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Study of Diurnal Anisotropy Variation in Cosmic Ray Intensity During Minimum Solar Activity Period

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Abstract

we present a comprehensive study of cosmic ray variations over the period from 1964 to 2018, encompassing solar cycles 20, 21, 22, 23, and 24. Both annual average and day-to-day variations have been analyzed to capture the temporal dynamics of cosmic ray intensity across multiple solar cycles. The study focuses particularly on periods of minimum solar activity, namely the years 1965, 1976, 1986, 1996, and 2008, when cosmic ray modulation is most pronounced and solar influences on galactic cosmic rays are minimal. Using data from multiple neutron monitoring stations worldwide, the amplitude (%) and phase (hours) of cosmic ray intensity at ground level were determined and grouped into equal intervals for detailed statistical analysis. The percentages of occurrence of days corresponding to different amplitude and phase intervals were calculated to evaluate patterns across varying phases of solar activity. This approach provides a systematic method for quantifying both the magnitude and timing of cosmic ray variations, allowing for inter-comparison across different solar minima and monitoring sites. Additionally, the study demonstrates the usefulness of long-term neutron monitor data in capturing subtle temporal trends and establishing empirical relationships between cosmic ray intensity and solar activity parameters. Overall, this work contributes to a deeper understanding of cosmic ray modulation over multiple solar cycles and lays the groundwork for improved predictive modeling of cosmic ray variations in relation to solar and heliospheric processes.

Keywords: Cosmic rays, diurnal variation, solar activity period

INTRODUCTION

With the discovery of light energy radiations of complex composition and wide energy range incident from all the directions on the top of the Earth's atmosphere (Hess, 1912), about 106 years ago, later termed as Cosmic Rays; a new era of research in the field of our studies of interplanetary space started. The cosmic ray research has offered a number of problems for investigation in astrophysics, solar physics, geophysics, high energy physics and elementary particle physics. This provides an opportunity to develop physical understanding of the Earth's near environmental and the electromagnetic processes which operate in the interplanetary medium.

Flux, composition and energy spectra of these radiations may alter dramatically during their passage in the space after leaving the source. These changes are termed as Cosmic ray modulation. Possible extra-terrestrial origin of the cosmic radiation was discovered by Hess in 1912 from the manned balloon flights using ionization chambers, which leads to the search of variability cosmic ray intensity, caused by solar characteristics (Aslam and Badruddin 2012, 2015, Thomas et al; 2014). [1-5]

Numerous researchers have conducted comprehensive studies on the time variation of cosmic ray intensity, critically analyzing various aspects of cosmic ray modulation (Lockwood, 1971;

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Pomerantz and Duggal, 1971, 1974; Rao, 1972; Agrawal, 1981; Venkatesan and Badruddin, 1990; Usoskin et al., 1998; Belov et al., 2000; Dubey et al., 2018). These modulation studies complement **in situ** measurements, together providing a more complete understanding of the processes and mechanisms operating in interplanetary space. It is well established that the variability in cosmic ray features results from multiple hemispheric phenomena, and no single factor can fully account for these variations. Several research groups and individual scientists have proposed empirical relationships to predict and explain cosmic ray modulation as a consequence of multiple solar parameters, including solar wind velocity, solar flares, and sunspot numbers (Belov et al., 1999; Giacalone, 2010; Dunai, 2010; Owens and Forsyth, 2013).

Over the years, several groups of researchers and individual scientists have proposed empirical relationships and models to explain and predict cosmic ray modulation as a function of multiple solar and heliospheric features, such as solar wind velocity, solar flares, sunspot numbers, and coronal mass ejections (Belov et al., 1999; Giacalone, 2010; Dunai, 2010; Owens and Forsyth, 2013). These studies have revealed that both long-term trends, such as solar cycles, and short-term transient events contribute significantly to cosmic ray intensity variations. For example, solar maximum periods are generally associated with enhanced modulation, resulting in lower cosmic ray flux reaching Earth, while periods of solar minimum exhibit comparatively higher cosmic ray intensities. Furthermore, the combined use of observational data and modeling approaches has improved our understanding of the transport processes, diffusion mechanisms, and energy-dependent modulation effects within the heliosphere. Overall, such comprehensive analyses not only enhance our knowledge of cosmic ray behavior but also provide critical insights into space weather phenomena and their potential impacts on Earth’s technological infrastructure and space exploration missions.[6-10]

Data Analysis

An attempt has been made to determine the detailed characteristics of diurnal anisotropy and to compare them with the earlier findings and existing models giving detailed nature of modulating interplanetary conditions.

Annual data during the solar cycles 20, 21, 22, 23, 24; for the period 1964-2018 on annual average basis as well as on day to day basis has been investigated. This period of investigation includes minimum solar activity periods, i.e.; 1965, 1976, 1986, 1996, 2008 of the solar activity this way period of investigation covers all the phases of solar activity.

The amplitude (%) and phase (Hrs) of anisotropy variation of cosmic ray have been analyzed through Fourier technique.

RESULT AND DISCUSSION

The diurnal amplitude and phase of cosmic ray intensity are obtained on a day to day basis for Oulu, Apatity, Kiel and Moscow neutron monitoring stations. The values of amplitude (%) and phase (Hrs) at ground are grouped for different equal intervals; percentages of occurrence of days for amplitude and phase in these intervals for all the neutron monitoring stations for different phases of solar activity have been calculated. The days with extra ordinary amplitude have not been taken into consideration, since on such days the sharp intensity gradients are likely to cause a large error in the determination of diurnal vector.

Table 1. Show the details of neutron monitor which are used for study.

Neutron monitor station	Geographic latitude (Deg.)	Geographic longitude (Deg.)	Cutoff rigidity (GV)
Oulu	65.05	25.47	0.8
Apatity	43.28	42.69	5.6
Kiel	54.3	10.1	2.36
Moscow	55.4	37.3	2.39

Figures 1, 2, 3, 4 and 5 show the distribution of occurrence of days for amplitude and phase of the diurnal vector during year 1965, 1976, 1986, 1996, 2008 i.e.; epoch of minimum solar activity. The diurnal amplitude (%) and phase (Hrs) versus percentage of days have been plotted in Figure 1 during 1965. Phase is seen to occur within the time interval near to later hour direction for all four neutron monitor stations on maximum number of days. The frequency distribution of Moscow neutron monitor station is well scattered, with near corotational to higher values for significant number of days.

It is evident from these histographic plots that the amplitude peak is quite distinctly sharp and lies at 0.2-0.3% for all four stations.

The diurnal amplitude (%) and phase (Hrs) versus percentage of days have been plotted in Figure 2 during 1976. Phase is seen to occur within the time interval near to early hours for all neutron monitor stations on maximum number of days. The frequency distribution of Oulu neutron monitor station is well scattered.

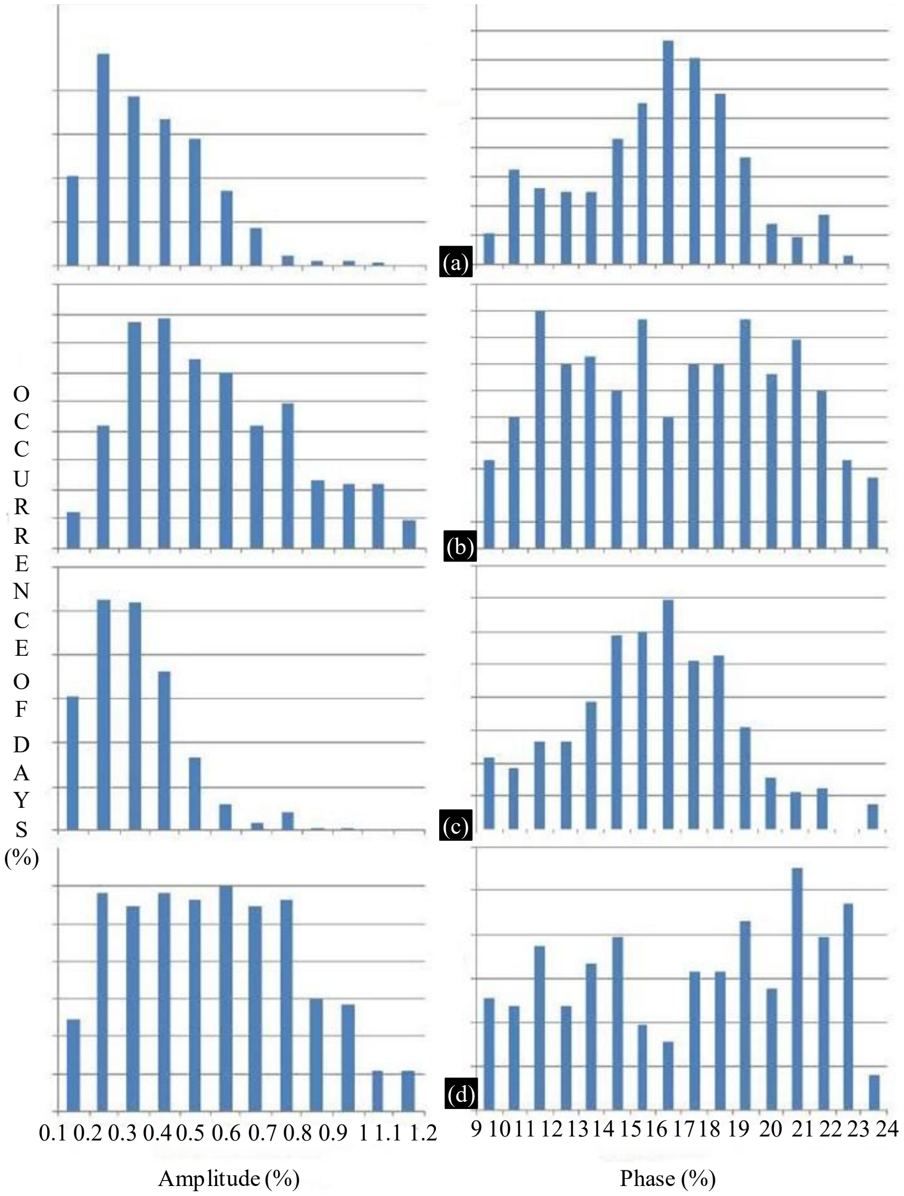

Figure 1. Histrographic plots showing percentage of occurrence of days (%) for (a) Oulu (b) Apatity (c) Kiel (d) Moscow phase (Hrs) during 1965.

It is evident from these histographic plots that the amplitude peak is quite distinctly sharp and lies at ≃ 0.3% for all four stations however, it shows quite wider distribution of amplitude in case of Oulu neutron monitor, which has low cut-off rigidity.

Figure 3 shows the statistical distribution of diurnal amplitude and phase during year 1986. The phase of diurnal anisotropy is found to be shifted either to corotational direction or to later hours for all neutron monitor stations. [11-13]

In case of Oulu neutron monitor station peak are more sharper and comparatively more number of days shift towards later hours.

The amplitude pattern of diurnal anisotropy during 1986 shows wider distribution and in histographic plots and the amplitude distribution peak show maximum occurrence of days in 0.2% and 0.3% intervals for all stations and amplitude is wider for Kiel station. The diurnal amplitude (%) and phase (Hrs) versus percentage of days of occurrence have been plotted in Figure 4 during 1996. The phase of diurnal anisotropy is found to be in early hours for all stations in maximum number of days for Oulu, Apatity and Kiel stations.

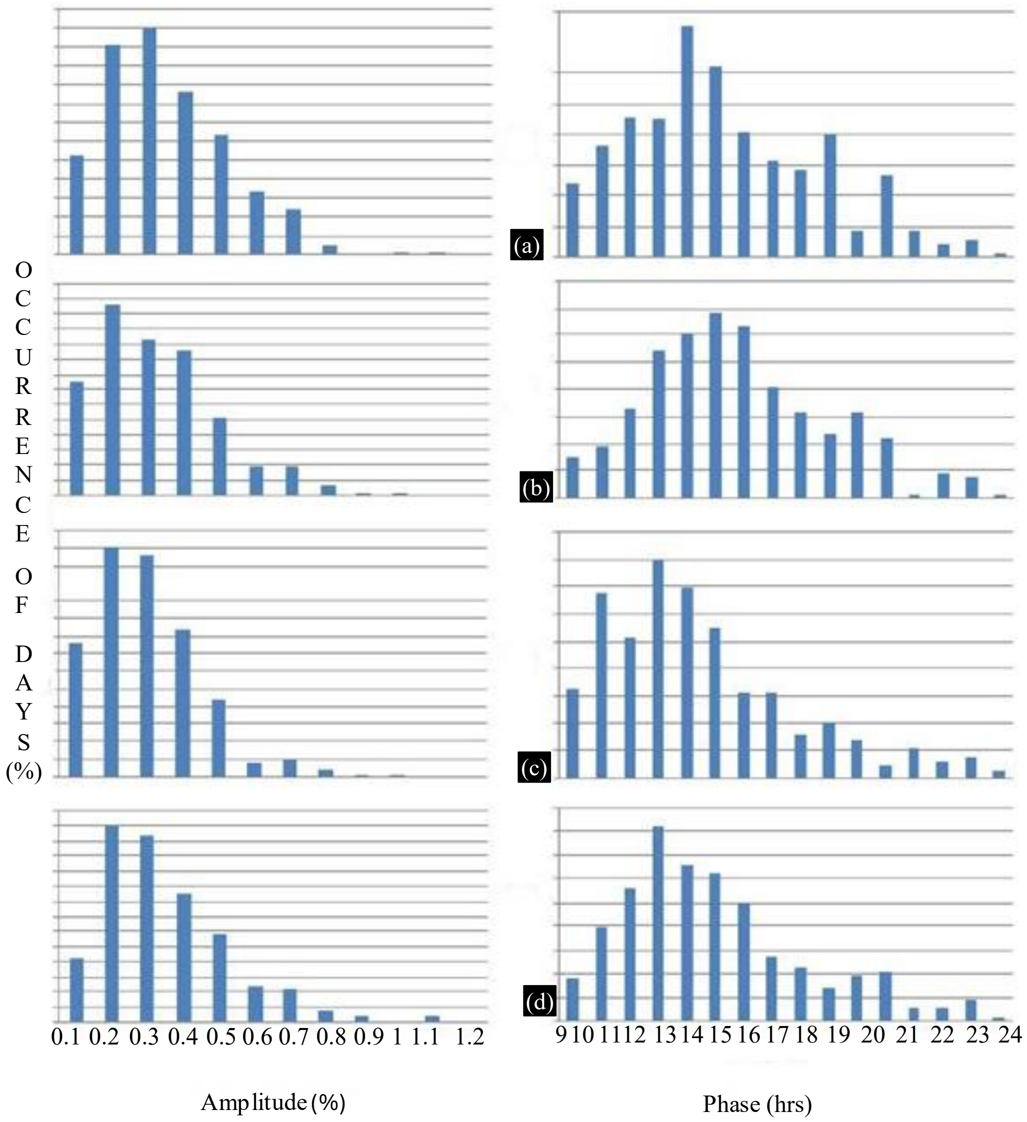

Figure 2. Histrographic plots showing percentage of occurrence of days (%) for (a) Oulu (b) Apatity (c) Kiel (d) Moscow NM station and phase (Hrs) during 1976.

The amplitude fairly lies in ≃ 0.2% range for all stations. Amplitude for Moscow

NM station is quite oftenly seen in even higher ranges of values.

Figure1 represents the frequency distribution of occurrence of phase and amplitude in various stations. In year 2008 diurnal Phase is seen near earlier or shift towards corotational direction for all neutron monitor stations. Shift towards corotational direction is more prominent for Oulu and Kiel stations. [14-20].

The maximum occurrence of amplitude lies between 0.2% - 0.4% showing wider distribution for all stations Figure 5.

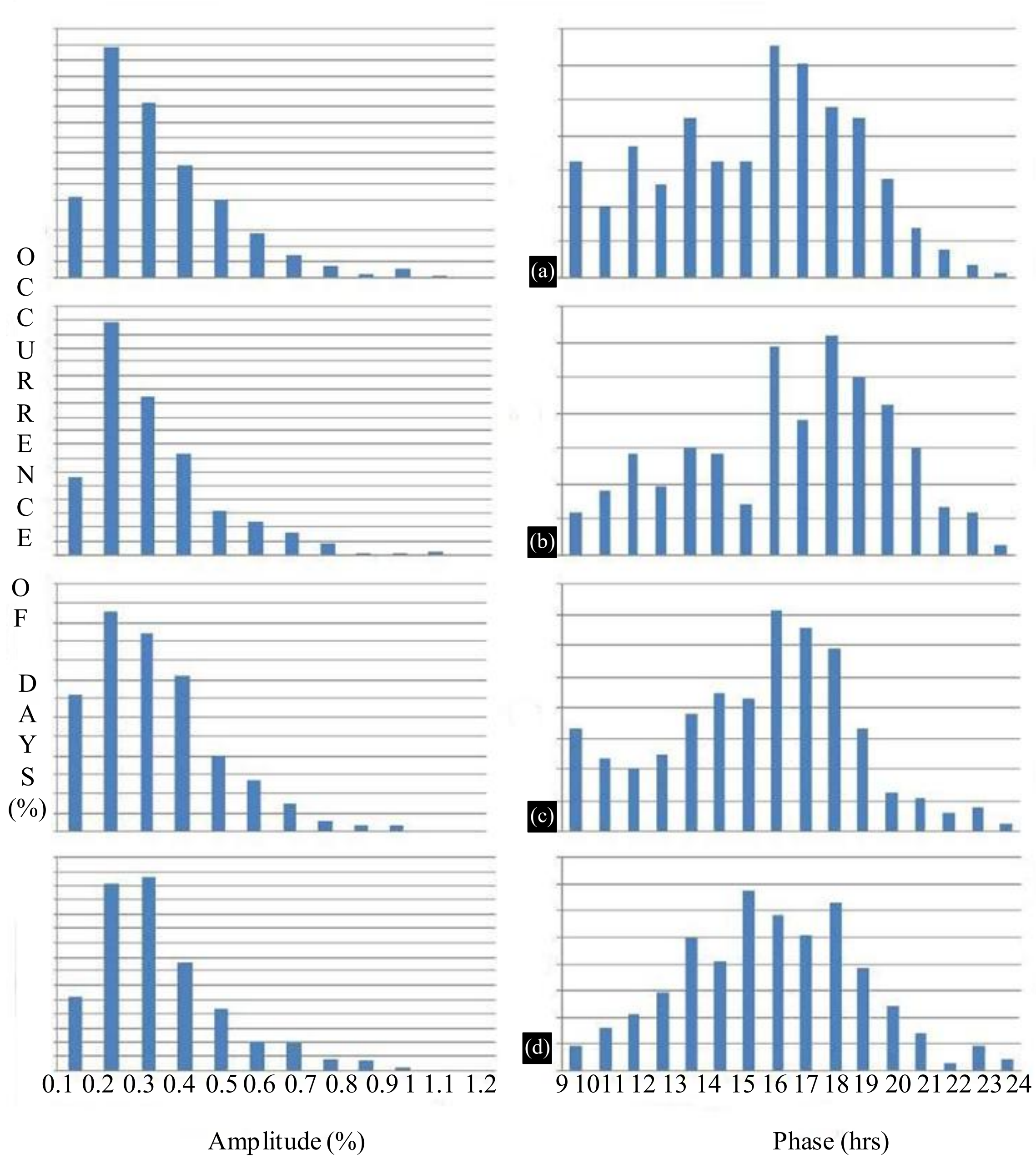

Figure 3. Histrographic plots showing percentage of occurrence of days (%) for (a) Oulu (b) Apatity (c) Kiel (d) Moscow NM station phase (Hrs) during 1986.

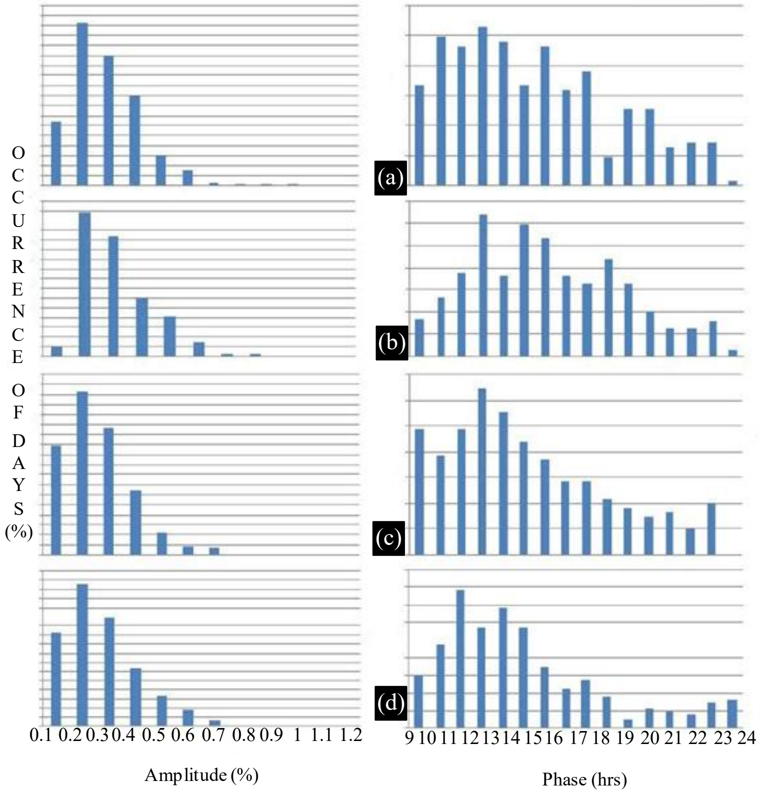

Figure 4. Histrographic plots showing percentage of occurrence for (a) Oulu (b) Apatity (c) Kiel (d) Moscow NM station phase (Hrs) during 1996.

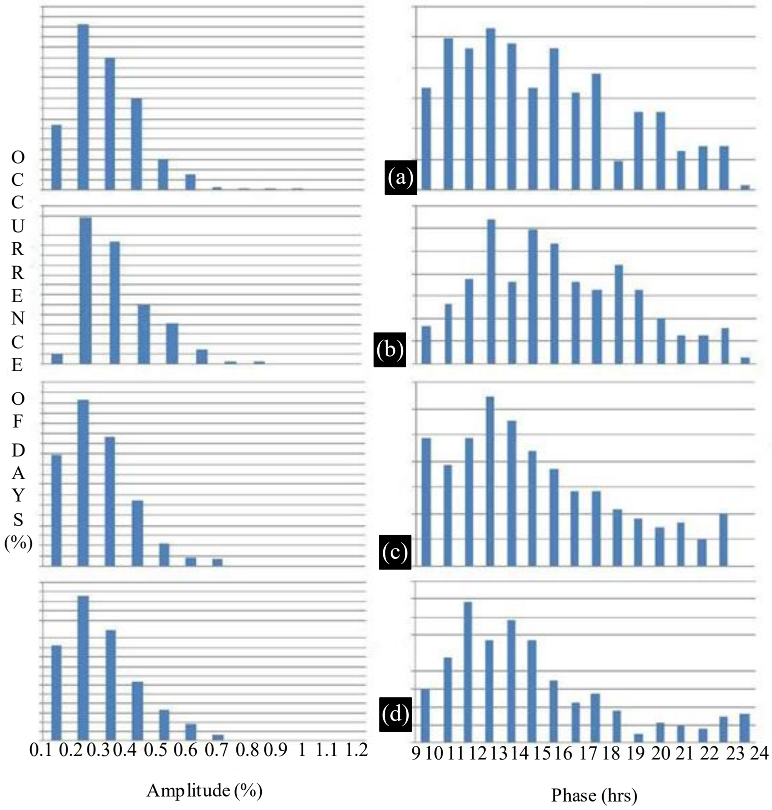

Figure 5. Histrographic plots showing percentage of occurrence of days (%) for (a) Oulu (b) Apatity (c) Kiel (d) Moscow NM station phase (Hrs) during 2008.

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CONCLUSION

The study of cosmic ray modulation provides crucial insights into the dynamic processes operating within the heliosphere and their interaction with galactic cosmic rays. The variability of cosmic ray intensity is a direct consequence of multiple solar and interplanetary phenomena, including changes in solar wind velocity, fluctuations in the interplanetary magnetic field, solar flares, coronal mass ejections, and the 11-year solar activity cycle. No single factor can fully explain the observed temporal and spatial variations, emphasizing the need for comprehensive, multi-parameter studies that combine both observational data and theoretical modeling. Modulation analyses, in conjunction with **in situ** measurements, allow for a more complete understanding of particle transport, diffusion, and energy-dependent effects, which are central to describing cosmic ray behavior throughout the heliosphere. Empirical models developed by numerous researchers have been instrumental in establishing quantitative relationships between cosmic ray intensity and various solar parameters, enabling predictions of modulation patterns under different heliospheric conditions. These studies have not only elucidated long-term trends associated with solar cycles but also highlighted the significant influence of short-term transient events, such as solar flares and high-speed solar wind streams. Understanding these modulation mechanisms is vital for space weather forecasting, as cosmic rays influence radiation exposure for satellites, astronauts, and even high-altitude aviation.

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