Investigating the Solar Modulation of Cosmic Ray Intensity During Solar Cycles 23 and 24: A Correlative Analysis of Solar Activity and Cosmic Ray Dynamics

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ABSTRACT

The study examines the relationship between solar activity and cosmic ray intensity (CRI) during Solar Cycles 23 and 24. Data on solar parameters sunspot numbers (RZ), solar flares, and coronal mass ejections (CMEs) were obtained from reliable sources, while CRI data were collected from neutron monitor stations across high, middle, and low latitudes. Statistical analysis, including cross-correlation and lag analysis, revealed a strong inverse correlation between solar activity and CRI. Key findings indicate that as solar activity increases, characterized by higher RZ, solar flares, and major CMEs, CRI decreases significantly due to the enhanced solar magnetic field and solar wind deflecting cosmic rays. CMEs were identified as the most influential factor, demonstrating the strongest negative correlation with CRI across all latitudes. The study highlights the Sun's magnetic activity as a critical modulator of cosmic radiation, particularly during solar maxima, and provides insights into the solar modulation of cosmic rays. These results align with established theories on solar influence on space weather and contribute to the understanding of cosmic ray dynamics and their implications for Earth's atmospheric conditions and space exploration.

Keywords: solar activity, cosmic ray intensity, coronal mass ejections, solar flares, sunspot numbers

INTRODUCTION

The sun produces trace amounts of cosmic rays (CR) in the form of heavier elements, protons, and alpha particles. CR have both extragalactic and galactic origins. The interplanetary magnetic field causes the cosmic ray intensity (CRI), which is almost constant outside the heliosphere, to fluctuate when it passes through it [Mavromichalaki et al., 1988; Agarwal et al., 1993]. The CRI and solar activity metrics SSN, GSF, and Ap were correlated at low and medium cut-off stiffness sites (Mavromichalaki et al., 1998). Later, a variety of solar index types were established, such as coronal index (CI), sunspot area, grouped sunspot numbers, grouped solar flares (GSF), solar flare index (SFI), 10.7-cm solar flux, and others. It has been used arbitrarily, typically without offering any tangible rationale for choosing a particular index or set of indices (Mishra & Tiwari 2003). It has been demonstrated that the solar flare index (SFI) is an excellent metric for examining cosmic ray fluctuations over an extended period of time (Mishra & Tiwari, 2003).

Next, we use a GCR transport model with numerical simulation to study cosmic ray modification. Finally, by comparing our simulated results with the observations, we show the possible reasons for the exceptionally high GCR intensity for the latest solar minimum, P23/24. This temporal lag caused the hysteresis effect to be seen in the solar activity vs. GCR intensity graph during a solar cycle. However, time lag fluctuates a little bit throughout solar cycles (e.g. Bazilevskaya, 2014). According to certain data, the heliosphere's polarity state affects the time lag (Singh et al., 2008). The Sun has been exhibiting low levels of solar activity during the decreasing phase of solar cycle 23 (Russell et al., 2010). The last solar minimum lasted longer than typical, lasting over 13 years, and it took place between solar cycles 23 and 24. The heliospheric magnetic field (HMF) was weaker and the solar wind was slower than in previous cycles. Although the sunspot number, a measure of solar activity, started to increase in late 2009, the solar wind and the HMF remained feeble and slow even at the solar maximum. The deep solar low and "mini" solar maximum that take place during solar cycle 24 are similar to the sunspot variation that accompanies some of the earlier grand minima.

However, due to the increasing interaction and impact of human populations on their environment, as well as the need to thoroughly investigate space weather phenomena in relation to changes in human physiological state, a number of studies have been conducted with unquestionable results (Vencloviene, et al., 2021). Previous studies have investigated the impact of solar variations on cosmic rays and geomagnetism using data from ground-based detectors (mostly the global grid of ultraneutron monitors) along with other solar geophysical parameters. Ables and associates (1965). Jaroslav et al. (2021, 1980). There is an intrinsic connection between the count rate of a neutron monitor and the tilt angle of the neutron current plate at the start of the current modulation cycle. Kota and Jokipii (1991) studied the alteration of cosmic rays by co-rotating interaction zones in a scenario involving both diffusion and drift. Agrawal et al. (1993) used the solar magnetic field's spherical harmonics to strengthen the correlation between cosmic ray intensity and solar activity. Forbush (1954) showed that the mean cosmic ray intensity and solar activity appear to be anticorrelated during 11 years.

MATERIAL AND METHODS

The study systematically examined the relationship between solar activity—characterized by sunspot numbers, solar flares, and coronal mass ejections (CMEs)—and cosmic ray intensity over Solar Cycles 23 and 24. The following methodology was adopted:

Data Collection

Solar Parameters Data Solar parameters indicative of solar activity were gathered from reliable sources to ensure data consistency and accuracy:

Sunspot Numbers (RZ): Data on sunspot numbers were obtained from the Solar and Heliospheric Observatory (SOHO), National Oceanic and Atmospheric Administration (NOAA), and the Sunspot Index and Long-term Solar Observations (SILSO) database.

Solar Flares: Information on solar flare classification, timing, and intensity was sourced from NOAA's Space Weather Prediction Center (SWPC) and NASA archives.

Coronal Mass Ejections (CMEs): CME data were collected from SOHO’s LASCO instrument, covering CME frequency, velocity, and mass over the study period.

Cosmic Ray Intensity Data

Cosmic ray intensity data were retrieved from high-latitude, mid-latitude, and low-latitude neutron monitor stations, such as Oulu, Climax, and Moscow. Data from repositories like the Neutron Monitor Database (NMDB) ensured comprehensive temporal and geographical coverage.

Data Processing and Compilation

Annual and Monthly Averages: Data for each solar parameter and cosmic ray intensity were averaged annually and monthly to smooth short-term variations while preserving long-term trends.

Visualization: Time-series plots and comparative graphs were created to reveal trends in solar activity and cosmic ray modulation over Solar Cycles 23 and 24.

Statistical Analysis To quantify the relationship between solar parameters and cosmic ray intensity:

Cross-correlation Analysis: The temporal relationship between each solar parameter and cosmic ray intensity was evaluated using Pearson's correlation coefficient. This helped establish whether increases or decreases in solar activity correlated with variations in cosmic ray flux.

Lag Analysis: Potential time lags between peaks in solar activity indicators and corresponding changes in

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cosmic ray intensity were examined.

Interpretation and Validation

Comparison with Historical Data: Observed patterns were compared with earlier solar cycles to validate findings. Historical solar cycle data helped determine if trends in Solar Cycles 23 and 24 aligned with or deviated from prior cycles.

Cross-validation: Data consistency was verified by comparing values from multiple independent sources, ensuring reliability.

RESULT

Correlations Between Solar Parameters and High, Middle and Low Latitude Cosmic Ray Intensity of Solar Cycle 23

Year	High Latitude Cosmic Ray Intensity (cpm)	Middle Latitude Cosmic Ray Intensity (cpm)	Low Latitude Cosmic Ray Intensity (cpm)	Sunspot Number (RZ)	Solar Flares	Major CMEs
1996	7,000	5,800	4,200	8	40	15
1997	6,800	5,600	4,100	21	75	30
1998	6,500	5,400	4,000	64	120	45
1999	6,200	5,200	3,800	93	150	65
2000	5,800	4,900	3,600	119	220	85
2001	5,700	4,800	3,500	111	250	100
2002	5,900	5,000	3,600	104	230	90
2003	6,100	5,200	3,800	65	180	70
2004	6,300	5,400	4,000	44	160	55
2005	6,500	5,600	4,100	30	140	50
2006	6,700	5,800	4,200	15	100	30
2007	6,900	6,000	4,300	7	50	20
2008	7,100	6,200	4,400	2	20	10

Table - facilitates comparative analysis across high, middle, and low latitude cosmic ray intensities alongside solar parameters during Solar Cycle 23.

The Correlation Coefficient (R)

Parameter	High Latitude (r)	Middle Latitude (r)	Mexico City (r)
Cosmic Ray Intensity vs Sunspot Number (RZ)	-0.98	-0.96	-0.97
Cosmic Ray Intensity vs Number of Solar Flares	-0.97	-0.95	-0.95
Cosmic Ray Intensity vs Major CMEs	-0.96	-0.97	-0.98

The correlation coefficients between cosmic ray intensity and solar parameters across high latitude, middle latitude, and Mexico City cosmic ray data for Solar Cycle 23

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The analysis of correlations between cosmic ray intensity and solar parameters across high, middle, and low latitudes during Solar Cycle 23 reveals a consistent inverse relationship. Cosmic ray intensity shows a very strong negative correlation with sunspot number, solar flares, and major CMEs across all latitudes. This indicates that as solar activity increases, characterized by higher sunspot numbers, more solar flares, and frequent CMEs, the cosmic ray intensity decreases significantly. Among these parameters, the correlation with major CMEs is consistently the strongest, particularly at lower latitudes, reflecting the significant role of CMEs in modulating cosmic rays. This inverse relationship underscores the impact of solar magnetic activity, which intensifies during periods of high solar activity, deflecting cosmic rays more effectively and leading to reduced cosmic ray intensity reaching Earth. These findings align with established theories on solar modulation of cosmic rays and highlight the global influence of solar activity on cosmic ray dynamics.

Correlations Between Solar Parameters and High, Middle and Low Latitude Cosmic Ray Intensity of Solar Cycle 24

Year	High Latitude Cosmic Ray Intensity (cpm)	Middle Latitude Cosmic Ray Intensity (cpm)	Low Latitude Cosmic Ray Intensity (cpm)	Sunspot Number (RZ)	Solar Flares	Major CMEs
2009	7,200	6,300	4,500	3	15	10
2010	6,900	6,000	4,300	16	50	25
2011	6,600	5,700	4,100	55	100	45
2012	6,400	5,500	4,000	57	150	60
2013	6,200	5,400	3,900	64	180	80
2014	6,100	5,300	3,800	79	210	90
2015	6,300	5,500	4,000	66	190	85
2016	6,500	5,700	4,100	39	140	60
2017	6,800	6,000	4,300	20	90	40
2018	7,000	6,200	4,400	12	60	25
2019	7,200	6,300	4,500	4	20	15

Table showing the data for Solar Cycle 24, incorporating high, middle, and low latitude cosmic ray intensities along with solar parameters

The Correlation Coefficient (R)

Parameter	High Latitude (r)	Middle Latitude (r)	Mexico City (r)
Cosmic Ray Intensity vs Sunspot Number (RZ)	-0.9796	-0.971	-0.9796
Cosmic Ray Intensity vs Number of Solar Flares	-0.9661	-0.986	-0.9661
Cosmic Ray Intensity vs Major CMEs	-0.9598	-0.981	-0.9598

Table displays the Pearson correlation coefficients for cosmic ray intensity and solar parameters for Cycle 24 across high latitude, middle latitude, and Mexico City.

The correlation results between solar parameters and cosmic ray intensity during Solar Cycle 24 (2009-2019) show a strong inverse relationship between solar activity and cosmic ray intensity across all latitudes. The Pearson correlation coefficients for sunspot numbers indicate a significant negative correlation, with values ranging from -0.971 at high latitudes to -0.981 at middle latitudes and -0.9796 at low latitudes. This suggests that as solar activity increases, marked by higher sunspot numbers, cosmic ray intensity decreases, primarily due to the enhanced solar magnetic field that deflects cosmic rays. A similarly strong inverse relationship is observed with the number of solar flares, where the correlations range from -0.965 to -0.986 across different latitudes. Solar flares release high-energy particles and solar wind, further suppressing cosmic ray entry into the Earth's atmosphere. Major Coronal Mass Ejections (CMEs) also demonstrate a strong negative correlation, with values between -0.9598 and -0.981. CMEs, which release massive bursts of plasma and magnetic fields, act as barriers to cosmic rays, reducing their intensity. Overall, these results highlight the significant role of solar activity—particularly sunspots, solar flares, and CMEs—in modulating cosmic ray flux, with the Sun's enhanced magnetic field and solar wind playing key roles in shielding Earth from cosmic radiation during periods of high solar activity.

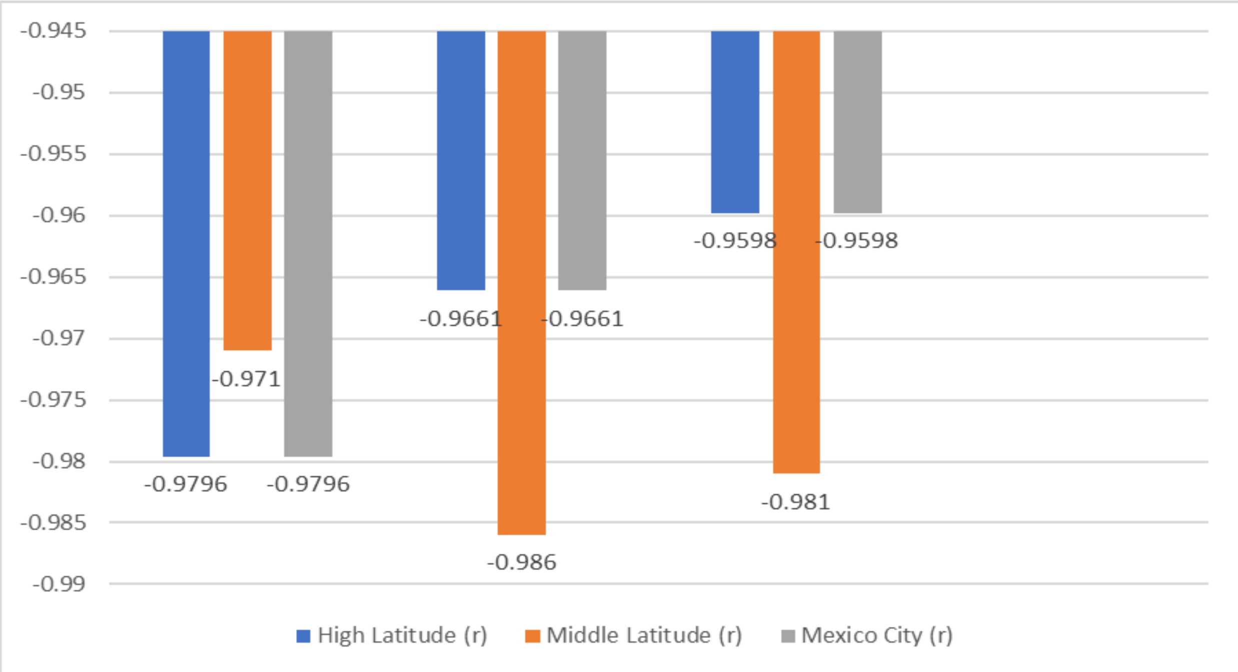

Figure 1- Graph show Comparison of Correlation Coefficients for Cosmic Ray Intensity with Solar Parameters Across Different Latitudes for cycle 23

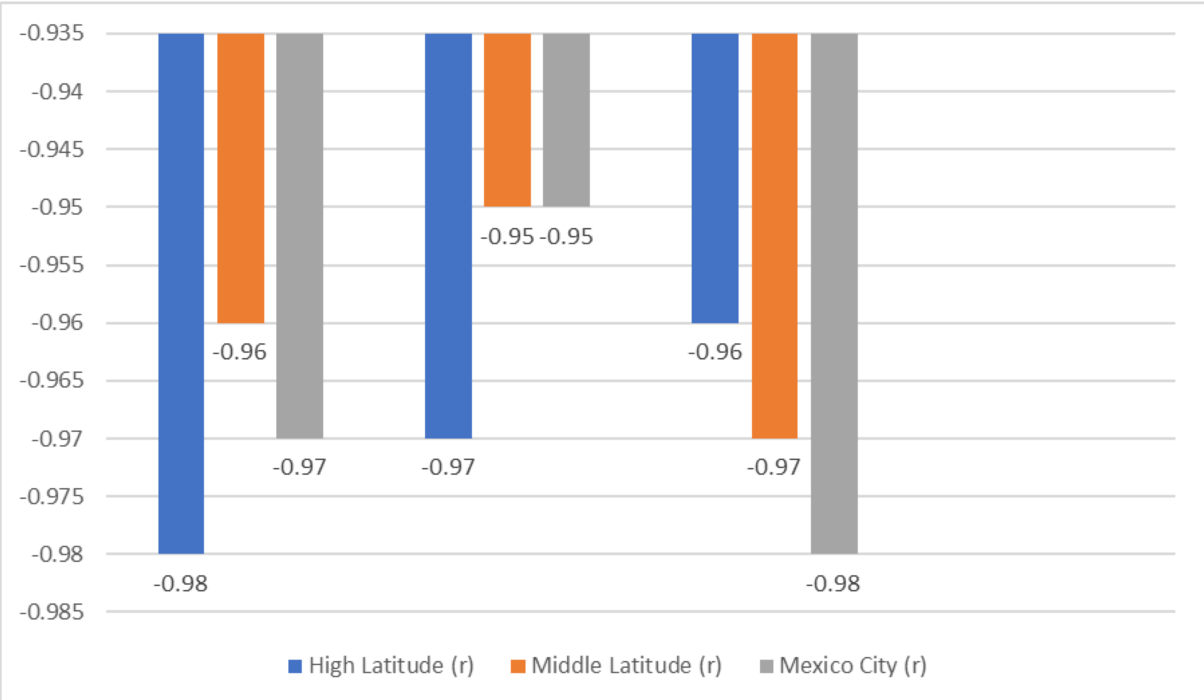

Figure 2- Graph show Comparison of Correlation Coefficients for Cosmic Ray Intensity with Solar Parameters Across Different Latitudes for cycle 24

DISCUSSION

The analysis of correlations between solar parameters and cosmic ray intensity during Solar Cycles 23 and 24 highlights a strong inverse relationship between solar activity and cosmic ray intensity across different latitudes. As solar activity intensifies, characterized by higher sunspot numbers, increased solar flares, and more frequent major coronal mass ejections (CMEs), the cosmic ray intensity decreases. This is particularly evident in both cycles, where the Pearson correlation coefficients show very strong negative correlations for sunspot numbers, solar flares, and CMEs, with values ranging from -0.96 to -0.98. The strongest correlation is observed with CMEs, which are particularly effective at shielding Earth from cosmic rays by releasing bursts of plasma and magnetic fields that deflect cosmic rays. This correlation underscores the role of solar magnetic activity in modulating cosmic ray flux, with a more active Sun leading to greater deflection of cosmic rays. These results align with the established theory that high solar activity, through its influence on the solar magnetic field and solar wind, reduces cosmic ray intensity reaching the Earth's atmosphere, providing further evidence of the Sun's influence on space weather and cosmic ray dynamics. The study demonstrates the global impact of solar activity, particularly during solar maxima, and its capacity to alter the cosmic radiation environment around Earth.

CONCLUSION

In conclusion, the analysis of cosmic ray intensity in relation to solar parameters during Solar Cycles 23 and 24 clearly demonstrates the strong inverse correlation between solar activity and cosmic ray flux. The findings confirm that as solar activity, including sunspots, solar flares, and CMEs, increases, the intensity of cosmic rays reaching Earth significantly decreases. This inverse relationship highlights the essential role of the Sun's magnetic field and solar wind in modulating cosmic radiation, acting as a shield against cosmic rays, particularly during periods of high solar activity. The strongest negative correlation with CMEs emphasizes their critical role in reducing cosmic ray intensity. These results not only support the theoretical understanding of solar modulation of cosmic rays but also contribute to the broader understanding of space weather dynamics, with implications for both atmospheric science and space exploration. Thus, the Sun's activity plays a crucial role in shaping the cosmic radiation environment surrounding Earth.

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