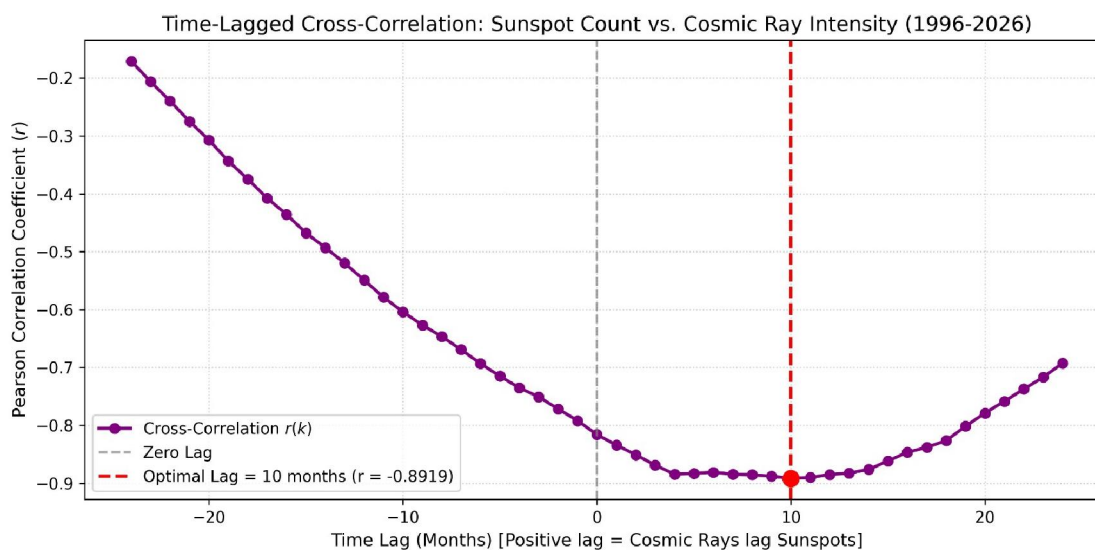


Figure 8. Time-lagged cross-correlation between sunspot number and pressure corrected cosmic-ray intensity for the full study period. The red dashed line indicates the lag corresponding to the strongest negative correlation ($r=-0.8919$) at 10 months.



The analysis also indicates that the relationship is not perfectly instantaneous or linear, suggesting the importance of heliospheric magnetic-field structure, solar-wind conditions, coronal mass ejections [11], cosmic-ray diffusion, particle drifts, and the 22-year magnetic polarity cycle.

From figure 7 it is clear that the sunspot number as well as cosmic ray intensity is different for odd and even cycles. Variations in SSN and cosmic ray intensity for odd solar cycles are longer than even solar cycles. The momentary time lag between cosmic ray intensity and sunspot activity for solar cycle 24 (even cycle) is only 4 months while for solar cycle 23 (odd cycle) is 14 months and for solar cycle 23 and for solar cycle 25 (upto August 2026, odd cycle) is 11. This reflects the difference in the cosmic ray modulation conditions for odd and even cycles and is probably associated with the influence of drift effects. [12] There are also observations that suggest that the time lag is not same, when studied during different polarity states of the heliosphere. [13]

IV. CONCLUSION

The ongoing study indicates a pronounced inverse association between sunspot counts and the neutron-monitor count rate across Solar Cycles 23 and 24, including the designated segment of Solar Cycle 25. The strongest negative correlation coefficients were -0.8882, -0.9082 and -0.8805, respectively, with optimal time lags of 14, 4 and 11 months. The correlation coefficient is -0.8919 for the entire study period (from 1996 to August 2026) with an appropriate lag of 10 months. These findings suggest that the correlation between solar activity and galactic cosmic-ray intensity is not immediate, and the assessed time delay differs across the examined periods. The noted variations could indicate alterations in heliospheric conditions and solar modulation mechanisms. Additional analysis is necessary to assess the statistical uncertainty of the lag estimates, and to determine the physical mechanisms responsible for the differences between cycles. It was also found variations in SSN and cosmic ray intensity for odd solar cycles are longer than even solar cycles. This investigation contributes to the understanding of solar–heliospheric interactions and their implications for cosmic-ray variability and space-weather research.

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REFERENCES

1. Singh, A., & Patel, K. (2021). Statistical study of solar activity parameters of Solar Cycle 24. *Journal of Scientific Research*, 65(1), 197–200. <https://doi.org/10.37398/JSR.2021.650125>
2. Persai, S. K., Jothe, M. K., Singh, M., & Shrivastava, P. K. (2015). Correlative study of cosmic ray intensity and sunspot number for the period of Solar Cycles 23 and ascending phase of 24. *International Journal of Science and Research*, 4(12), 2239–2240. <https://www.ijsr.net/archive/v4i12/NOV152547.pdf>
3. Abunina, M., Mavromichalaki, H., Shlyk, N., Abunin, A., Gerontidou, M., Belov, A., Belov, S., Yanke, V., & Triantou, A. (2024). Precursory signs of large Forbush decrease in relation to cosmic rays equatorial anisotropy variation. *Atmosphere*, 15(7), Article 742. <https://doi.org/10.3390/atmos15070742>
4. Onuchukwu, C. C., Dio, E., & Leghara, E. (2024). A study of cosmic ray variability during a solar magnetic cycle (Solar Cycles 23 and 24). *Asian Basic and Applied Research Journal*, 6(1), 192–224. <https://doi.org/10.56557/abaarj/2024/v6i1153>
5. Chika, Onuchukwu C. and Dio E., A Study of Cosmic Ray Variability During A Solar Magnetic Cycle (Solar Cycles 23 And 24), (2024) , Research Square, DOI: <https://doi.org/10.21203/rs.3.rs-5178521/v1>
6. Kojima, H., Hayashi, Y., Hayashi, K., Ito, N., Kawakami, S., Matsuyama, T., Minamino, M., Nonaka, T., Okuda, T., Ogio, S., Oshima, A., Shimizu, N., Gupta, S. K., Iyer, A., Jangadeesan, P., Jain, A., Karthikeyan, S., Mohanty, P. K.,



- Nayak, P. K., Rao, B. S., Ravindran, K. C., Sivaprasad, K., Tanaka, H., & Shibata, S. (2007). The change in cosmic ray intensity variation with the solar wind velocity variation (using GRAPES-3 muon narrow-angle telescopes and Kiel neutron monitor). In Proceedings of the 30th International Cosmic Ray Conference (ICRC 2007).
7. Tiwari, C. M., Sharma, D., Tiwari, L., Saxena, A. K., & Tiwari, D. P. (2011). Study of anisotropic variation of cosmic rays intensity with solar activity. *Natural Science*, 3(2), 101–103. <https://doi.org/10.4236/ns.2011.32014>
8. World Data Center SILSO, Royal Observatory of Belgium. (n.d.). Sunspot data. <https://doi.org/10.24414/qnza-ac80>
9. Sergey A. Koldobskiy, Riikka Kähkönen, Bernhard Hofer, Natalie A. Krivova, Gennady A. Kovaltsov, Ilya G. Usoskin; Time Lag Between Cosmic-Ray and Solar Variability: Sunspot Numbers and Open Solar Magnetic Flux; *Solar Physics* (2022) 297:38; <https://doi.org/10.1007/s11207-022-01970-1>
10. Singh, M., Nigam, S. K., & Shrivastava, P. K. (1999). The aspect of time lag in long-term cosmic ray intensity variation with solar activity. *Indian Journal of Radio & Space Physics*, 28, 211–215.
11. Persai, S. K., Jothe, M. K., & Singh, M., Study Of Halo CME as a Indicator of Intense Geomagnetic Storm; *International Journal of Research and Analytical Reviews*; May 2019, Volume 6, Issue 2 pp. 730-733
12. Usoskin I. G., K. Mursula, Kananen H., & Kovaltsov G.A.; Dependence of Cosmic Rays on Solar Activity for Odd and Even Solar Cycles; *Adv. Space Res* 2001 Vol. 27, No. 3, pp. 571-576
13. Singh M., Badruddin B., Asiri H., Hysteresis, Time Lag, and Relation between Solar Activity and Cosmic Rays During Solar Cycle 24; *New Astronomy*, vol. 89, Art. no. 101652, 2021, doi: 10.1016/j.newast.2021.101652.

