Educational Administration: Theory and Practice
2024, 30(6), 1981-1990
ISSN: 2148-2403
https://kuey.net/

Research Article

DECADES OF DIURNAL ANISOTROPY: UNRAVELLING THE TIME OF MAXIMUM OF DIURNAL ANISOTROPY

Rakesh Kumar Gautam[1*], S.K. Dubey[2]

[1*]Govt. Polytechnic College, Satna (M.P.), email-rkgautam.gpcs@gmail.com
[2]Madhya Pradesh Bhoj (Open) University, Bhopal (M.P.), email-sushil.dubey.jabalpur@gmail.com

Citation: Rakesh Kumar Gautam[1], (2024), Decades of Diurnal Anisotropy: Unravelling the Time of Maximum of Diurnal Anisotropy, Educational Administration: Theory and Practice, 30(6), 1981-1990, Doi: 10.53555/kuey.v30i6.5629

ARTICLE INFO

ABSTRACT

The diurnal anisotropy in cosmic ray intensity has been the subject of continuous observation and study over the past seven decades. This phenomenon is characterised by diurnal variations in the direction of arrival of cosmic rays and plays an important role in the spatial distribution and propagation mechanism of these high-energy particles. The time of maximum of diurnal anisotropy, which is a key parameter in understanding the fundamental process, has displayed variations that have been attracting researchers for years. This study used 60 years of neutron monitor data to analyse the phase diurnal anisotropy of the cosmic ray flux. The data were collected from the Inuvik and Moscow neutron monitor stations and analysed using the Fourier analysis method. The dataset spanned six decades and was used to identify anisotropic patterns. The results showed that the phase of diurnal variability changed slightly between the A>0 and A<0 polarity epochs, indicating a shift in the anisotropy of the cosmic ray flux arriving at the Earth. During 2019–20, the phase of diurnal anisotropy shifted towards the early hours. This study aimed to better understand these temporal variations.

Keywords: - Diurnal anisotropy, Solar activity, Polarity reversal, Heliospheric, Interplanetary Magnetic field, Cosmic ray intensity, Solar wind speed

Introduction

The study of diurnal anisotropy in cosmic ray intensity is of paramount importance in the field of astrophysics because it provides insights into the dynamic processes of the heliosphere. Diurnal anisotropy refers to daily fluctuations in cosmic ray intensity and directionality observed on Earth, which have been consistently documented for almost seven decades (Belov et al., 2023). These fluctuations are primarily caused by the Earth's rotation and the spatial distribution of cosmic rays in the interplanetary medium (Bieber, 1991). The phase of diurnal anisotropy is a crucial indicator of the distribution of cosmic rays (M. Singh & Badruddin, 2006), it is influenced by solar activity and heliospheric parameters, resulting in a complex and incompletely understood pattern (Tiwari et al., 2012).

At 18:00 local time, time of maximum has been hypothesised to arise owing to steady radial cosmic ray streaming near Earth, possibly caused by minor irregularities in large-scale fields that can result in steady radial streaming near Earth, which is a fraction of the solar wind velocity (Parker, 1964). Ananth et al. (1992) considered the phase of diurnal anisotropy, which is subject to significant variations related to magnetic activity, to be composed of two components: one at 18:00 h in the co-rotation direction and the other at 15:00 h at 45°. The S-N line in the east is caused by the reversal of the solar polar magnetic field, resulting in net cosmic ray streaming in the 18:00 direction, which is aligned with the interplanetary magnetic field (Forbush, 1969). The phase of diurnal variability, which is influenced by the polarity of the solar polar magnetic field over a 22-year cycle, shifts by 2-3 hours from the solar maximum to the minimum (El-Borie et al., 1996; Yi & Oh, 1999). The occurrence of the phase at stations with lower cut-off rigidity is considerably influenced by the drift effect, which is determined by the reversal of the polarity of the solar magnetic field, as mentioned by (Sabbah, 2013). The research conducted by (Tiwari et al., 2005) documented a significant phase shift towards earlier hours starting in 1995, which was particularly evident in 1996 and 1997. This shift is more pronounced at lower latitudes than at higher or mid-latitudes. However, the time of maximum recorded by the high-latitude stations was similar to that of the middle-latitude stations, as noted by Chilingarian and Mailyan (2009). Munakata et al. (2014) further revealed that, during periods of low solar activity, especially in A > 0 epochs, the phase of diurnal anisotropy in free space tends to shift to earlier hours, a finding previously reported by (Sabbah, 2013). This change was attributed to a decrease in the anisotropy component, which aligned with the average magnetic field. Kota & Jokipii (1991) pointed out that the diurnal anisotropy is mainly controlled by 11-year and 22-year cosmic ray modulation cycles, which are driven by drift, except during periods close to sunspot maxima. However, Potgieter (1995) suggested that the role of drift becomes uncertain with increasing solar activity.

The diurnal anisotropy phase exhibited variations with solar cycles, displaying systematic discrepancies between odd and even sunspot cycles, as reported by (Storini et al.,1994). In their research, (A. Singh et al., 2011) identified a substantial diurnal phase shift during the early hours of the descending phase of even solar cycles, while observing no significant changes during the descending phase of odd solar cycles. They also found that the diurnal phase shift was significantly greater during the early hours of the ascending phase of odd solar cycles compared to that of even solar cycles. This study aims to integrate long-term observational data to examine changes in the time of maximum of diurnal anisotropy and to investigate the contributing factors using neutron monitor station data spanning over six solar cycles.

Background and Literature Survey

This phenomenon of diurnal anisotropy of cosmic rays is attributed to an excess of particles arriving from the asymptotic direction at 1800 h local time (Duggal et al., 1970), which refers to variations in the flux of cosmic rays over the course of the day. The diurnal anisotropy is a result of various mechanisms, including the transverse diffusion, convective flow of cosmic rays, and E x B drift (Rao et al., 1972). Additionally, diurnal anisotropy can exhibit symmetrical and antisymmetrical variations with specific phases of solar cycles that reflect the complex interactions of cosmic rays with solar and heliospheric conditions (Chirkov et al., 1968; Forman & Gleeson, 1975). The phase of diurnal anisotropy has two separate independent diurnal components, with maximum asymptotic directions of 128° and 90° east of the sun–earth line (Duggal et al. 1970). The diurnal variation of cosmic rays consists of a convective radial component, which moves cosmic rays radially away from the Sun, as well as a diffusion component, in which cosmic rays spread towards the Sun along the interplanetary magnetic field (IMF) lines in the heliosphere. However, Jokipii et al. (1977) pointed out that the drift motions of charged particles may play an important role in modulation. This finding was further confirmed by Moraal et al. (1979). The model of (Moraal et al., 1979) predicts that when the Northern Hemisphere region points towards the Sun, positively charged particles will flow from the ecliptic to poles of Sun, causing decrease in the intensity of positively charged particles seen near the Earth.

The phase of diurnal anisotropy has shown interesting changes over the decades (Singh & Badruddin, 2006) observed that the phase of diurnal anisotropy varies with a period of two solar cycles, approximately 22 years. However, during significantly low-amplitude anisotropic wave train events from 1981 to 1994, the phase of diurnal anisotropy shifted towards earlier hours and did not follow the solar cycle (Mishra & Mishra, 2008). (Mavromichalaki, 1989) observed a systematic shift towards earlier hours from 1970 to 1977. Kumar (1998) revealed that a shift to early hours during specific periods is related to the polarity of the solar magnetic field, Park (2018) confirming a 22-year periodicity. The studies of (Modzelewska et al., 2021; Park, 2018) have shown that the diurnal phase tends to shift towards later hours during the maximum solar activity years compared with the minimum solar activity years. Furthermore, Okiyi et al. (2017) suggested that phase variation has components of both 22-year and 11-year cycles, influenced by solar polar magnetic field reversal and interplanetary magnetic field strength changes associated with sunspot cycles. These findings collectively highlight the complicated cyclic nature of the phase of cosmic ray diurnal variability. The time of maxima for cosmic ray diurnal variation can vary between solar minima and maxima, with shifts to later hours during solar cycle 23 compared with earlier hours in solar cycle 22 (Dubey et al., 2018).

Data Collection and Methodology

The neutron monitor (NM) serves as a sensitive detector for the detection of secondary cosmic ray particles, more specifically neutrons, generated through interactions of primary particles with the Earth's atmosphere. NM data are of great significance as they provide valuable insights into the time-based and spatial characteristics of the cosmic ray flux. Hourly NM data that had been pressure-corrected from the Inuvik and Moscow stations were downloaded, and the specifications of the NMs are listed in Table 1. The cosmic ray data was obtained from <http://cr0.izmiran.ru/common/links.htm>, while the annual average of F10.7 cm radio flux, solar wind speed (km/s), and interplanetary magnetic field (nT) data were obtained from <https://omniweb.gsfc.nasa.gov/form/dx1.html>. It is imperative to ensure the accuracy of the dataset; thus, days marked by the Forbush decrease and significant transient variations caused by ground-level enhancements in the cosmic-ray intensity were excluded. The criterion for selecting a neutron monitoring station is that continuous data must be acquired without interruption for more than five solar cycles. To analyse the phase diurnal isotropy, the first harmonic of the time series was calculated using Fourier analysis. The average daily anisotropy vectors were calculated by averaging daily values over a year. In this study, a comprehensive analysis of diurnal variability in cosmic ray flux using pressure-corrected NM data for the period–1964-2023 was presented.

Table I

SN	Neutron Monitor	Vertical Cut-off Rigidity	Geo. Latitude	Geo. Longitude	Span
1	INUVIK	0.17 GV	68.35 N	(-133.72) W	1964-2022
2	MOSCOW	2.43 GV	55.47 N	37.32 E.	1964-2022

Results and Discussion

This study was conducted on both the ascending and descending phases of solar cycles (SCs) 20, 21, 22, 23, 24, and early 25, with special emphasis on the minimum conditions of solar cycles 22/23 and 24/25. Significantly, both the solar activity and strength of the interplanetary magnetic field (IMF) gradually declined to a low level, reaching its lowest level in 2009 and continuing to weaken. There was a good correlation between F10.7 and B of 0.78. The decrease in magnetic field B during the decline phase was almost parallel to the decay of solar activity (10.7 cm solar flux), especially during SC-22, 23, and 24, and there was no correspondence in SC-20. The minimum levels of solar activity (F10.7) during SC-20/21, 21/22, and 22/23 were comparable, whereas the maximum levels were dissimilar. After 2009, the average solar activity declined to its lowest during the entire observation period since SC-20. The annual average solar wind speed decreased from SC-24 to 378 km/s by 2020. B had a moderate correlation with solar wind speed, but both showed similar changes after 2009. For the parameters shown in the bottom panel of Figure 1-2; the product BV correlates well with the IMF, therefore, it is suitable for representing heliospheric conditions. Figures 1-2 depict the diurnal anisotropy phase changes at the Inuvik and Moscow NM stations, respectively, from 1964 to 2023. The parameters shown are solar activity (F10.7 cm radio flux, which is a vital indicator of solar activity), IMF strength (B), solar wind speed (V), and the product BV. The passage between the two continuous vertical lines in the figures represents the periods of the corresponding solar cycles. The dotted vertical lines represent the positive and negative polarity epochs of the polar solar magnetic field.

The phase of diurnal anisotropy demonstrates cyclic variation that repeats every ~22 years. This phenomenon has been extensively researched and validated by numerous experts, as evidenced by the findings presented in Figures 1 and 2. Diurnal anisotropy exhibits a more persistent structure in its minima, whereas its time series displays significant changes and a scattered structure in its maxima. Observations indicate that the minima of the phase occurred in 1976, 1996, and 2019, corresponding to periods of low solar activity. Initially, between solar cycles 23/24 (2007–2009), the phase displayed a relatively stable structure. As the solar maximum approached 2012–2014, the diurnal variation became more unpredictable at the Inuvik NM station than at the Moscow station. Nevertheless, fluctuations in phase were observed throughout the solar cycle, although they were more pronounced in odd solar cycles at both NM stations. The greatest shift in phase towards the early hours, typically occurring 3-4 hours, has been observed. Additionally, there have been occurrences of short-term phase shifts towards later hours in 1974, 1987, 1990, 1999, and 2011 at the Inuvik station and in 1965, 1968, and 1991 at the Moscow NM station. Conversely, a short-term phase shift towards the early hours was observed in 1972, 1989, 1992, 2000, and 2009 at Inuvik NM, and in 1967, 1973, 1992, and 2009 at Moscow station. Tezari & Mavromichalaki, (2016) also identified a short-term phase shift during the descending phase of Solar Cycle 23 and the ascending phase of Solar Cycle 24. They highlighted that this shift was particularly noticeable at the peak of these cycles.

The phase of diurnal anisotropy with solar activity is shown in the top panels of Figures 1 and 2, which is consistent with the parameterisation presented by (Ahluwalia, 1988). The convection diffusion model adequately described the solar diurnal variation during 1960–70, 1980–90, and 2001–10 for the Inuvik Neutron Monitor Station. The diurnal variation of cosmic rays has a convective radial component, carrying cosmic rays radially away from the Sun, along with a diffusive component in which cosmic rays diffuse into the heliosphere towards the Sun along the interplanetary magnetic field (IMF) lines. A trend of shifting towards the early hour direction in the diurnal phase was found during the years of minimum solar activity in 1976, 1986, 1995–1996, and 2019–20. A greater shift towards early hours was seen for both neutrons during 1996–97. However, the observed phase in 2019-20 is significantly low during the entire observation period.

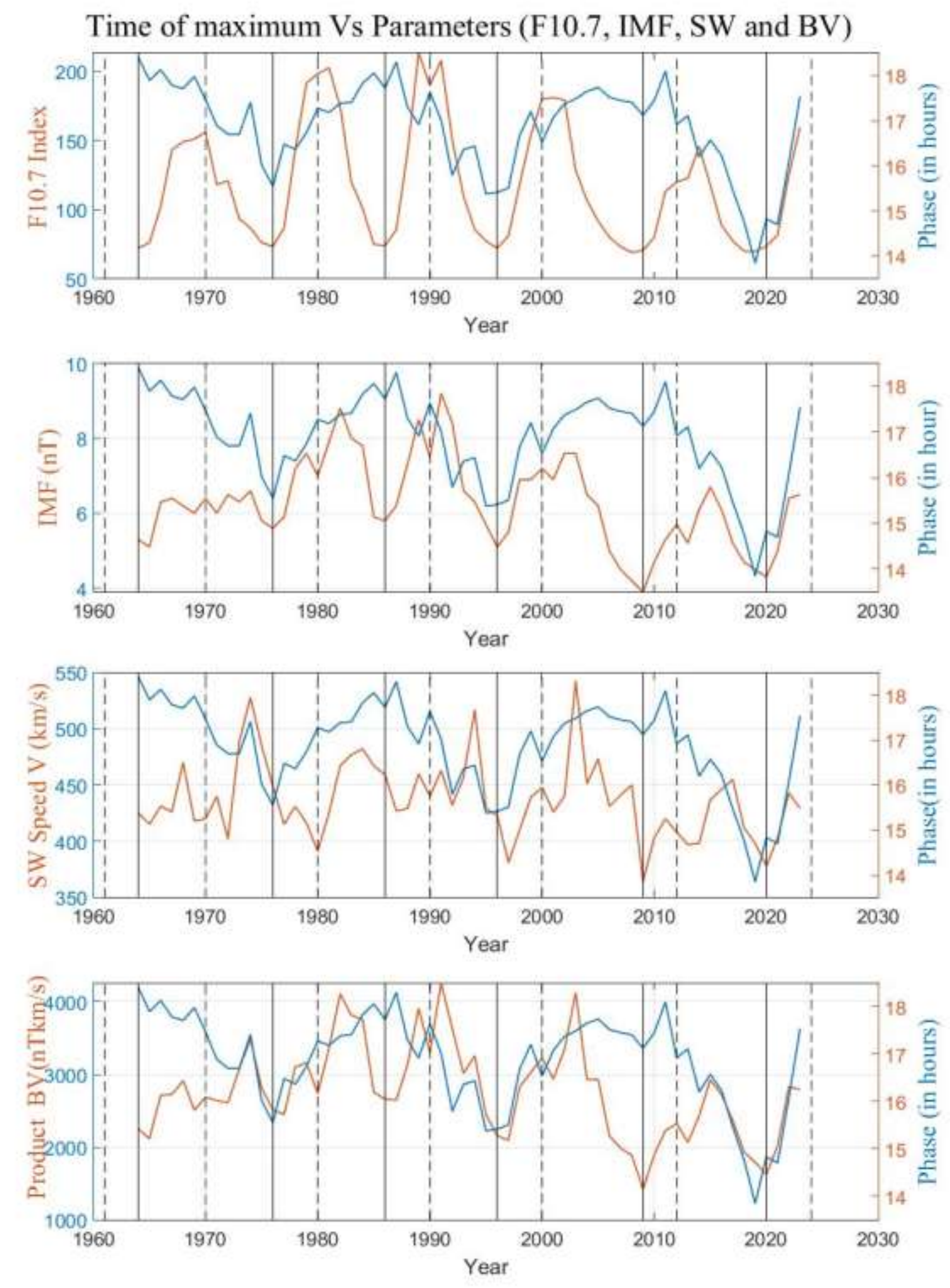

Figure 1 shows the variation in the diurnal phase with solar activity, IMF, solar wind speed and BV for the INUVIK neutron monitor station. The solar activity cycles from solar cycle 20 to early 25 (1964 to 2023) is shown between two consecutive continuous vertical lines, while the positive polarity epoch and negative polarity epoch of the Sun's magnetic field are shown between the vertical dotted lines.

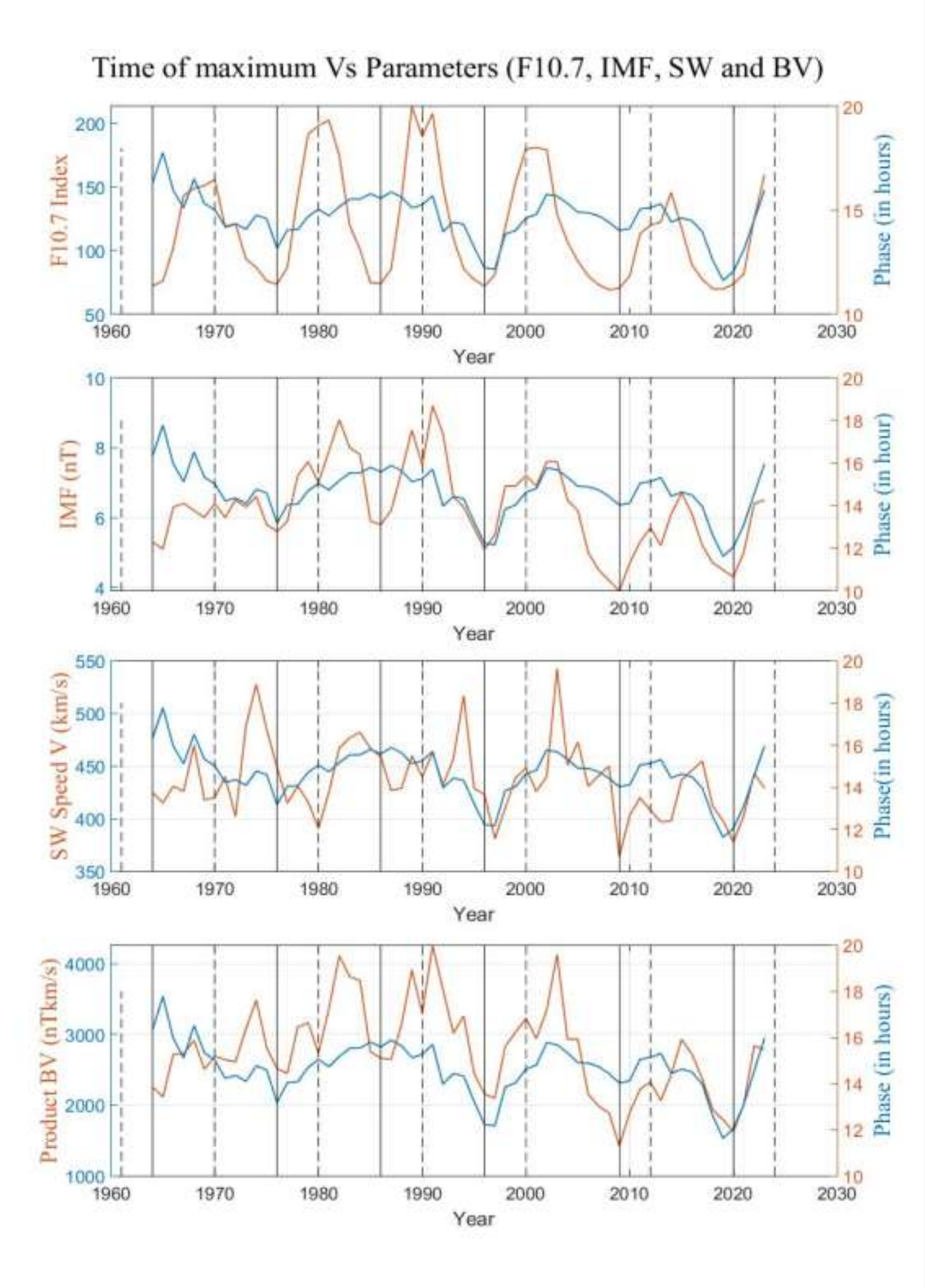

Figure 2 shows the variation in the diurnal phase with solar activity, IMF, solar wind speed and BV for the MOSCOW neutron monitor station. The solar activity cycle from solar cycle 20 to early 25 (1964 to 2023) is shown between two consecutive continuous vertical lines, while the positive polarity epoch and negative polarity epoch of the Sun's magnetic field are shown between the vertical dotted lines.

These observations on change in diurnal phase pattern are important because they provide understanding into the dynamics of the heliosphere and its influence on cosmic ray modulation (Potgieter, 2010). The shift in phase towards early hours indicate complex interactions between solar activity, interplanetary magnetic fields, and cosmic ray propagation as well. Diurnal variability is controlled by solar wind perturbations and the Earth's magnetic field (Starodubtsev et al., 2023). In summary, the diurnal phase changes in cosmic ray variability reflect dynamic processes controlled by the heliospheric atmosphere and its interaction with cosmic rays. These changes are not only of scientific interest, but also have practical implications for understanding space weather and potentially climate studies (Harrison & Stephenson, 2006; Kudela et al., 2000; Potgieter, 2010; Starodubtsev et al., 2023).

To offer a comprehensive view of diurnal anisotropy, our study extended beyond examining fluctuations in the anisotropy phase in relation to the solar activity index (F10.7). We conducted a thorough analysis of the phase of anisotropy with the strength of the IMF (B), solar wind speed (V), and their combined product BV. The phase of diurnal anisotropy exhibited interesting relationships with other solar parameters. Notably, the minima of the time of maximum diurnal anisotropy align with the minima of the Interplanetary Magnetic Field (IMF) strength (B), although there are exceptions. For instance, in 2020, the value of B reached a minimum, whereas the maximum value corresponded to 2019. However, the change in the diurnal phase did not consistently follow variations in solar wind speed (V). Although V exhibits minima in 1997 and 2020 and diurnal phases in 1996 and 2019, its correlation with the phase is almost identical to that of solar activity (F10.7) and IMF. However, the minima of V do not precisely coincide with those of the phase.

The expected anisotropy in cosmic ray intensity is largely expected to manifest as a co-rotating component, oriented towards 18:00 local solar time. Although the diurnal phase does not appear to have any significant relationship with solar wind speed, in the medium-to high-speed range, it was established that the phase of cosmic ray intensity corresponded with local solar noon. As the average speed of the solar wind diminished from it peaks, a shift in phase towards earlier was observed. The decrease in the mean speed of the solar wind results in a shift in the phase towards earlier hours, deviating from the position predicted by the Parker model by approximately 4-6 hours.

This deviation can be partly attributed to the deflection of cosmic rays by the Earth's magnetic field. There is a significant correlation between the diurnal phase and the parameter BV, which appears to be largely unaffected by the solar wind velocity. Studies by (El-Borie et al., 1996) suggested that the phase of diurnal anisotropy is more likely to be shifted towards earlier hours due to streams generated by solar flares. In a study conducted by (Sabbah, 2013), it was observed that the phase of diurnal anisotropy at higher cut-off rigidity stations shifts towards earlier hours, occurring two years after the peak in wind speed for conditions where $A > 0$. Notably, the change in phase seems to be more closely correlated with the parameter BV, which represents the product of the IMF strength (B) and solar wind speed (V). Ahluwalia (2005) has previously demonstrated that the modulation function, which is a measure of how cosmic ray intensity varies with cut-off rigidity, is closely related to the BV product at Earth's orbit. It is worth noting that there is a strong correlation between BV and both the solar activity index (F10.7) and IMF strength. In conclusion, while solar wind speed alone does not have a direct good correlation with solar activity, the BV product has emerged as a valuable tool for understanding cosmic ray modulation.

The analysis of Figures 3 and 4 reveals temporal variations in the time of maximum that are associated with the phases of solar activity. According to the data, there is a noticeable shift in the time of maximum during the transition from the ascending to the descending phase of solar cycles 20, 22, and 24, this shift occurs earlier in the day. However, for odd-numbered solar cycles 21 and 23, the shift is towards later hours, these findings align with those of (A. Singh et al., 2011). In the descending stage of even solar cycles, the time of maximum shifts to earlier hours compared with the ascending phase. This temporal shift correlates with the Sun's magnetic field polarity transition from negative to positive as it moves from the ascending to descending phase. The time of maximum is shifted towards early hours for a positive polarity ($A>0$) of the global Heliospheric Magnetic Field (HMF), whereas a negative polarity ($A<0$) results in a delay towards later hours, using 18:00 as the reference time. These observations are consistent with modulation theory, which encompasses diffusion and drift processes (Wozniak et al., 2022). The gradient and curvature of the heliospheric magnetic field induce a global drift, which is evident in the radial component of GCR anisotropy. During the ($A < 0$) cycle, the radial component was oriented away from the sun, whereas in the ($A > 0$) epoch, it was directed towards the sun. This drift phenomenon contributes to the 22-year cycle of the GCR anisotropy variation (Iskra et al., 2019).

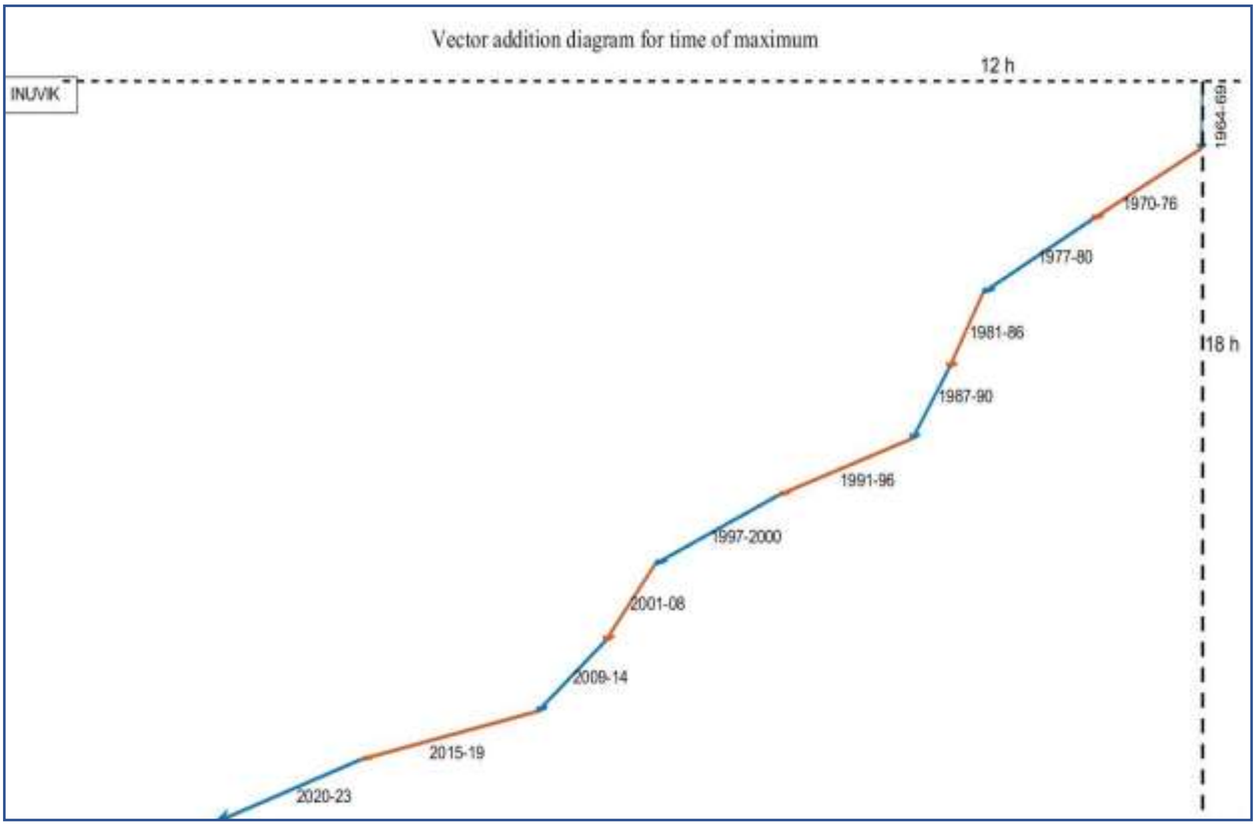

Figure 3 shows an addition diagram of phase anisotropy vector with solar cycle progression for the INUVIK neutron monitor station, in which the phase vector is averaged over the ascending and descending phases of the solar cycle.

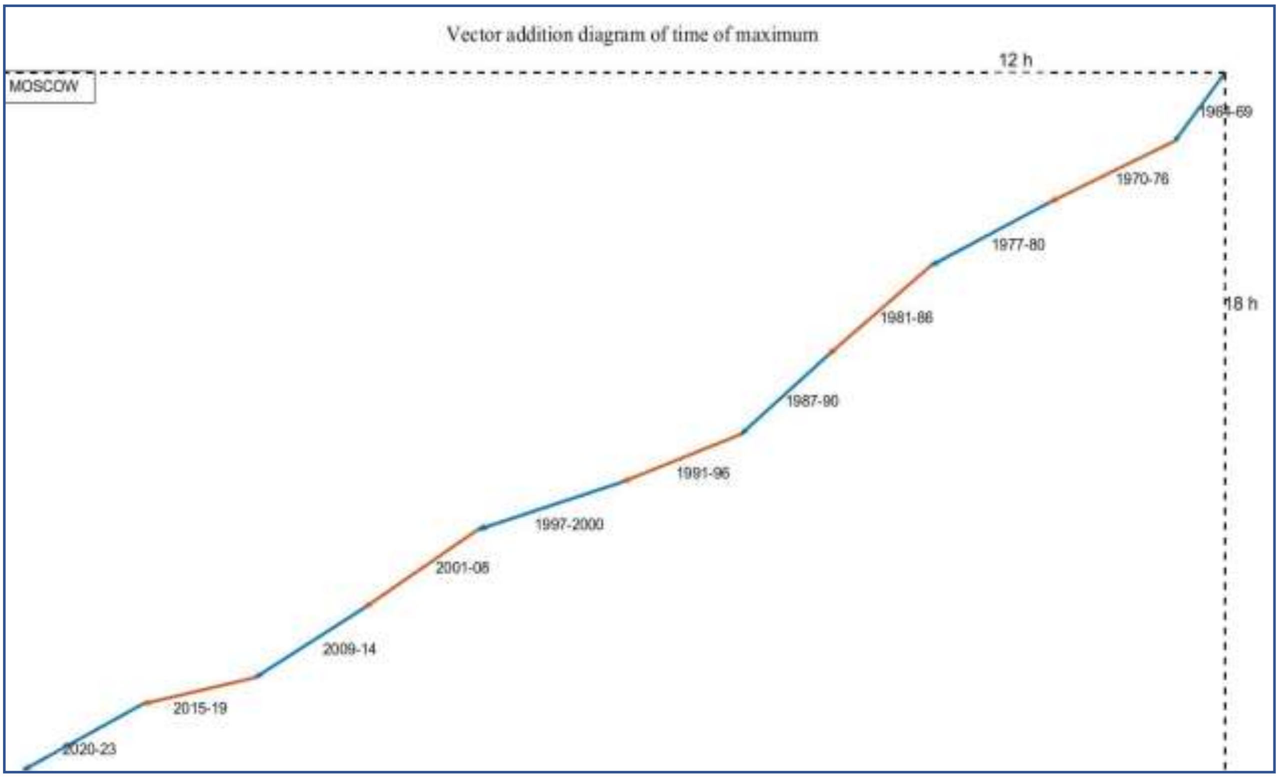

Figure 4 shows an addition diagram of phase anisotropy vector with solar cycle progression for the MOSCOW neutron monitor station, in which the phase vector is averaged over the ascending and descending phases of the solar cycle.

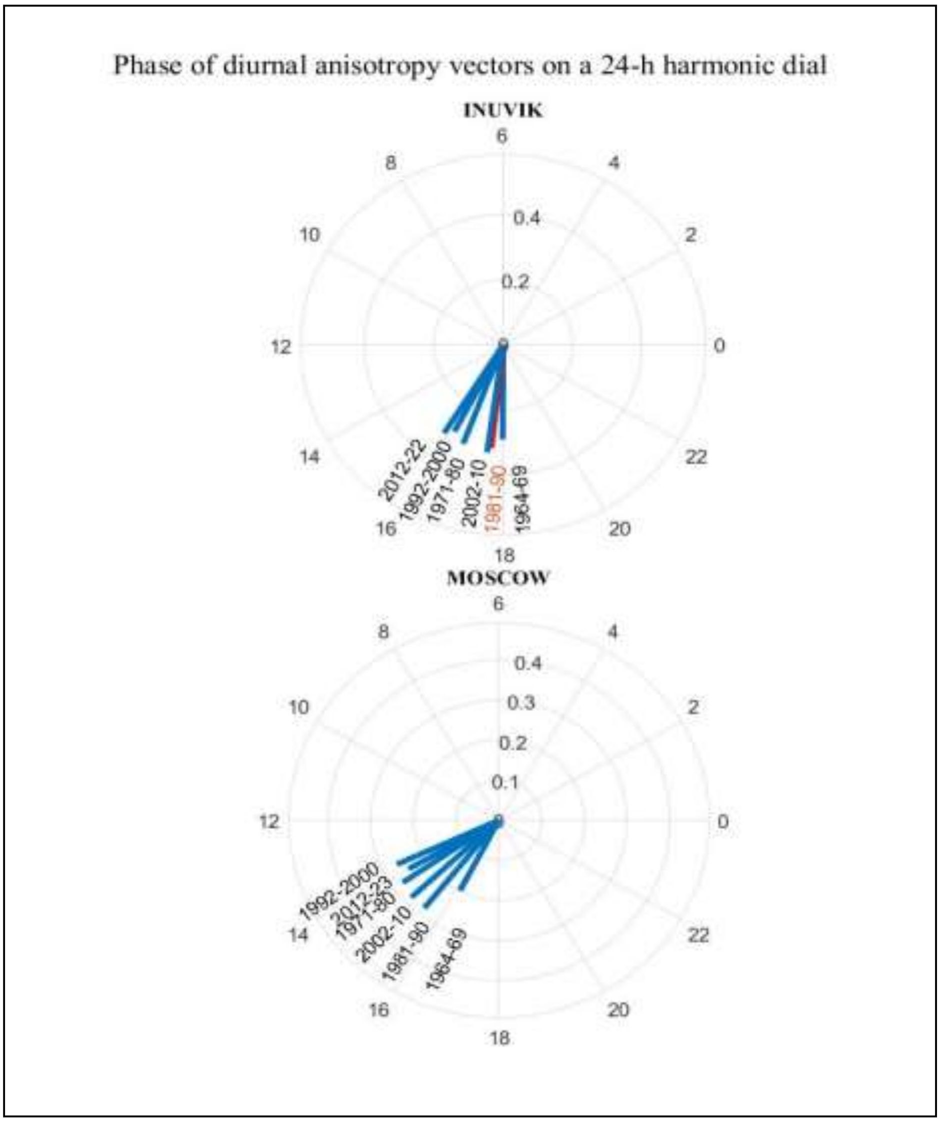

Figure 5 Harmonic dial representations of the diurnal anisotropy averaged over solar polarity epochs $A < 0$ (1964–1969, 1981–1990, 2002-2010) and $A > 0$ (1971–1980, 1992-2000, 2012-2023) polarity epoch for NM stations INUVIK, MOSCOW.

To investigate the phase variation in relation to the polarity reversal of the solar magnetic field, the 24-hour harmonic dial diagrams have been utilized, as illustrated in Figure 5. These diagrams demonstrate that during the positive polarity epoch of the solar polar field, the diurnal phase shifts to an earlier hour as compared to the negative polarity epoch. The phase of diurnal anisotropy, particularly at lower rigidity stations, is significantly influenced by the solar magnetic field polarity reversal, which is attributable to the drift effect, as proposed by (Sabbah, 2013). The sector structure effect of the interplanetary magnetic field on the diurnal anisotropy of galactic cosmic rays is believed to be related to heliospheric current sheet drift. Moreover, the 22-year variation in the diurnal anisotropy of galactic cosmic rays is thought to be associated with drifts caused by the gradient and curvature of the regular interplanetary magnetic field across different solar magnetic cycles with (A>O) and (A<O), as suggested by (Alania et al., 2001). They further explained that the drift effects in the diurnal anisotropy, induced by the gradient and curvature of the global solar magnetic field, are reflected in the radial component of the diurnal anisotropy. Specifically, for (A>O) magnetic cycles, the radial component is oriented towards the sun, whereas for (A<O) cycles, it is directed away from the sun.

Conclusion

In this study, three parameters and a derived parameter were utilised along with diurnal phase data to investigate their interrelationships. By examining information from two neutron monitors with low cut-off rigidity across five solar cycles in both the ascending and descending phases and in both positive and negative solar magnetic field polarities, the following observations were made:

1. The diurnal anisotropy phases exhibited a ~22-year periodicity, with minimum values recorded in 1976, 1996, and 2019.
2. At solar minimum, the phase shifts to an early by 3-4 hours compared to solar maximum. The annual phase at both NM stations displayed superimposed periods of one and two sunspot cycles. A short-term shift towards later hours was observed at Inuvik in 1974, 1987, 1990, 1999, and 2011, and at the Moscow station in 1965, 1968, and 1991.
3. The phase of diurnal anisotropy shows different patterns in odd and even solar cycles, and according to the data, there is a significant shift occurring earlier in the day with as moving from ascending to descending phase for solar cycles 20, 22, and 24, while for odd-numbered solar cycles 21 and 23, the opposite change was observed.
4. The diurnal phase of GCR during the solar minimum between Solar Cycles 20/21 (1976), 22/23 (1996), and 24/25 (2019) displayed a more persistent structure, while near the solar maximum, it became more random. Additionally, the phase of anisotropy during the solar minimum between SC-24/25 (2018-2019) was lower than that during the solar minimum between Solar Cycles 22/23 (1996) and 20/21(1976).
5. The polarity of the Solar Magnetic Field determines the phase of anisotropy, with positive polarity (A>0) resulting in earlier hours and negative polarity (A<0) leading to later hours. The patterns of maximum and minimum diurnal variations differ between the positive and negative polarity cycles.

Bibliography

1. Ahluwalia, H. S. (1988). Is there a twenty-year wave in the diurnal anisotropy of cosmic rays? *Geophysical Research Letters*, *15*(4), 287–290. https://doi.org/10.1029/GL015i004p00287
2. Ahluwalia, H. S. (2005). Cycle 20 solar wind modulation of galactic cosmic rays: Understanding the challenge. *Journal of Geophysical Research: Space Physics*, *110*(A10). https://doi.org/10.1029/2005JA011106
3. Alania, M. V., Aslamazashvili, R. G., Bochorishvili, T. B., Iskra, K., & Siluszyk, M. (2001). The role of drift on the diurnal anisotropy and on temporal changes in the energy spectra of the 11-year variation for galactic cosmic rays. *Advances in Space Research*, *27*(3), 613-618.
4. Ananth, A. G., Agrawal, S. P., & Rao, U. R. (1974). Study of cosmic ray diurnal variation on a day-to-day basis. *Pramana*, *3*, 74-88.
5. Ananth, A.G., Venkatesan, D., & Pillai, S. (1993). Long-term changes in the cosmic-ray diurnal anisotropy. *Solar physics*, *143*, 187-196.
6. Bieber, J. W., & C. J. (1991). Cosmic-ray diurnal anisotropy, 1936-1988-Implications for drift and modulation theories. *Astrophysical Journal*, *372*, 301–313.
7. Bieber, J.W., & Chen, J. (1991). Cosmic-ray diurnal anisotropy, 1936-1988-Implications for drift and modulation theories. *Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 372, May 1, 1991, p. 301-313.*, *372*, 301-313.
8. Chilingarian, A., & Mailyan, B. (2009). Investigation of daily variations of cosmic ray fluxes in the beginning of 24 th solar activity cycle. *Proc. of the 31st ICRC, Lordz*, 1-4.
9. Chirkov, N. P., Krymsky, G. F., & Kuzmin, A. I. (1968). On the nature of some anomalies in the cosmic-ray distribution. *Canadian Journal of Physics*, *46*(10), S614–S616. https://doi.org/10.1139/p68-308
10. Dubey, A., Kumar, S., & Dubey, S. K. (2018). Variation in diurnal phase of cosmic ray intensity during 1986–2017. *Res. Rev. J. Phys*, *7*(3), 20.
11. Duggal, S. P., Forbush, S. E., & Pomerantz, M. A. (1970). The variation with a period of two solar cycles in the cosmic ray diurnal anisotropy for the nucleonic component. *Journal of Geophysical Research*, *75*(7), 1150–1156. https://doi.org/10.1029/JA075i007p01150
12. El-Borie, M. A., Sabbah, I. S., & Bishara, A. A. (1996). Diurnal variations of cosmic rays during a solar magnetic cycle. *Astronomische Nachrichten*, *317*(4), 267–272. https://doi.org/10.1002/asna.2113170405
13. Forbush, S. E. (1969). Variation with a period of two solar cycles in the cosmic-ray diurnal anisotropy and the superposed variations correlated with magnetic activity. *Journal of Geophysical Research*, *74*(14), 3451–3468. https://doi.org/10.1029/ja074i014p03451
14. Forman, M.A., & Gleeson, L. J. (1975). Cosmic-ray streaming and anisotropies. *Astrophysics and Space Science*, *32*(1), 77–94. https://doi.org/10.1007/BF00646218
15. Gleeson, L.J., Moraal, H., & Webb, G.M. (1979). Effects of charged particle drifts on the modulation of the intensity of galactic cosmic rays. In *16th International Cosmic Ray Conference, Vol. 3. Published by the Institute for Cosmic Ray Research, University of Tokyo, 3-2-1, Midori-cho Tanashi, Tokyo 18 JAPAN Edited by Saburo Miyake. International Union of Pure and Applied Physics.; Nihon Gakujutsu Kaigi.; Nihon Butsuri Gakkai. LCCN: 80-502341, p. 1* (Vol. 3, p. 1).
16. Harrison, R.G., & Stephenson, D. B. (2006). Empirical evidence for a nonlinear effect of galactic cosmic rays on clouds. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *462*(2068), 1221–1233. https://doi.org/10.1098/rspa.2005.1628

17. Iskra, K., Siluszyk, M., Alania, M., & Wozniak, W. (2019). Experimental Investigation of the Delay Time in Galactic Cosmic Ray Flux in Different Epochs of Solar Magnetic Cycles: 1959 – 2014. *Solar Physics*, *294*(9), 115. https://doi.org/10.1007/s11207-019-1509-4
18. Jokipii, J. R., Levy, E. H., & Hubbard, W. B. (1977). Effects of particle drift on cosmic-ray transport. I - General properties, application to solar modulation. *The Astrophysical Journal*, *213*, 861. https://doi.org/10.1086/155218
19. Kota, J., & Jokipii, J. R. (1991). The role of corotating interaction regions in cosmic-ray modulation. *Geophysical Research Letters*, *18*(10), 1797–1800. https://doi.org/10.1029/91GL02307
20. Kudela, K., Storini, M., Hofer, M. Y., & Belov, A. (2000). *Cosmic Rays in Relation To Space Weather*. http://spaceweather.com/
21. Kumar, S., Shrivastava, S. K., Dubey, S. K., & Gulati, U. (1998). Effect of solar poloidal magnetic field reversal on diurnal anisotropy of cosmic ray intensity on quiet days.
22. Mavromichalaki, H. (1989). Application of diffusion-Convection model to diurnal anisotropy data. *Earth, Moon, and Planets*, *47*(1), 61–72. https://doi.org/10.1007/BF00056331
23. Mishra, R.K., & Mishra, R.A. (2008). Low amplitude anisotropic wave trains in cosmic rays. *Astroparticle Physics*, *28*(6), 553–564. https://doi.org/10.1016/J.Astropartphys.2007.10.003
24. Modzelewska, R., Krasińska, A., Wawrzaszek, A., & Gil, A. (2021). Scaling Features of Diurnal Variation of Galactic Cosmic Rays. *Solar Physics*, *296*(8). https://doi.org/10.1007/s11207-021-01866-6
25. Munakata, K., Kozai, M., Kato, C., & Kóta, J. (2014). Long-term variation of the solar diurnal anisotropy of galactic cosmic rays observed with the Nagoya multi-directional muon detector. *Astrophysical Journal*, *791*(1). https://doi.org/10.1088/0004-637X/791/1/22
26. Okiyi, U., Okpala, K. C., Tsor, J. O., & Egbunu, F. (2017). Variability of quiet-time diurnal amplitude and phase of cosmic ray count rates in the mid- and high latitudes. *International Journal of Physical Sciences*, *12*(22), 295–307. https://doi.org/10.5897/IJPS2017.4676
27. Park, E. H., Jung, J., Oh, S., & Evenson, P. (2018). Solar cyclic modulation of diurnal variation in cosmic ray intensity. *Journal of Astronomy and Space Sciences*, *35*(4), 219-225.
28. Parker, E.N. (1964). Theory of Streaming of Cosmic Rays and The Diurnal Variation. In *Planet. Space Sci* (Vol. 1, Issue 2). Pergamon Prclls Ltd.
29. Potgieter, M.S. (1995). The long-term modulation of galactic cosmic rays in the heliosphere. *Advances in Space Research*, *16*(9), 191-203.
30. Potgieter, M.S. (2010). The dynamic heliosphere, solar activity, and cosmic rays. *Advances in Space Research*, *46*(4), 402–412. https://doi.org/10.1016/j.asr.2009.09.016
31. Rao, U. R., Ananth, A. G., & Agrawal, S. P. (1972). Characteristics of Quiet as Well as Enhanced Diurnal Anisotropy of Cosmic Radiation. In *Planet. Space sci* (Vol. 20).
32. Sabbah, I. (2013). Solar magnetic polarity dependency of the cosmic ray diurnal variation. *Journal of Geophysical Research: Space Physics*, *118*(8), 4739–4747. https://doi.org/10.1002/jgra.50431
33. Singh, A., Tiwari, A. K., & Agrawal, S. P. (2011). Study of the diurnal variation of cosmic rays during different phases of solar activity. *Proceedings of the 32nd International Cosmic Ray Conference, ICRC 2011*, *6*, 120–132. https://doi.org/10.7529/ICRC2011/V06/0072
34. Singh, M., & Badruddin. (2006). Study of the cosmic ray diurnal anisotropy during different solar and magnetic conditions. *Solar Physics*, *233*(2), 291–317. https://doi.org/10.1007/s11207-006-2050-9
35. Starodubtsev, S. A., Gololobov, P. Y., Zverev, A. S., & Grigoryev, V. G. (2023). Cosmic Ray Fluctuations and Mhd Waves in The Solar Wind. *Solar-Terrestrial Physics*, *9*(2), 73–80. https://doi.org/10.12737/stp-92202309
36. Storini, M., Borello-Filisetti, O., Mussino, V., Parisi, M., & Sýkora, J. (1995). Aspects of the long-term cosmic-ray modulation: I. Solar-cycle ascending phases and associated green corona features. *Solar Physics*, *157*, 375-387.
37. Tezari, A., & Mavromichalaki, H. (2016). Diurnal anisotropy of cosmic rays during intensive solar activity for the period 2001-2014. *New Astronomy*, *46*, 78–84. https://doi.org/10.1016/j.newast.2015.12.008
38. Tiwari, A. K., Singh, A., & Agrawal, S. P. (2012). Study of the Diurnal Variation of Cosmic Rays during Different Phases of Solar Activity. *Solar Physics*, *279*(1), 253–267. https://doi.org/10.1007/s11207-012-9962-3
39. Tiwari, C.M., Tiwari D.P. and Pankaj K. Shrivastava. (2005). Anomalous behaviour of cosmic ray diurnal anisotropy during descending phase of the solar cycle-22. *Current Science*, *88*(5).
40. Witold Wozniak, Iskra, K., & Siluszyk, M. (2022). The Asymptotic Directions of Approach and the Magnetic Rigidity Cutoff of Cosmic Ray Particles for Airports at Different Latitudes and Longitudes. *Kinematics and Physics of Celestial Bodies*, *38*(6), 300–315. https://doi.org/10.3103/S088459132206006X
41. Yi, Y., & Oh, S. Y. (2008). Modulation cycles of GCR diurnal anisotropy variation. In *Proc. 30th Int. Cosmic Ray Conf*