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Multiple Linear Regression Analysis of Galactic Cosmic Ray Modulation during Solar Cycle 24

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Abstract

Galactic cosmic ray modulation linked with solar activity, present study investigates the modulation of Galactic Cosmic Rays (GCRs) during Solar Cycle 24 by using monthly averaged pressure-corrected neutron monitor observations and selected solar and heliospheric parameters. The monthly averages of Sun Spot Numbers data for the duration of Solar Cycle 24 is analysis and the regression analysis was to quantify the individual and combined effects of the selected solar parameters on the observed variations in GCR intensity during Solar Cycle 24. The results demonstrate that Galactic Cosmic Ray intensity is strongly controlled by variations in solar activity throughout Solar Cycle 24. The highest GCR intensities occurred during the solar minimum, whereas the lowest intensities coincided with the solar maximum.

Keywords: Galactic Cosmic Ray, Modulation, Solar Cycle, Heliosphere, Intensity

1. Introduction

Galactic cosmic ray modulation in the heliosphere is anti-correlated with solar activity and has an 11-year cycle change and cosmic ray strength brought by 11-year cycle of any solar activity is known as cosmic ray modulation. As it is known that the maximum cosmic-ray intensity levels are reached during solar-minimum conditions in which the protons (89%), helium nuclei (10%), and around 1% other heavier elements produced the cosmic rays (CRs), these high energy charged particles comes from the outside the solar system. These charged particles are known as primary CRs, when they reach the top of the Earth's atmosphere, and secondary CRs are also known as air showers which are produced when CRs come with the contact of atmospheric constituents. The Earth is constantly bombarded these energetic particles, which play a significant role in solar-terrestrial connections. Ground-based neutron monitors have been tracking the cosmic ray flow for a decade, all the CRs data provide information of an integrated atmospheric energy flux. The energy spectra of cosmic rays are only directly accessible for low energies and sporadic balloon- or space-borne studies during the past few decades. Because various detectors are sensitive for different cosmic ray energies, it is conventional to utilize neutron monitor count rates (or cosmogenic isotope data) as a direct indicator of cosmic ray intensity. The differential energy spectrum of cosmic rays and its temporal fluctuations are essential for study extra terrestrial effects and several other cosmic reasons. As a result, solar activity may be described in terms of its effect on the heliospheric environment and cosmic ray modulation. To better understand the idiosyncrasies of the odd–even solar cycles, it is crucial to study the influence of the curvature of the

interplanetary magnetic field (IMF) on the propagation of cosmic rays. Galactic cosmic ray modulation throughout the 11-year solar modulation cycle is mostly determined by the polarity of the solar magnetic field. The gradient and curvature drift that cosmic rays encounter as they travel through the heliosphere in the direction of Earth are greatly influenced by large-scale variations in the polarity and structure of the solar magnetic field. These changes also have an impact on the heliospheric current sheet's tilt angle, which controls charged particle transit routes. High-energy cosmic rays interact with atmospheric nuclei when they penetrate Earth's atmosphere, creating secondary particle cascades is shown in the figure 1. Because solar magnetic activity, heliospheric conditions, and cosmic ray modulation are closely related, fluctuations in the interplanetary magnetic field cause changes in cosmic ray strength measured close to Earth.

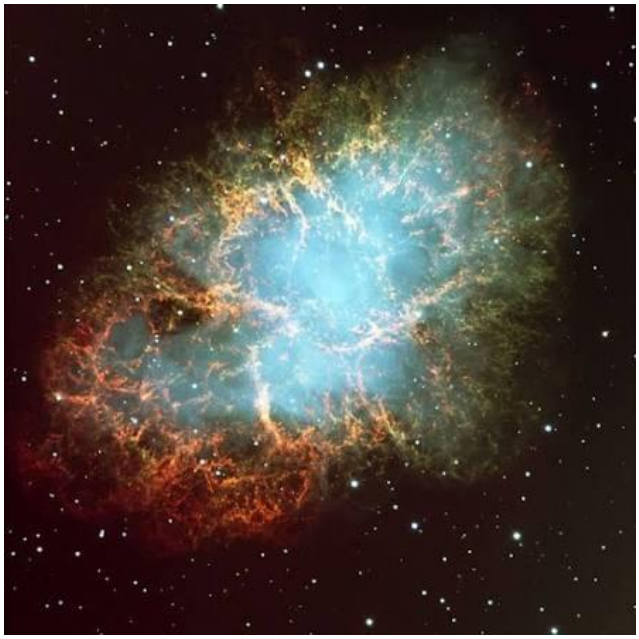


Fig 1: Galactic Cosmic Ray penetration into the Earth Atmosphere

The energy range of primary ranges from 109 EV to 1020 EV or higher, while cosmic rays with energies up to 1015 EV are considered as being of galactic cosmic ray origin. It is supported by neutron monitor observations which showing the supernova which traces the galaxy CR and accelerators up to energies close to the first slope (~3×1015 eV) in the CR energy spectrum. The CR flux reaching out the Earth's atmosphere and decreases rapidly with energy, at the first knee, cosmic ray flux is 1 m^2 particle per year whereas at the ankle (~10^{19} eV) in the energy spectrum, flux is particle 1 km^2 per year. It is shown the interaction and formation of cosmic ray intensity with earth environment is very complex and complicated. The preliminary findings of the CLOUD (Cosmics Leaving Outdoor Droplets) experiment at CERN in Geneva, Switzerland, are promising for the investigation of potential cosmic ray effects on clouds formation. Change in the CRs during the ionization affects with local atmospheric electrical conductivity, global electric circuit, nucleation rates during the cloud lightning discharges and some space weather phenomena are responsible. A connection between CRs and climate will be investigated because of cloud formation, lightning strikes, and other space weather events which have impact on earth environment. When cosmic rays hit the Earth's atmosphere, they infiltrate the biosphere and cause a range of biological consequences, including blood pressure, heart rate, chromosomal aberration, cell

death and mutation, and cancer. An overview's main goal is to increase knowledge about cosmic rays. The most significant goal is to link cosmic rays to different atmospheric physical processes and their effects on human health.

Since the late 19th century, scientists have been fascinated by the ionization of the atmosphere close to the Earth's surface. It was generally accepted that radioactive radiation from the Earth itself was the main source of ionization in the atmosphere. Sir Henri Becquerel's seminal discovered the radioactivity in 1896, this theory states that the declining impact of terrestrial radioactive sources would cause the strength of ionization to gradually decrease with altitude.

However, observations taken with high-altitude balloons contradicted this notion. Contrary to popular perception, these balloon studies showed that ionization levels rose with altitude. This surprising discovery implied the presence of an additional, until unknown source of atmospheric ionization and it was need to identify this new source became a significant focus in atmospheric and cosmic ray research.

In 1925, Robert Millikan coined the phrase "cosmic ray," proposing that these rays come from alien origins. The scientific community's focus was shifted from terrestrial to cosmic sources of atmospheric ionization thanks in large part to Millikan's work. Cosmic rays impacting on Earth are charged particles, primarily bearing a positive charge, according to later research by Clay and Berlage (1932). According to their findings, protons, which are hydrogen nuclei, make up the majority of the fundamental cosmic rays. Primary and secondary cosmic rays are two major groups into which cosmic rays may be divided. Primary cosmic rays, also known as Galactic Cosmic Rays (GCRs), are those that come from outside the solar system. These high-energy particles reach the Earth's atmosphere after traveling across space. When primary cosmic rays interact with interstellar matter or the Earth's atmosphere, they produce secondary cosmic rays, which are particles generated from these collisions. The composition of cosmic rays is notably different from that of the solar system's material. While protons dominate, heavier nuclei such as carbon (C), nitrogen (N), oxygen (O), and iron (Fe) are more abundant in cosmic rays than in the solar system. The exact composition of primary cosmic rays outside the Earth's atmosphere varies depending on the energy range observed, reflecting the complex processes involved in their origin and propagation through space. Secondary cosmic rays consist of nuclei that are not commonly found as products of nuclear synthesis or remnants of the Big Bang. Among these, the presence of light nuclei such as **lithium (Li), beryllium (Be), and boron (B)** is particularly significant. These light elements are found in cosmic rays at abundances more than **10,000 times greater** (over four orders of magnitude) than in the solar system. This disparity is attributed to the fragmentation process, where collisions between primary cosmic rays and interstellar matter cause heavier nuclei to break apart, producing these lighter nuclei. This process of fragmentation, often called **spallation**, mainly affects heavier nuclei like carbon, nitrogen, oxygen, and iron, generating secondary light nuclei that are detected in cosmic rays. The relative abundance of these light nuclei in cosmic rays is vastly greater than their presence in the solar atmosphere, where their abundance is roughly **10^-7** that of helium. In summary, cosmic rays play a crucial role in atmospheric ionization and provide valuable insights into astrophysical processes beyond our solar system. The study of cosmic rays has evolved from early 20th-century balloon experiments to sophisticated particle detection and analysis, enhancing our understanding of both particle physics and cosmic phenomena. This extended understanding highlights the dynamic and complex nature of cosmic rays and their interactions with the Earth's atmosphere, bridging the fields of

astronomy, physics, and atmospheric science. The present research utilizes the Multiple Regression approach to investigate variations in Cosmic Ray modulation with their Sunspot Number trace. The degree of anti-correlation changes over time and at different periods of a given solar cycle. The most important measure of solar activity, which is dependent on the solar dynamo process, is the change in sunspot numbers. Because the solar and large-scale interplanetary magnetic fields have different polarities, the modification of galactic cosmic rays by diffusion, convection, and adiabatic slowing causes distinctive variations between neighboring solar cycles. Once every eleven years, close to the peak of solar activity, the polarities of the solar magnetic field switch sign.

2. Methodology

Data Sources

The present study investigates the modulation of Galactic Cosmic Rays (GCRs) during Solar Cycle 24 using monthly averaged, pressure-corrected neutron monitor observations and selected solar and heliospheric parameters. Pressure-corrected monthly GCR intensity data were obtained from the **Oulu Neutron Monitor Station**, Finland (65.05° N, 25.47° E; vertical cutoff rigidity = 0.81 GV). The Oulu Neutron Monitor is operated by the Cosmic Rays Group of the University of Oulu, Finland, as part of the ReSoLVE Centre of Excellence and the Sodankylä Geophysical Observatory. The station operates a 9NM64 neutron monitor together with a muon telescope for continuous observations of cosmic ray intensity. In addition, complementary observations are obtained from the Concordia Station in Antarctica using a double mini neutron monitor. These facilities provide continuous, high-quality measurements that are widely used in studies of solar modulation of cosmic rays. The pressure correction removes atmospheric effects from the measured neutron count rates, allowing the observed variations to be attributed primarily to changes in solar and heliospheric conditions. The data were retrieved from the Oulu Cosmic Ray Station database (http://cosmicrays.oulu.fi). Monthly averaged values of Sunspot numbers obtained from the OMNIWeb database maintained by the Goddard Space Flight Center (GSFC), Space Physics Data Facility (SPDF), NASA (https://omniweb.gsfc.nasa.gov).

Neutron Monitor Measurements

A neutron monitor is a ground-based detector that indirectly measures the intensity of high-energy galactic cosmic rays entering Earth's atmosphere. The primary cosmic rays, consisting mainly of protons and alpha particles, collide with atmospheric nuclei and produce cascades of secondary particles. Among these secondary particles are neutrons, which are detected by neutron monitors. Consequently, variations in neutron count rates provide a reliable measure of changes in the intensity of galactic cosmic rays reaching Earth.

OMNIWeb Database

The solar and interplanetary parameters used in this investigation were obtained from the NASA OMNIWeb database. The OMNI data set combines and cross-calibrates measurements from several spacecraft, including the IMP series, Pioneer 10, Pioneer 11, IMP 8, and later space missions, to produce

a continuous record of near-Earth solar wind plasma, interplanetary magnetic field, solar activity indices, geomagnetic indices, and energetic particle observations.

The OMNI database provides hourly and monthly averaged data products beginning in the early 1960s. The data are processed to account for differences among spacecraft and are propagated to the Earth's bow shock, ensuring consistency for scientific analysis. The OMNIWeb interface allows users to retrieve, visualize, and download selected parameters in various formats and has become one of the most widely used resources for heliospheric and space weather research.

3. Data Analysis

The monthly averages of Sun Spot Numbers data for the duration of Solar Cycle 24. Time-series analysis was carried out to investigate the temporal evolution of SSN parameter throughout the solar cycle. To investigate the combined influence of solar and heliospheric parameters on Galactic Cosmic Ray (GCR) intensity, Multiple Linear Regression (MLR) analysis was employed. Multiple linear regressions is one of the most widely used statistical techniques for predictive analysis, as it explains the relationship between a single continuous dependent variable and two or more independent variables. In the present study, the pressure-corrected monthly GCR intensity was considered the dependent variable like Sunspot Number (SSN).

The multiple linear regression model used in this study is expressed as the objective of the regression analysis was to quantify the individual and combined effects of the selected solar parameters on the observed variations in GCR intensity during Solar Cycle 24. The regression coefficients were estimated using the least-squares method, and the statistical significance of the model and individual predictors was evaluated using the coefficient of determination ((R^2)), adjusted (R^2), F-test, and t-tests at an appropriate level of significance. The validity of the multiple linear regression model was assessed by examining the standard assumptions of linear regression. A linear relationship between the dependent and independent variables was assumed. The residuals were examined for normality and homoscedasticity to ensure constant variance across the range of fitted values. Multicollinearity among the predictor variables was evaluated using correlation analysis and the Variance Inflation Factor (VIF), ensuring that the independent variables were not excessively correlated. Residual plots were also inspected to verify that the model assumptions were reasonably satisfied. Multiple linear regression fits a regression hyperplane through a multidimensional space formed by the predictor variables. Unlike simple linear regression, which relates one independent variable to one dependent variable, MLR simultaneously considers the effects of several predictors. This approach enables a more comprehensive assessment of the relative importance of Sun Spot Number controlling the modulation of galactic cosmic rays during Solar Cycle 24.

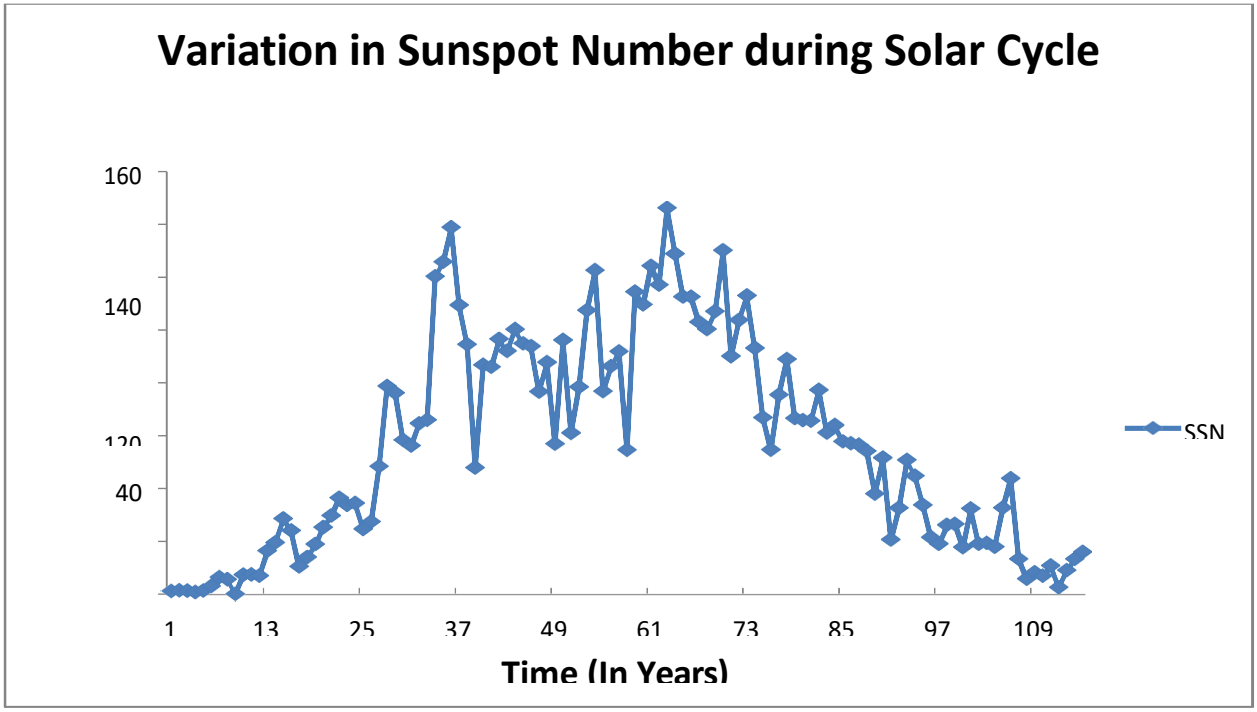


Fig 2:- Monthly Averaged GCR Value during Solar Cycle 24

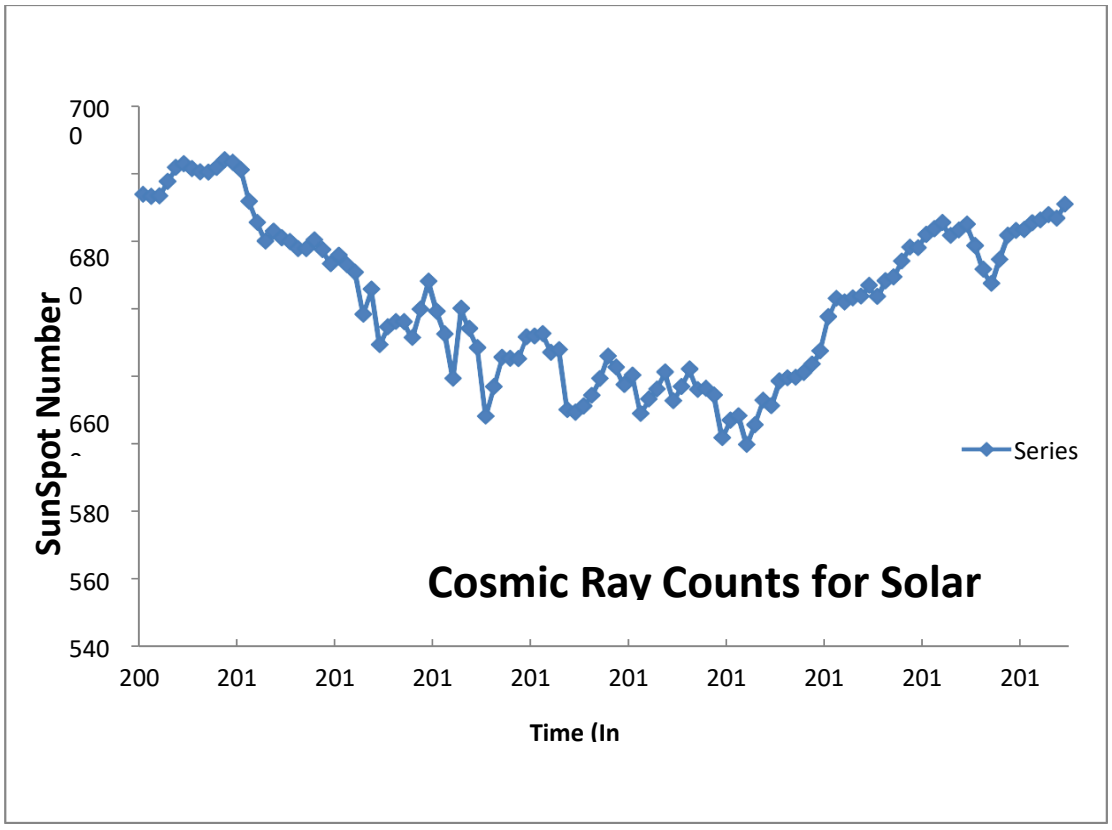


Fig 3:- Monthly averaged Sunspot Number Values during Solar cycle 24

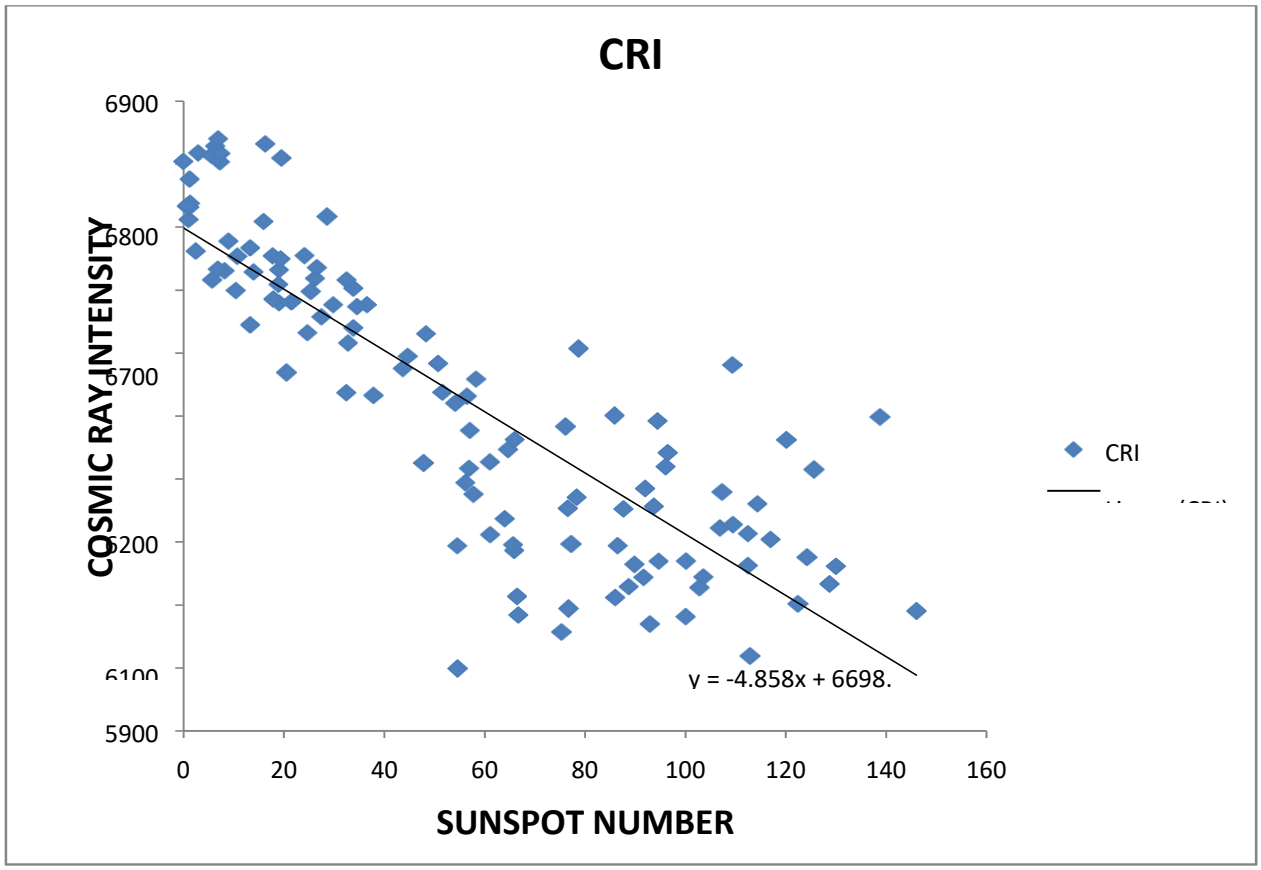


Fig 4:- Multiple Regression Scatter Plots between Cosmic Ray Intensity and Sun-Spot Number

In the figure 2 illustrates the monthly averaged pressure-corrected Galactic Cosmic Ray (GCR) intensity recorded by the Oulu Neutron Monitor during Solar Cycle 24 (2009–2018). The GCR intensity exhibited a clear solar cycle dependence. At the beginning of Solar Cycle 24 (2009–2010), the neutron monitor recorded the highest cosmic ray intensity, reaching approximately 6800 counts. As solar activity increased during the ascending phase of the cycle, the cosmic ray intensity gradually decreased. The minimum GCR intensity was observed around the solar maximum (2013–2014), where the neutron counts dropped to nearly 5900 counts. During the declining phase of the solar cycle (2015–2018), the GCR intensity increased steadily, approaching values comparable to those observed during the previous solar minimum. This behavior confirms the well-established inverse relationship between solar activity and galactic cosmic ray intensity. During periods of high solar activity, enhanced solar wind and stronger interplanetary magnetic fields provide greater shielding against incoming galactic cosmic rays, thereby reducing the number of particles reaching Earth's atmosphere. Conversely, during solar minimum conditions, weaker heliospheric magnetic fields allow a larger flux of galactic cosmic rays to penetrate the heliosphere and reach Earth. In the figure 3 presents the monthly averaged Sunspot Number (SSN) during Solar Cycle 24. The sunspot number remained relatively low during 2009, representing the solar minimum. Thereafter, SSN increased progressively during the ascending phase, reaching its maximum value of approximately 145 around 2014. Following the solar maximum, the sunspot number gradually declined toward the end of the cycle, reaching values close to zero by 2018. The temporal variation of SSN closely follows the characteristic 11-year solar activity cycle. The increase in sunspot number corresponds to enhanced solar magnetic activity, frequent solar flares, and

coronal mass ejections (CMEs), while the declining phase reflects the gradual weakening of solar magnetic activity. In the figure 4 shows the regression relationship between cosmic ray intensity and sunspot number. The regression analysis reveals a negative linear relationship between GCR intensity and SSN. The fitted regression equation,

[CRI = -4.858(SSN) + 6698]

indicates that an increase of one unit in sunspot number is associated with an average decrease of approximately **4.86 neutron counts** in cosmic ray intensity. The negative slope confirms that cosmic ray intensity decreases with increasing solar activity. This inverse relationship is a consequence of enhanced solar magnetic fields and increased solar wind turbulence during periods of high solar activity, which reduce the penetration of galactic cosmic rays into the inner heliosphere. During solar minimum, weaker heliospheric conditions permit greater cosmic ray influx, resulting in higher neutron monitor count rates. The scatter distribution suggests that although sunspot number is an important predictor of cosmic ray modulation, additional heliospheric parameters—including the interplanetary magnetic field (IMF), solar wind velocity, and F10.7-cm solar radio flux—also contribute to the observed variations. Therefore, multiple linear regression analysis provides a more comprehensive explanation of GCR modulation than simple linear regression alone.

4. Conclusion

The results demonstrate that Galactic Cosmic Ray intensity is strongly controlled by variations in solar activity throughout Solar Cycle 24. The highest GCR intensities occurred during the solar minimum, whereas the lowest intensities coincided with the solar maximum. This inverse relationship is consistent with the theory of solar modulation of cosmic rays, whereby enhanced solar magnetic fields, increased solar wind pressure, and greater heliospheric turbulence during active phases of the solar cycle inhibit the transport of galactic cosmic rays toward Earth. The regression analysis further confirms that increasing solar activity leads to a systematic reduction in cosmic ray intensity. When combined with additional heliospheric parameters such as the IMF, solar wind velocity, and F10.7-cm solar radio flux, the analysis provides a comprehensive understanding of the physical processes governing GCR modulation during Solar Cycle 24.

This study examined the modulation of Galactic Cosmic Ray (GCR) intensity during Solar Cycle 24 using pressure-corrected monthly averaged observations from the Oulu Neutron Monitor Station. The relationship between GCR intensity and key solar and heliospheric parameters, including Sunspot Number (SSN), Interplanetary Magnetic Field (IMF), Solar Wind Velocity (SWV), and F10.7-cm solar radio flux, was investigated using multiple linear regression analysis. The results demonstrate a pronounced inverse relationship between GCR intensity and solar activity. Cosmic ray intensity reached its maximum during the solar minimum and decreased significantly during the solar maximum, confirming the modulation of galactic cosmic rays by enhanced solar magnetic activity and heliospheric conditions. The regression analysis further revealed that the selected solar and interplanetary parameters collectively influence the observed variations in GCR intensity, indicating that cosmic ray modulation is governed by the combined effects of solar wind, magnetic field strength, and solar radiation rather than

by a single parameter alone. These findings are consistent with the established theory of solar modulation and highlight the effectiveness of multiple linear regression in quantifying the contribution of various solar activity indicators.

Future research can extend this work by incorporating data from multiple neutron monitor stations with different geomagnetic cutoff rigidities to investigate the rigidity dependence of cosmic ray modulation. The inclusion of additional parameters, such as the heliospheric current sheet tilt angle, coronal mass ejections (CMEs), geomagnetic indices (Dst, Kp, and Ap), and solar energetic particle events, may further improve the understanding of cosmic ray transport in the heliosphere. Advanced modelling approaches, including machine learning algorithms and physics-based cosmic ray transport models, can also be employed to enhance the prediction of GCR intensity and space weather conditions. Furthermore, extending the analysis to multiple solar cycles, including Solar Cycle 25, will provide deeper insight into long-term solar modulation processes and improve the accuracy of space weather forecasting.

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