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Cosmic-Ray Modulation in relation to Solar and Heliospheric Parameters

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Abstract

The behaviour of several solar activity indices and heliospheric characteristics over the solar cycle 24 is compared to long-term fluctuations in cosmic rays. Before, the linear combination of the sunspot number, the solar cycles 22, 23, and 24's cosmic ray intensity, the number of group solar flares, and the geomagnetic indices Ap, Kp and aa. We observed the relationships between solar-heliospheric variables, such as the interplanetary magnetic field, coronal mass ejections, the tilt of the heliospheric current sheet, and cosmic-ray modulation, after applying this model to the current solar cycle, which is marked by many peculiarities and extreme solar events. By analysing monthly cosmic-ray data from the Neutron Monitor Stations of Oulu (0.81 GV), Beijing (cutoff rigidity 9.56 GV) and Moscow (2.42 GV), It was looked at how these characteristics affected the cycle's ascending, maximum, and declining phases. It is demonstrated that the majority of the modulation potential variations during this cycle can be reproduced using a combination of these factors. An extensive analysis of the time profiles, correlations, and time lags of the cosmic-ray intensity versus these parameters across the entire studied period of 1996–2022, reveals the cycle's distinctive characteristics as being strange. Also, the acquired hysteresis curves and correlative analysis intervals of the cycle provide noticeably distinct behaviour between solar and heliospheric parameter behaviour.

Keywords: Cosmic Ray Intensity; Geomagnetic Activity; Solar Activity.

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1. Introduction

The universe is filled with cosmic rays, which are high-energy particles that originate from far-off astronomical sources. These cosmic rays interact with many celestial bodies, including our solar system. The route they take through space is not simple, though. The impact of solar and heliospheric characteristics increases as they pass through the interstellar medium and get closer to the heliosphere. Cosmic-ray modulation, the mechanism through which solar and heliospheric effects change the intensity and energy spectrum of cosmic rays, has attracted a lot of attention from scientists (Ferreira & Potgieter 2017). A huge region controlled by the solar wind and magnetic field from the Sun, the heliosphere serves as a shield to modify cosmic rays arriving from the interstellar medium. Understanding this modulation is essential for understanding cosmic-ray propagation in general, as well as its effects on space missions, space weather, and prospective ramifications for terrestrial and extraterrestrial habitats.Cosmic-ray modulation and its intricate interaction with solar and heliospheric parameters have been the subject of extensive inquiry by scientists and space missions over the years (Potgieter 2013). The heliospheric environment and, in turn, cosmic ray propagation are greatly influenced by solar activity, which is characterised by variations in the solar magnetic field, solar wind speed, and solar energetic particle events.

Recent decades have seen a significant increase in the research of 11-year variability characteristics due to the persistent recoding of cosmic beam strength by neutron screen technology. The greatest forbush declines, which last for a while, are followed by parallel abrupt decreases that further diminish overall force, according to Lockwood (1960), who called attention to this phenomenon. Agrawal (1983) proposed that the extreme inversion of the Sun's attractive field that took place in 1969–1970 was the cause of a 22-year tweak. Webb, (2012). Agrawal et al. (1993), Singh & Mishra (2019), Ahluwalia, H.S., & Lopate (2001), and many others have described a few study efforts to elucidate long-term Cosmic beam strength change taking into consideration part of the time lag between sunspot numbers. The long-term management of astronomical beam strength was attempted to be clarified utilising a unique balancing parameter (Bakare & Chukwuma 2010, Prasad et al 2021). According to actual tests, the power of a long-range cosmic beam can be calculated based on the combined influence of a few geomagnetic highlights (Calisto et al. 2011, Singh et al. 2015). They come to the conclusion that the solar wind's enormous scale structure is what causes the cosmic beam force diversity to cycle every 11 years.

In addition, the heliosphere's general dynamics and structure, including the solar magnetic polarity, the strength of the heliospheric magnetic field, and the heliospheric current sheet, can have a substantial impact on cosmic ray modulation (Usoskin & Kovaltsov 2020). In respect to solar and heliospheric characteristics, cosmic ray modulation is a topic that this paper tries to thoroughly review at this time. The mechanisms underlying cosmic-ray modulation and its variability over various solar cycles and heliospheric circumstances will be covered as we delve into the important empirical and theoretical results. We'll also look at the practical ramifications of cosmic-ray modulation, such as its possible impact on space missions, its function in forecasting space weather, and its contribution to our understanding of the broader interstellar and intergalactic medium. We intend to advance our knowledge of cosmic-ray modulation and its relationship to solar and heliospheric parameters as well as the larger cosmic environment and its

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complex interactions with our solar system. This information improves our understanding of astrophysical processes while also advancing attempts to study and use the newest space technology.

2. Methodology

A wide range of statistical and data science approaches are used to analyse the results. There have been many graphs, charts, plots, and relationships considered for both long- and short-term investigations of cosmic ray modulation. We'll make use of regression analysis. The degree to which a dependent variable and a set of independent variables are connected can be ascertained through regression analysis. Regression analysis is a useful tool for descriptive data analysis because it may be used without making any assumptions about the underlying processes that generate the data. We used data from 1996 to 2022, including the upturn periods of solar cycles 22 to 24 and 25, to compare solar/geomagnetic activity and cosmic ray intensity (CRI). The geomagnetic Ap index is crucial for long-term monitoring of solar activity for the reasons listed below (Lee and Fisk 1981; Kane 2007). We selected sunspots (Rz), solar wind velocity (V), geomagnetic disturbance index (Ap), and magnetic field (B) for this purpose. The product of the solar wind plasma velocity (V) and the strength of the interplanetary magnetic field (b) determines the modulation parameter (V * B). The CRI data from three neutron monitoring sites—Oulu (0.81 GV), Moscow (2.41 GV), and Beijing (9.56 GV—were used in this investigation.). Data for solar and geomagnetic parameters are obtained from monthly averaged data from various websites. www.geomag.bgs.ac.uk/daaservice/dat, data source: National Geophysical Data Center (http: http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html).

3. Result and Discussion

The solar-terrestrial interaction can help to explain some of the 11- and 22-year variations in galactic cosmic rays. Cosmic ray intensity (sunspot numbers Rz) has been discovered to be influenced by the solar cycle, with maximum intensity occurring seven months after sunspot minima. However, not all solar cycles are like this. The time between the solar cycle and the cosmic ray cycle varies depending on the solar cycle. It also varies depending on where the solar cycle is in. In the past, researchers have examined both the number of sunspots and the power of cosmic rays (Forbush, 1957; Ifedili 2001; Agrawal 1983; Mishra & Mishra 2018; Sham & Mishra 2019; Ross & Chaplin 2019). They discovered an inverse relationship between the quantity of sunspots and cosmic ray intensity. Based on solar illumination, cycles 23 and 24 of the astronomical beam force (CRI) and sunspot counts (Rz) were connected (Draper and Smith 1998). The correlative analysis used the annual mean benefits of the super-neutron screens in Beijing, Oulu, and Moscow. It is confirmed that there is a negative correlative behaviour between infinite beams and sunspot counts between 1996 and 2022. Using annual mean estimations of sunspot counts (Rz) and infinite beam force, a relationship coefficient was created for the period 1996 to 2022, spanning sun-based cycles 22 and 24. Figure (1) shows that the CRI from Beijng increases during periods of high solar activity, and Figure (2) shows that there is an anti-correlation between the CRI and Rz, B, and V that is found to be -0.60, -0.3, and -0.3 for the solar cycle 22 to 24.

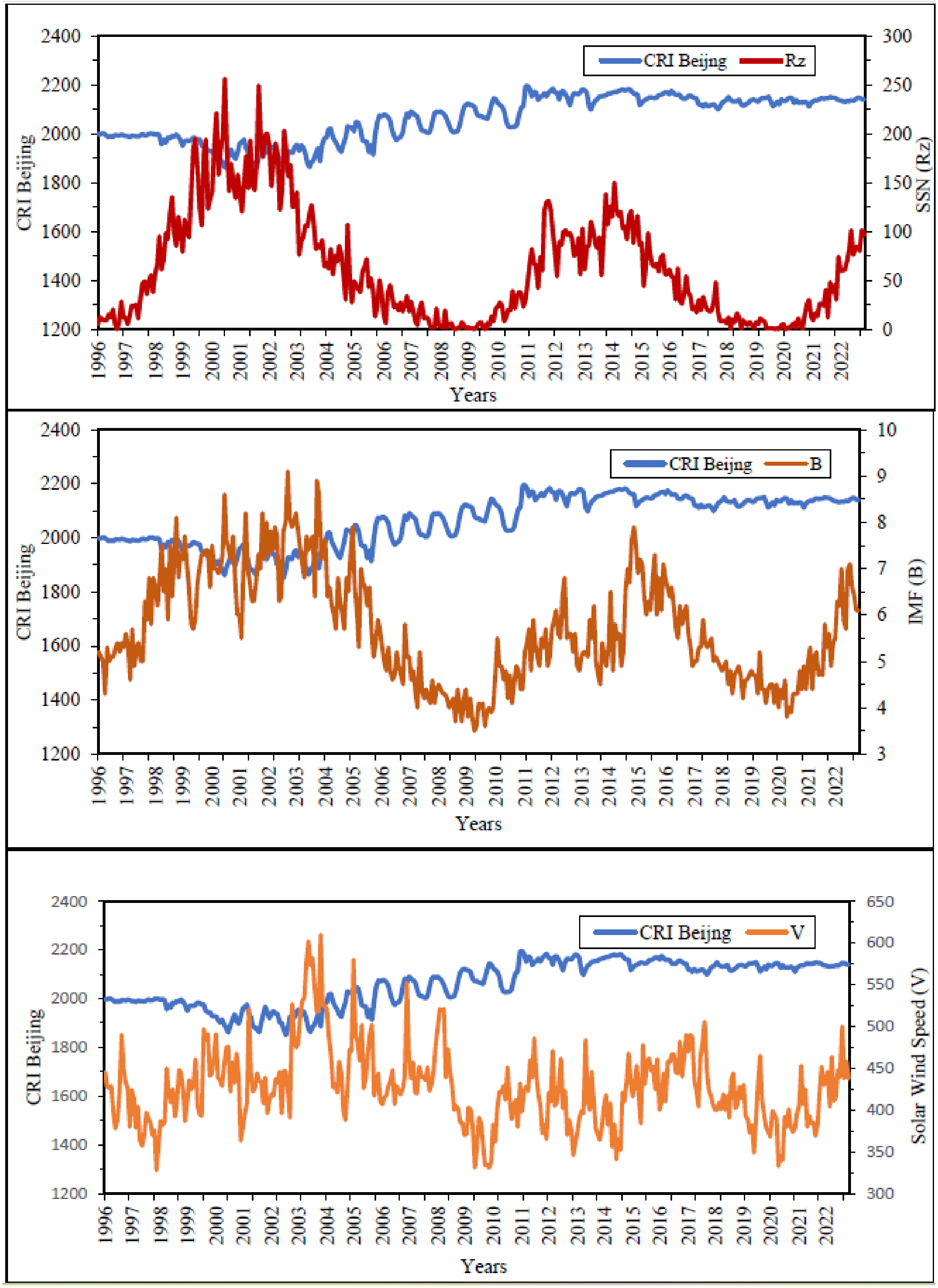

Fig (1): Cosmic Rays Intensity for Beijing Stations Along with Geomagnetic Magnetic Field (B), Solar Wind Velocity (V) &Sunspot Number (Rz) For Years 1996-2021.

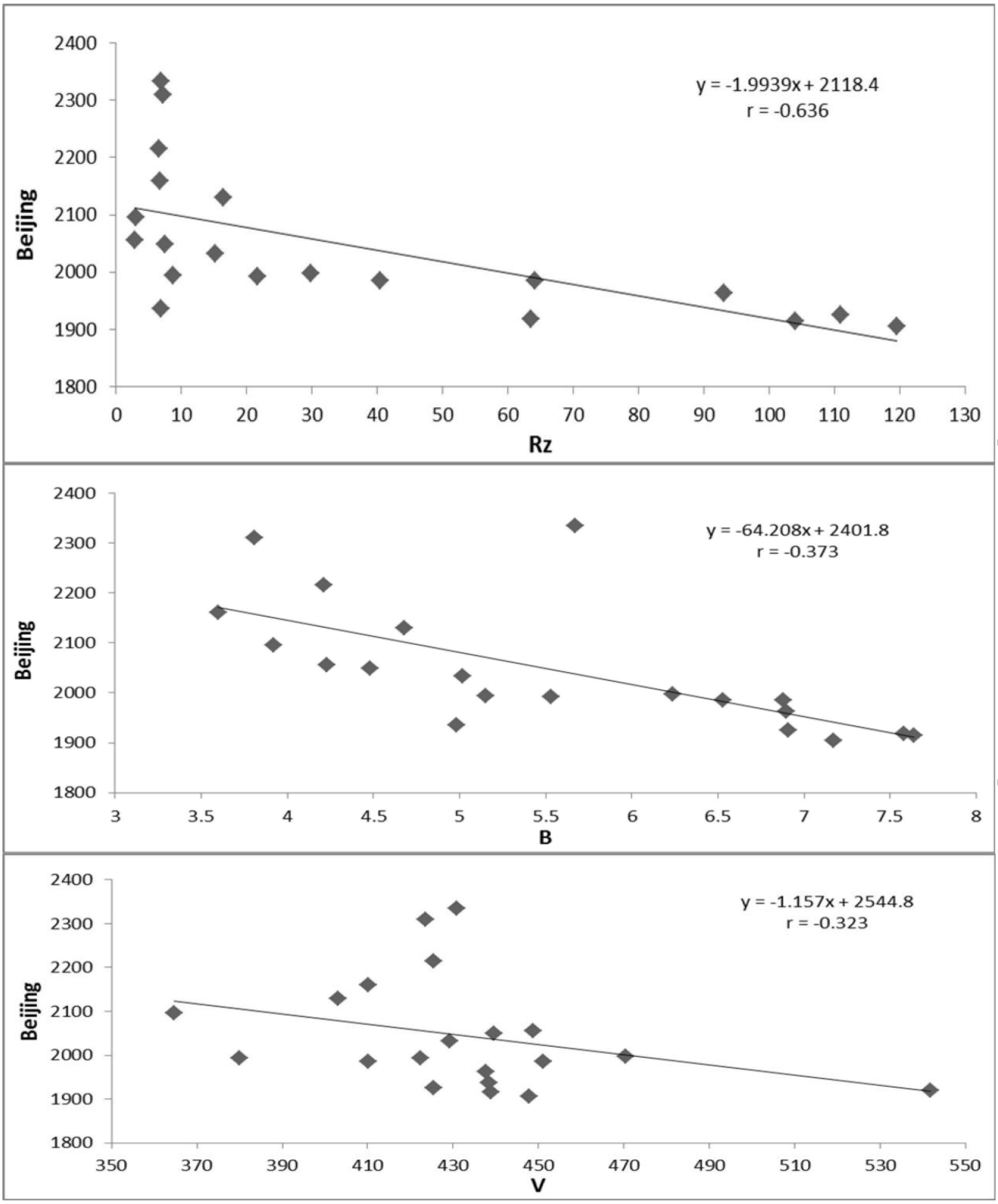

Fig (2): Correlative cross plot between Beijing& Geomagnetic magnetic field(B), solar wind velocity (V) & sunspot number (Rz) for years 1996-2021.

3.1. Solar and Heliospheric Parameters' Influence on Cosmic-Ray Modulation

A number of solar and heliospheric characteristics have an impact on the modulation of cosmic rays in the heliosphere (Ferreira & Potgieter 2017). Cosmic rays are significantly modulated by solar activity, which is demonstrated by variations in the solar magnetic field and solar wind speed. The intensity of the solar magnetic field increases during periods of high solar activity, which enhances the speed of the solar wind and improves the interstellar medium's ability to block cosmic rays. As a result, at these times, cosmic ray intensity that enters the inner solar system drops (Moraal, H., & Potgieter 2015).

3.2. Solar Cycles and Cosmic-Ray Modulation

The modulation of cosmic rays is significantly influenced by the solar cycle, which lasts about 11 years (Potgieter 2013). Cosmic ray strength falls at the solar maximum, when solar activity is at its highest, and reaches its lowest levels as a result of the sun's stronger magnetic field and the heliosphere's expansion. The inner solar system experiences an increase in cosmic ray flow during the solar minimum, which has low solar activity. Although it is not constant throughout the cycle, observations have indicated that cosmic-ray modulation is most pronounced during solar maximum (Strauss 2019). The varying solar cycles' variation in solar and heliospheric parameters is a factor in the complex cosmic-ray modulation patterns.

3.3. Heliospheric Magnetic Field and Current Sheet

Cosmic ray propagation is substantially influenced by the heliospheric magnetic field and its accompanying structures, including the heliospheric current sheet. A region of increased magnetic turbulence is the heliospheric current sheet, a large-scale structure formed by the interaction of the solar wind and the magnetic field of the Sun. As charged particles, cosmic rays interact with the current sheet's chaotic magnetic field by scattering and diffusing (Usoskin & Kovaltsov 2020). As a result of this process, cosmic rays are modulated overall, changing in strength and energy spectrum as they pass through the heliosphere. Space Weather and Space Mission Implications. For the accurate forecasting of space weather and the security of space missions, it is essential to understand cosmic-ray modulation in connection to solar and heliospheric factors. Astronauts and spacecraft may be exposed to radiation from galactic cosmic rays, especially during times of heightened cosmic-ray flux. Space agencies can plan and carry out missions with sufficient shielding and measures to reduce the possible dangers associated with high cosmic-ray intensities by observing and forecasting cosmic-ray modulation patterns.

3.4. Connection to Interstellar and Interplanetary Environment

Cosmic-ray modulation research offers important new perspectives on the larger interstellar and interplanetary environment. Cosmic ray interactions with the heliosphere provide a chance to learn more about the interstellar medium's characteristics and the heliosphere's physical makeup. The heliosheath, where the solar wind interacts with the interstellar medium, and the heliopause, where the solar wind meets the pressure of the interstellar medium, are two more areas that can be better understood by knowing cosmic-ray modulation in the heliosphere

4. Conclusion

A fascinating area of study with significant consequences for astrophysics, space weather, and space exploration is the modulation of cosmic rays in the heliosphere, which is regulated by solar and heliospheric factors. The most important discoveries and theoretical foundations of cosmic-ray modulation have been highlighted in this extensive overview, which also emphasises the importance of solar activity and the influence of heliospheric magnetic fields on cosmic-ray propagation. We are more prepared to explore the depths of space and comprehend how celestial activities within our solar system and beyond are connected as we continue to develop our understanding of cosmic-ray modulation. We found a high correlation between the number of geomagnetic unusually quiet days and the size of the upcoming solar cycle. Solar cycle 25 was shown to be more active and to have an effect on the space weather when solar cycles 23 and 24 were added to it. Models based on statistics predict that the monthly sunspot count will likely peak in 2013 between 50 and 70. According to models based on the strength of the solar polar magnetic field, the peak might occur as early as in 2012. Comparing cycle 25 to more recent cycles is an intriguing way to track its development.

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