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Exploring Heliospheric Conditions on Diurnal Variability of Galactic Cosmic Rays: A Current Perspective

Rakesh Kumar Gautam

Lecturer, Government Polytechnic College, Satna, M.P., India

Abstract: *The diurnal variability of cosmic rays remains an attractive phenomenon with important implications for our understanding of cosmic ray transport and modulation. This study examines the current understanding of the diurnal variability of cosmic rays, focusing on the influence of solar activity, interplanetary magnetic field (IMF), and solar wind speed on the observed diurnal anisotropy patterns. An attempt is made to identify some key open questions and future research directions, with an emphasis on fully uncovering the current anomalies in both the amplitude and phase of diurnal anisotropy and estimating their future implications. Examination of data from four neutron monitors from 1986 to 2022 revealed a significant decrease in the amplitude and phase of diurnal anisotropy within the transition period of solar cycles24/25. This reduction in diurnal cosmic ray modulation deviates from the patterns observed in prior solar cycles. Our findings explore the interplay between heliospheric conditions and cosmic ray transport and provide insight into the evolving nature of solar modulation and its impact on galactic cosmic ray behavior near Earth. This research contributes to the enhancement of the models of space weather and cosmic ray forecasting.*

Keywords: Diurnal anisotropy, Interplanetary magnetic field, Solar poloidal magnetic field, and Polarity reversal

I. INTRODUCTION

The diurnal variability of galactic cosmic rays (GCR) serves as a valuable indicator of the heliospheric modulation process and the electromagnetic state of the interplanetary space around the Earth (Forbush 1954; Kumar et al., 2002.; Parker, 1964). These variations in cosmic ray intensity, which are influenced by solar activity and the structure of the interplanetary magnetic field (IMF), exhibit a characteristic amplitude and phase within each solar cycle (Nagashima et al., 1998). A complete knowledge of the IMF is important to understand this variation as a small-scale feature in the heliosphere, which can significantly affect the phase and amplitude of diurnal anisotropy (Bieber & Evenson, 1998). Cane et al., (1999) proposed that the long-term modulation of cosmic rays is mainly influenced by the magnetic field of the Sun and its global changes. Diurnal anisotropy and IMF strength exhibit distinct cyclic variations (El-Borie et al., 1996). They observed a larger diurnal amplitude in the descending phase of solar cycles 20 and 21 due to the high-speed solar wind. Solar wind speed affects cosmic rays by influencing the size of the heliosphere, when solar wind speed is high, the heliosphere expands, creating a more effective shield against incoming cosmic rays (Potgieter, M.S. 2013; Hill, M.E., et al., 2020). Conversely, during periods of low solar wind speed, the heliosphere contracts, allowing more cosmic rays to penetrate.

Extensive studies to date have documented a relationship between the diurnal variability of cosmic rays and the 11-year solar cycle. Although the modulation mechanisms are very complex, they are a complex process that unfolds throughout the heliosphere and is influenced by many factors. While no single solar or heliospheric parameter, no matter how advanced, can fully explain variations in cosmic rays (Chowdhury et al., 2016), drift effects are known to play an important role in modulations (Jokipi 1977)

A positive relationship exists between diurnal anisotropy and solar wind speed. As a result, the anisotropy in cosmic ray intensity is predicted to be primarily a co-rotating element that aligns with 18:00 local solar time. (Koi et al., 2023; McNally et al., 2023) reported that as the average speed of the solar wind escalates from low to moderate levels, there is

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a corresponding rise in cosmic ray moon intensity. McNally et al., (2023) also observed that, this amplitude does not significantly change when the solar wind velocity shifts from moderate to high. In addition, the cosmic ray muon intensity phase tends to coincide with the local solar noon.

Solar cycle 23 started in August 1996 and concluded in December 2008, and its activity levels were relatively normal compared with the preceding solar cycles (Kane, 2002; Tony Phillips, 2008). Solar cycle 24 started in December 2008 and ended in December 2019. Solar activity remained low until the beginning of 2010; the peak of this SC was significantly lower than that of recent solar cycles. In 2009, solar activity exhibited notable deviations from past solar minima. The sun activity was unusually quiet, and the heliospheric magnetic field strength was over 20% lower than that of other recent minima of SC-23/24 (Moraal & Stoker, 2010). Tiwari and Tiwari (2005) found anomalies in diurnal anisotropy in the descending phase of solar cycle 22.

Various studies have shown that the orientation of the IMF plays an important role in the diurnal variability of CRs. For a negative polarity state (A<0), the strength of the interplanetary magnetic field (IMF) and solar activity are more pronounced (Sabbah, 2013). They also proposed that the amplitude of the diurnal anisotropy is more noticeable, and the time of maximum shifts toward later hours in the day in (A<0), as compared with the positive polarity state (A>0).

However, (Thomas et al., 2017) reported similar amplitude and distinct local time of maximum between the epochs of positive and negative polarity states. In addition, a strong correlation was observed between the amplitude of diurnal anisotropy and IMF strength (Munakata et al., 2014; Sabbah, 2013).

The periodic change in the cosmic ray intensity depends on the solar wind and the interplanetary magnetic field (IMF). Sabbah and El Borie, (1996) found that the diurnal anisotropy has a low correlation with the solar wind, but is strongly influenced by the fast solar wind streams that come from the gaps in the sun's atmosphere. They confirmed that, these streams make the lesser amplitude of diurnal anisotropy and move the time of maximum to earlier hours. Ahluwalia, (2005) showed that the modulation function, which describes how the cosmic ray intensity changes with cut-off rigidity, is related to the product of the solar wind speed (V) and the IMF strength (B) at the Earth's orbit. He suggested that BV is an important factor for cosmic ray modulation. Sabbah, (2000b)confirmed this idea by finding that the diurnal anisotropy of the cosmic ray variation increases during the descending phase of the solar cycle, because of the increase in VB. This shows that both the solar wind speed and the IMF affect the cosmic ray intensity.

Tezari and Mavromichalaki (2016) observed a short-term phase shift during the descending phase of SC-23 and the ascending phase of solar cycle SC-24, whereas a large shift was observed during the maximum of SC-23 and SC-24.(Singh et al., 2011; Tiwari et al., 2012) observed that during the raising phases of even-numbered SCs, there is a significant shift in the diurnal phase to earlier hours. This contrasts with the negligible phase shift observed during the descending phases of odd-numbered solar cycles. In addition, they noted that the mean vector diurnal amplitudes during the rising periods of both odd and even solar cycles showed a consistent pattern, remaining unchanged from one period to the next, as well as between the odd and even cycles.

This paper presents a comprehensive study of diurnal anisotropy and anomalies that occurred in both the amplitude and phase of GCR diurnal variability during SC-22 to SC-24/25. This investigation aims to offer insights into the unique characteristics of solar cycles 24/25 and enhance our understanding of long-term trends in cosmic ray modulation by comparing it with previous results.

II. DATA ANALYSIS

In this study, four neutron monitors covering the cutoff rigidity range from 0.65 to 2.43 GV were included, allowing the observation of diurnal anisotropy in high and middle latitudes. Because of their nearly identical longitudes, these monitors share a comparable local time. Table 1 details the setup for the four neutron monitoring stations: Apatity (Russia), Oulu (Finland), Newark (USA/Bartol), and Moscow (Russia). Pressure-corrected hourly data from these monitors from 1986 to 2022 were obtained from the NMDB website and the IZMIRAN network of neutron monitor stations. Annual averages of solar wind speed (km/s) and annual average of interplanetary magnetic field (nT) were obtained from https://omniweb.gsfc.nasa.gov/form/dx1.html. To remove ground-level enhancement (GLE), the annual average of the amplitude was calculated from the daily variation data set, and high amplitude values were removed from this set. Time series studies provide a simple and quick harmonic analysis by averaging the hourly cosmic ray intensity change over a year and identifying the time of its maximum.

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Table I

SN	Neutron Monitor	Vertical Cut-off Rigidity	Geo. Latitude	Geo. Longitude
1	Apatity	0.65 GV	67.57 N	33.4 E
2	Oulu	0.8 GV	65.05 N	-25.47 E
3	Newark	2.09 GV	39.70 N	-75.70 W
4	Moscow	2.43 GV	55.47 N	37.32 E

III. RESULTS AND DISCUSSION

The Sun plays a key role in shaping the structure of the heliosphere that influencing the intensity distribution of cosmic rays. This achieved through various factors such as the level of solar activity, tilt angle of the heliospheric current sheet, speed of the solar wind, and strength and turbulence of the interplanetary magnetic field (Aslam & Badruddin, 2012). It would be interesting to compare the changes in diurnal anisotropy with solar activity, solar wind speed, and IMF during both phases of solar cycles 22, 23, 24, and early 25.

The $F_{10.7}$ cm solar radio flux is a measure of solar activity in the upper chromospheres and lower corona. The solar activity parameters are generally inversely related to the intensity of cosmic rays over a long period. In this observation, the amplitude of diurnal anisotropy varied with the 11-year solar activity cycle (Tezari & Mavromichalaki, 2016; Tiwari et al., 2012 and references therein), which is consistent with previously well-known findings. As Figure 1 shows, the amplitude vector follows the same pattern as $F_{10.7}$ cm solar radio flux changes over 1986–1990 and achieves a minimum value at with solar cycle minima SC-22/23 (1996), 23/24 (2009), and 24/25 (2019). The amplitude of diurnal anisotropy was found to be the lowest in the transition period (2019-20) of 24 and 25 solar cycles. This type of anomaly was found in 1996, but in 2019–20 this value was found to be less than that in 1996. The maxima of the amplitude of diurnal anisotropy are more scattered, whereas the minima correspond to the solar cycle minima. **This phenomenon may be attributed to notable disturbances within the heliosphere** (Zuberi M, 2023)**.**The phase of diurnal isotropy varies approximately according to a well-known fact with a 22-year cycle (Tezari et al., 2016; Tiwari et al., 2012 and references therein), reaching its minimum value in 1996 and 2019, as shown in figure 2. Like the amplitude vector, the time of maximum is spread at its maximum values and consistent with solar cycle minima at minimum values. The diurnal anisotropy vectors were examined by plotting them on a 24-h harmonic dial (Figure 3 and 4) after classifying and averaging them into the polarity state period of the solar poloidal magnetic field (SPMF).

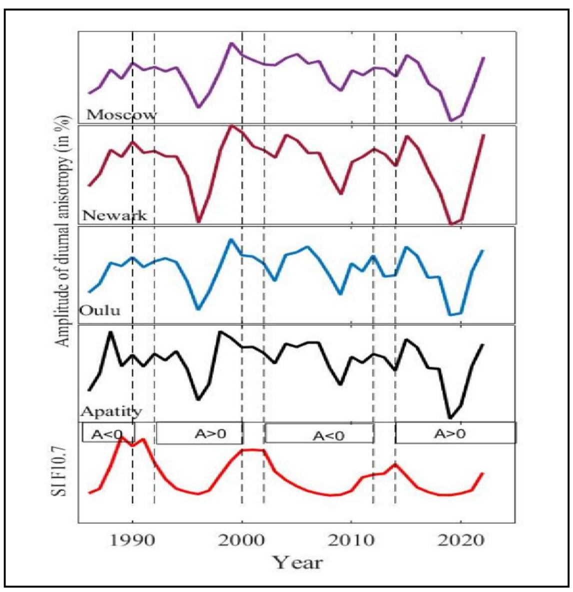

Figure 1The variation of the diurnal anisotropy amplitude vector with the solar radio flux 10.7 cm for the neutron monitors Apatity, Oulu, Newark,

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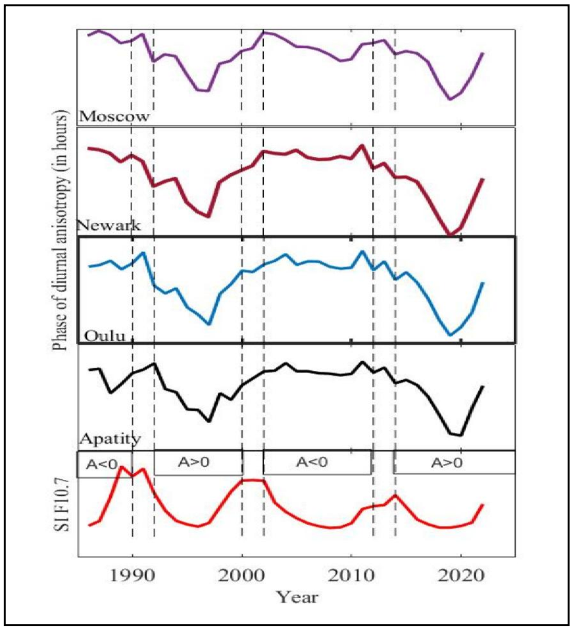

Figure 2The variation of the diurnal anisotropy phase vector with the solar radio flux 10.7 cm for the neutron monitors Apatity, Oulu, Newark, and Moscow.

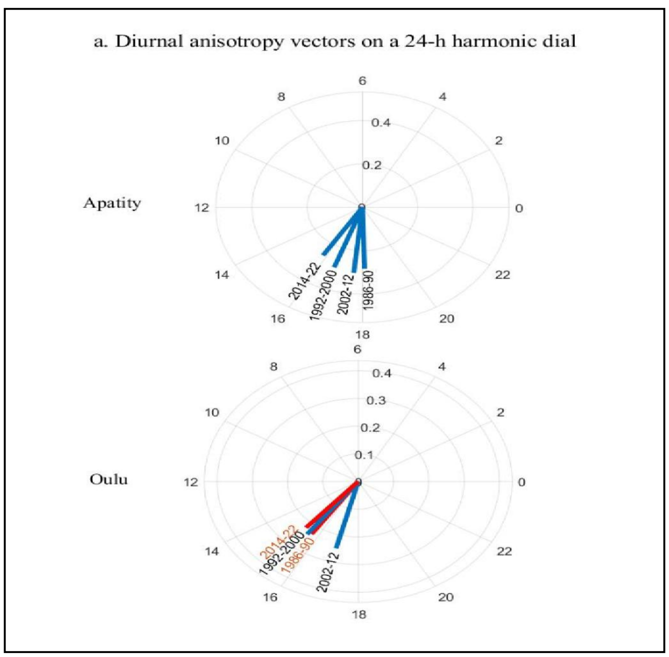

Figure 3 shows the phase of diurnal isotropy on a 24-hour harmonic dial which is determined by averaging for positive and negative epoch of the

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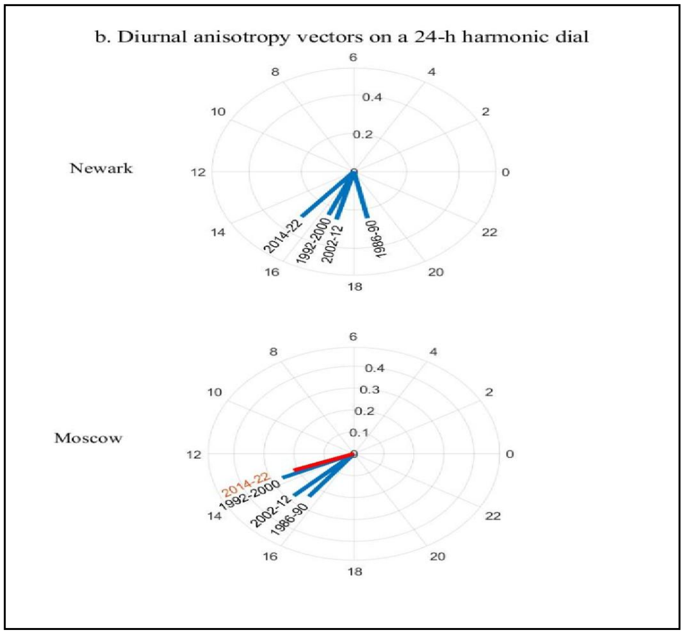

Figure 4shows the phase of diurnal isotropy on a 24-hour harmonic dial which is determined by averaging for positive and negative epoch of the solar magnetic field for neutron monitor Newark and Moscow.

Specifically, the time periods considered are as follows: 1986–1990 (A < 0), 1992–2000 (A > 0), 2002–2012 (A < 0), and 2014–2022 (A > 0). An intriguing observation is that the phase shift to earlier hours begins after solar polarity reverses from negative (A < 0) to positive (A > 0) states (e.g., around 1992).

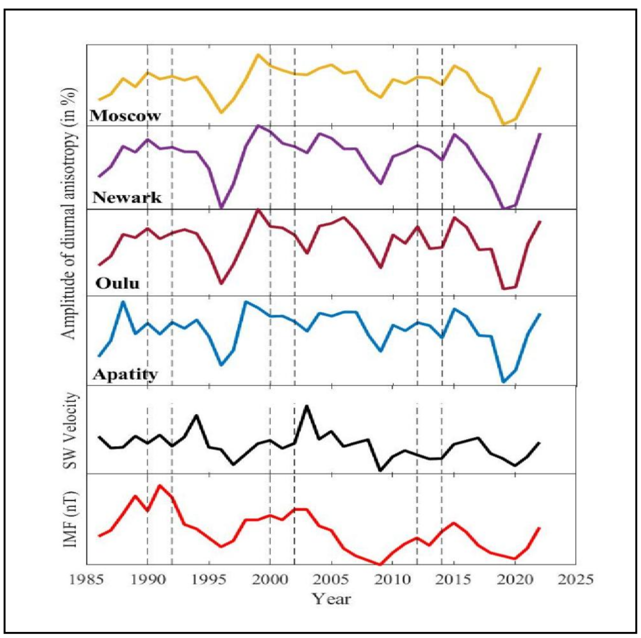

Figure 5 Shows the variation of the diurnal anisotropy amplitude vector with the IMF and solar wind speed for the neutron monitors Apatity, Oulu, Newark, and Moscow,

This shift continues until the subsequent solar minimum (around 1996), reaching its minimum phase at or near the solar minimum. Subsequently, approximately 22 years after the 1990 polarity reversal, when the SPMF returns to the same

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polarity state (A > 0), the phase shift to earlier hours reappears. It reaches its minimum value near the solar minimum of 2009 and then gradually recovers toward the pre-reversal level. When the SPMF again returns to the same polarity state (A>0) in 2014, the time of maximum shifts to early hours and reaches its historic low value at solar minimum 2019; then, it starts to recover up to 2022, as shown in Figure (2 to 4).

These observations strongly support the observations of (Singh & Badruddin, 2006). Singh & Badruddin, (2006) suggest that the time of maximum diurnal anisotropy is influenced primarily by the orientation of the solar magnetic field rather than by solar activity or co-rotating high-speed streams.

The plots of the amplitude and phase of diurnal anisotropy with the mean yearly interplanetary magnetic field (IMF) values are illustrated in (Figure 5 and 6) shown a very similar pattern of variation, suggesting an 11-year cycle. The fluctuation in the amplitude vector exhibits temporal variations from 1986 to 1991, with transitions occurring from low to moderate and subsequently from moderate to high levels, excluding observations from the Apatity neutron monitor station. Notably, distinct deviations from this pattern are observed during the periods of 1996 to 1998 for Apatity and 1996 to 1999 for the remaining three neutron monitors, as well as from 2009 to 2012 and 2020 to 2022, mirroring trends observed in the Interplanetary Magnetic Field (IMF).In contrast, in 1996 and 2019, the minimum of the diurnal phase is obtained close to the minimum of the IMF.

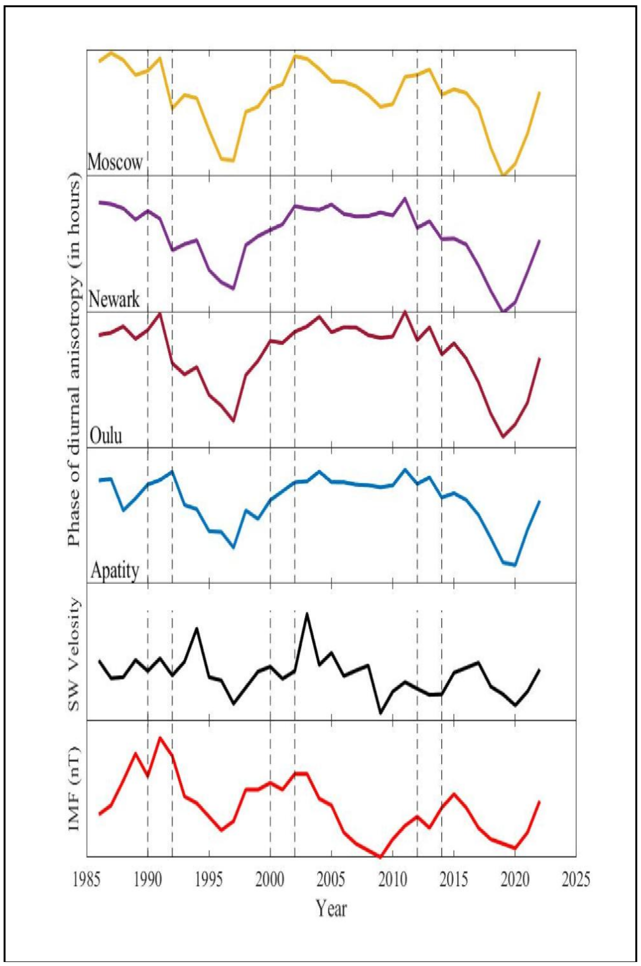

Figure 6 Shows the variation of the diurnal anisotropy phase vector with the IMF and solar wind speedfor the neutron monitors Apatity, Oulu, Newark, and Moscow.

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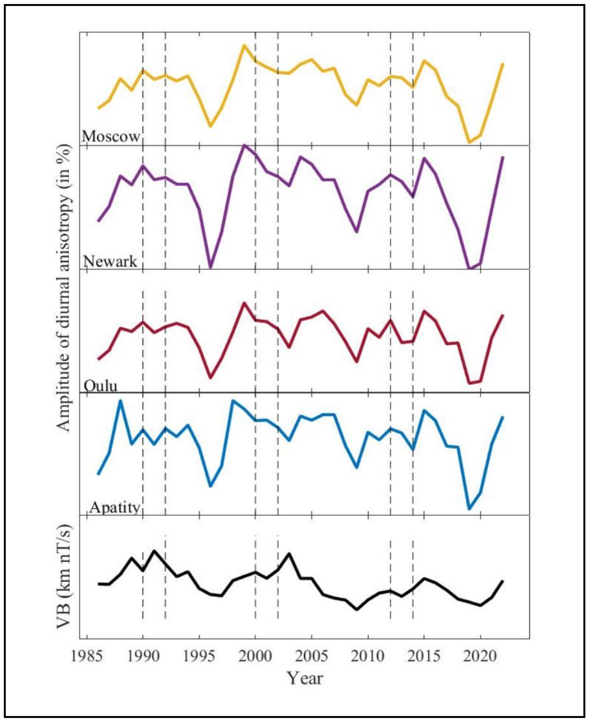

Figure 7 Shows the variation of the diurnal anisotropy vector with product of the IMF and solar wind speed for the neutron monitors Apatite, Oulu, Newark, Moscow,

The direction of the IMF is determined by the solar wind velocity (Zuberi M, 2023). Among the three processes, convection, diffusion, and drift, which are responsible for modulation of cosmic rays, the solar wind speed is related to convection, whereas diffusion depends on the strength of the interplanetary magnetic field and its variations (Aslam and Badruddin, 2012). The expectation is that the time of maximum of diurnal anisotropy will mainly show a co-rotating component pointing to 18:00 h local solar time, but observations show that as the solar cycles progress, the phase shifts to noon time lowest in SC-24.

The diurnal anisotropy vectors and solar wind speed data spanning the timeframe from 1986 to 2022 are graphically represented in Figure 5. The variations in solar wind speed do not precisely align with those of the F10.7 variations, noteworthy synchronizations between the peaks of the interplanetary magnetic field (IMF) and solar wind speed are observed. Specifically, the peak of the yearly average of the IMF coincides with that of the solar wind in 2003, with the yearly average of the solar wind peak lagging by three years in 1991(1994) and by two years in 2015 (2017).

The speed is slowest during the latest minimum of cycle 23, compared with the previous three minima. The mean yearly solar wind speed variation not showed a similar variation pattern. The diurnal amplitude and solar wind speed correlations were weaker than the amplitude and IMF correlations.

This implies that IMF diffusion has a greater impact on diurnal anisotropy than solar wind convection (Koi et al., 2023; Zuberi M, 2023). In the observations, the amplitude increased as the solar wind velocity increased from low to modest, but it did not change much when the velocity increased from modest to high. The amplitude of daily anisotropy was found to be minimum in 2009 and 2020 at the time of minimum solar wind speed. Observations also indicated that the phase was aligned with local solar noon, but it shifted to earlier hours when the solar wind velocity decreased. The phase of diurnal anisotropy was found to be at a minimum near the minimum solar wind speed in 1997 and 2020.

In this analysis, it is observed that the diurnal amplitude is firmly correlated with the IMF but not assertively correlated with the solar wind speed.

When we studied separate plots of diurnal amplitude and phase with the product BV (km nT/s) of solar wind speed V (km/s) and interplanetary magnetic field B (nT), we concluded that diurnal amplitude has a good correlation with VB. The diurnal amplitude was found to be minimum at the minima of VB in 1996 and 2009 and 2019 (figure 7), and the time of maximum diurnal anisotropy was found to be minimum at the minima of VB in 1997 and 2019 (Figure 8). Hence, both solar wind and IMF collectively increase modulation, as observed by (Ahluwalia, 2005; Sabbah, 2000b).

IV. CONCLUSION

In 37 years of data analysis from four neutron monitors, the diurnal isotropy vector amplitude and phase were studied along with the solar activity parameters $F_{10.7}$, interplanetary magnetic field, solar wind speed, and the product of solar wind speed and interplanetary magnetic field VB. After considering the preceding discussion, we can draw the following conclusions:

1. From Solar Cycle 22 to 24/25, diurnal amplitude, and phase change according to 11-year and 22-year cycles, respectively, which is now a well-known fact.
2. The diurnal phase appears to shift toward noon from the co-rotational direction at 18.00 h local time, as the solar cycles advance from 22 to 24.
3. The maxima of the amplitude of diurnal anisotropy are more spread, whereas the minima correspond to the solar cycle minima.
4. The amplitude and phase of diurnal anisotropy were found to be the lowest in the transition period (2019-20) of 24 and 25 solar cycles. This type of anomaly was found in 1996, but in 2019–20 this value was found to be less than that in 1996.
5. The phase shift to earlier hours begins after the solar polarity reverses from negative ($A < 0$) to positive ($A > 0$) states.
6. The results show that, with some deviations, the changes in the amplitude vector in 1986–1990, 1996–1998, 2009–2012, and 2020–2020 correspond to IMF transitions from low to medium levels and later to high levels. Whereas, in 1996 and 2019, the minimum of the diurnal phase was obtained close to the minimum of IMF.
7. During the observation period, the solar wind does not seem to significantly influence diurnal isotropy. However, the combination of solar wind speed and IMF (VB) appears to be a more effective parameter, consistent with the conclusions of Ahluwalia (2005) for 1964–1976 and Sabah (2000) for 1967–1986.
8. The decrease in diurnal amplitude at the end of Solar Cycle 24 and the beginning of 25 compared to previous solar cycles indicates that the Sun is entering the Secular Mimina, as pointed out by (Rahmanifard et al., 2022) in his analysis of solar cycle from 1 to 24.

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