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"Impact of Solar Parameters on Cosmic Ray Intensity Modulation During Solar Cycles 23 and 24: A Comprehensive Review"

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ABSTRACT

This study explores the modulation of cosmic ray intensity (CRI) by solar and interplanetary factors during Solar Cycles 23 and 24. Four scenarios were analyzed, incorporating parameters like sunspot number (SN), interplanetary magnetic field (IMF), heliospheric current sheet (HCS), and plasma velocity, with distinct variations observed across latitudes. Data from neutron monitors revealed that strong geomagnetic storms, such as those in May 2017, caused significant CRI decreases, influenced by parameters like solar wind speed, IMF BzB_zBz, and Dst-index. Theoretical models, including the Parker and Fisk fields, highlight the role of the heliospheric magnetic field (HMF) and solar wind dynamics in CR modulation but require further refinement. Observations of long-term variations, Forbush decreases, and ground-level enhancements underscore the complex interplay of solar activity and cosmic ray dynamics, offering insights into space weather prediction and heliospheric processes.

Key words- *Solar Cycles 23, Solar Cycles 24, interplanetary magnetic field, cosmic ray intensity, heliospheric magnetic field*

INTRODUCTION

Both galactic and extragalactic cosmic rays originate outside of the solar system, however some cosmic rays (CR) have proton origins from the sun as heavier elements and alpha particles.

Outside of the heliosphere, the cosmic ray intensity remains constant, but when they approach through it, the interplanetary magnetic field causes modulation (Mavromichalaki et al., 1988; Agarwal et al., 1993). The ground-based neutron monitors (Moscow 2.43GV) are the source of the data. In addition to solar flare index (SFI), solar flux (SF), and group solar flare (GSF), solar indices are used to identify solar activity. Similar to Earth, the sun has an approximate 11-year cycle. The inverse relationship between cosmic ray intensity and solar wind velocity was initially noted by Forbush (Forbush,1988, Singh et al., 2013).

Still, a lot of researchers are pursuing more verification. A time-lag in the relationship between solar activity parameters and cosmic ray intensity indicates that the magnitude of modulation varies from cycle to cycle in the massive zone of the heliosphere and the diffuse propagation of cosmic ray particles (Nagashima et al., 1979). With some time-lag, there is a negative correlation between solar activity parameters and the 11-year variations in cosmic ray strength observed on Earth (Forbush et al., 1954). The time-lag between sunspot number and cosmic ray intensity causes a sort of hysteretic effect between long-term perturbations in solar activity parameters and cosmic ray intensity, as has been seen by numerous researchers (Moraal et al., 1976).

According to models of cosmic ray modulation based on the observed reversal of the sun's magnetic field polarity after every 11-year solar cycle, curvature, and gradient drift in the large scale magnetic field of the heliosphere, the cosmic ray intensity curve also appears to follow a 22-year cycle with alternate maxima that are flat-topped and peaked (Jokipi et al., 1981).

Cosmic Ray Intensity and Geomagnetic Indices During Solar Cycles 23–24

Cosmic ray intensity (CRI) changes are examined along with their relationships to geomagnetic indices and solar wind parameters from various locations. CRI data from the neutron monitor database over the MWSN, DOMC, and HRMS stations were used in this study. According to the study's findings, the MWSN station had a higher CRI than the DOMC and HRMS stations. However, compared to MWSN and HRMS stations, the CRI over DOMC is significantly smaller. It's interesting to note that during a period of intense geomagnetic storms in May 2017, the CRI values at all sites dropped in comparison to January 2020. Additionally, the continuous wavelet transform (CWT) result demonstrated that, in comparison to January 2020, a stronger power spectrum in CRI was seen in May 2017. This is because the strength of geomagnetic storms (strong storms) and the southward changes of the interplanetary magnetic field (IMF Bz) component have a greater modulation of cosmic ray intensity than weak storms. The Dst-index shows that perturbations of the ring current cause the value of CRI to decrease upon reaching Earth, and it is observed that CRI decreases in a pattern resembling that of the Earth's magnetic field. The coefficients of interplanetary electric field (IEF Ey), f10.7-index, Kp, and Ap-indices peak with a very high value of 1 for a zero lag, indicating a good positive correlation between the parameters, according to the correlation analysis of CRI over DOMC, MWSN, and HRMS stations, as well as the solar wind parameters and geomagnetic indices for both strong and moderate events. On the other hand, assuming a zero lag, the IMF Bz, solar wind speed, and Dst-index coefficients peak with extremely high values of 0.2 and 0.5, showing weaker and greater correlations between the parameters included for the study. (Uga and others, 2023)

Composition, and Modulation of Cosmic Rays

High-energy particles known as cosmic rays move through space at almost the speed of light. Although protons, or hydrogen nuclei, are the most common type of these atomic nuclei stripped of their electrons, nuclei as heavy as lead have been discovered (Hillas et al., 2005). It is believed that a variety of sources, such as the remnants of black holes, neutron stars, and supernovae, as well as more unusual materials from the sun, stars, and higher radio galaxies, produce cosmic rays (Firoz et al., 2010; Horowitz et al., 2019; Diehl et al., 2022).When atoms and energetic particles collide in the upper atmosphere, a series of secondary particles are created that descend through the sky and land on the surface of the Earth. According to Mirova et al. (2015) and Zreda et al. (2012), protons comprise around 90% of all incoming cosmic ray particles, while helium nuclei make up 9% and electrons make up 1%. The distribution of magnetic fields in the vast heliosphere affects the cosmic ray time profile observed on Earth's surface due to the complex history of cosmic rays prior to their arrival on the planet (Kudela et al., 2000; Aartsen et al., 2016; Buchvarova et al., 2022). A compression area in the solar wind, characterized by forward and backward shocks, may be identified with an increase in the amplitude of the interplanetary magnetic field (IMF) (Pogorelov et al., 2007; Hajra et al., 2021).

Solar Modulation of Cosmic Ray Intensity: Variations and Anisotropies

Cosmic ray strength varies across a broad variety of time scales due to solar events. As the particles move through the solar wind, the observed flux is altered and made anisotropic, and it is sometimes boosted by the intermittent release of solar cosmic rays. A theoretical model that specifies the role of the various solar-controlled parameters that define the electromagnetic properties of the interplanetary medium represents both quasi-static phenomena (the long-term omnidirectional intensity variation and the steady state diurnal anisotropy) and transient fluctuations (disturbed daily variation and Forbush decrease) as well as the spatial distribution of solar flare particles. Spacecraft have yielded a great deal of information about the atmospheric conditions. The in situ measurements, however, are restricted to a small area close to the ecliptic plane. As a result, theoretical predictions based on them sometimes do not match observations of fluctuations in cosmic ray strength. Therefore, a three-dimensional framework is required to tackle the modulations and anisotropies. Therefore, it makes sense to try to infer from observations of the sun itself the characteristics of the pertinent inaccessible parts of the heliosphere. By connecting the different cosmic ray events to variations both within and between solar cycles, these characteristics may be ascertained. In order to ascertain the solar cycle dependence of the following effects, data spanning at least two solar cycles are examined: solar cosmic ray events (ground level enhancement and polar cap absorption), long-term variations in the omnidirectional intensity, Forbush decreases, and solar diurnal variations. In 1974, Pomerantz et al.

Cosmic ray variability

Three space "frontiers," the first of which is perhaps the least understood, shield life on Earth from cosmic rays:

(1) the dynamic heliosphere with the solar wind and the accompanying turbulent HMF.

(2) The dynamic nature of the Earth's magnetic field, such as the significant changes that have been taking place over southern Africa in recent decades. This indicates that during the last 400 years, there have been notable variations in the geomagnetic cut-off stiffness for cosmic rays, substantial enough that the change in cosmic ray flux affecting Earth may be comparable to the relative change in flux over a solar cycle (Shea and Smart, 2004). In addition to reversing its magnetic polarity over an extended period of time (the previous reversal occurred 780,000

years ago, thus the next one is thought to be long overdue), the magnetosphere can endure changes in space weather caused by the Sun.
(3) The atmosphere, with all of its intricate chemistry and physics. As air pressure rises, the cosmic ray strength falls exponentially. Through changes in the Earth's orbit and fluctuations in solar irradiation, for example, the Sun has a major role in atmospheric changes.

Modeling the heliospheric modulation of cosmic rays

Basic but largely unknown information is needed for realistic modeling of cosmic ray modulation in the heliosphere. First, as beginning conditions at the postulated outer heliospheric border, which is generally regarded as the HP, the local interstellar spectra for the various cosmic ray species are required. Significant progress has been made in modeling these galactic spectra using galactic propagation models, although nothing is known about the majority of these spectra at energies below a few GeV due to heliospheric modulation (Moskalenko et al., 2002). Second, it is necessary to specify the heliosphere's structural structure and geometry, including the locations of the TS and HP. Thirdly, information regarding the worldwide, three-dimensional solar wind and HMF profiles is needed. Little was known about the latitudinal dependence of these entities prior to the Ulysses mission (Marsden, 2002). We can already specify the solar wind profile in detail, however it was discovered that a rotating dipole might not be able to adequately simulate it for the HMF. Interesting advancements in cosmic ray modulation have been facilitated by this factor. The "ultimate" alternative was suggested by Fisk (1996), although the "Parker HMF" is currently used in the polar regions with a major change. Unfortunately, the ‘Fisk-field’ is complicated and cannot be addressed straightforwardly in ordinary numerical models (Burger et al., 2007).

SOLAR WIND AND HELIOSPHERIC MAGNETIC FIELD

Global magnetic field geometry

Parker (2001) examined how the solar wind receives an embedded solar magnetic field from the solar corona's expansion, which eventually transforms into the HMF. For the HMF, he had anticipated a well defined spiral structure (Parker, 1958). Although there have been changes to this field over the years, Fisk's (1996) discovery that the rigid rotation of polar coronal holes and the differential rotation of the Sun have a substantial impact on the structure of the HMF led to the development of second generation global HMF models, which are much more complicated and contentious and, as a result, have not yet fully been understood for what they might mean for CR modulation (e.g., Sternal et al., 2011, and references therein). To settle the issue, MHD modeling will need to be used to examine these particular traits. CR modeling continues to make extensive use of the Parker-type field and its mild modification (e.g., Smith and Bieber, 1991). Also also Heber and Potgieter's (2006) review. At maximum, the Sun mainly uses CMEs to communicate its message of an increased magnetic field (lower diffusion coefficient) to the heliosphere; as the cycle decreases, high-speed streams become more significant (e.g., during the mini-cycles of 1974, 1984, and 1994). HSSs from polar coronal holes (Wang and Sheeley 1994) are the primary source of cycle-to-cycle variation in B that drives modulation at solar minima, when CMEs are rare.

The decline in the average contribution of HSSs to B from ~2.8 nT in 1976/1986/1996 to ~1.2 nT in 2009 (thus accounting for the drop in B from ~5.4 nT to ~3.9 nT) was the cause of the high Newark neutron monitor counting rate in 2009 when compared to the average rate for 1976, 1986, and 1996. Between the minima preceding Cycles 23 and 24, the solar polar field strength decreased by around 45% (Svalgaard et al. 2005; Cliver and Ling (2010) equated the SSW with a floor, or constant baseline level, in the solar wind), which is directly reflected in the 2009 decline in BHSS. A floor like that won't affect the long-term or 11-year fluctuation in GCR intensity.

At the beginning of the modulation cycle in A positive epochs (the rise of odd-numbered solar cycles), when GCRs react weakly to rises in B (and tilt angle), the impacts of large-scale curvature and gradient drifts are most noticeable. The weaker response of the GCR intensity to changes in B at such times is attributed to the drift-induced preference for positively charged particles to approach the inner heliosphere from the poles at these times (Jokipii and Thomas 1981) and the relative confinement of CMEs to low latitudes at the onset of the solar (modulation) cycle (Gopalswamy et al. 2010). CMEs form at ever-higher latitudes as the cycle progresses. The polar areas can be engulfed by large, broad CMEs that originate at latitudes above ~30–40° and start to "close the shell" in the inner heliosphere (McDonald et al. 1993; Cliver et al. 1993; Cliver and Ling 2001a; Lara et al. 2005). Particle intake from over the Sun's poles during A positive cycles is faster than inflow via the wavy neutral sheet during the comparable period of A negative cycles, as shown by Potgieter and Le Roux (1994).

Accordingly, during A positive cycles, GCR recovery durations are shortened (Wibberenz et al. 2002). Because of this, substantial modulation does not start at the beginning of odd-numbered solar cycles until it reaches the polar regions.

Cosmic Rays and ACR Intensities Across Solar Cycles

The variations in ACR oxygen intensities between A > 0 and A < 0 from the cycle 20/21 minimum through the cycle 22/23 minimum, as well as between the inner and outer heliosphere, were satisfactorily explained by a phenomenological model (Stone and Cummings 1999) that linked the HCS tilt angle to ACR gradients. Since the launch of the Advanced Composition Explorer (ACE) spacecraft in August 1997, GCRs and ACRs have been measured by the Cosmic Ray Isotope Spectrometer (CRIS; Stone et al. 1998a) and Solar Isotope Spectrometer (SIS; Stone et al. 1998b) aboard ACE. These instruments allow for thorough comparisons of cosmic-ray modulation effects over more than one solar cycle by providing a continuous, high-precision data collection that spans the current A < 0 solar minimum and the end of the last A > 0 solar minimum through solar maximum. We use publicly available neutron monitor readings to extend the GCR measurements to earlier solar cycles. A time series spacing of 2–5 years, an attractor dimension of around 2–3, and an embedding dimension of 3–4 were recommended by the first nonlinear time series investigations of solar activity indicators (Kurths and Ruzmaikin 1990; Gizzatullina et al. 1990).

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