

Long-Term Variations of Diurnal Cosmic-Ray Anisotropy (1976–2025): Relationships with Solar Activity and HCS Tilt

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Abstract: *This study investigates the long-term behaviour of the diurnal anisotropy of galactic cosmic rays (GCRs) in response to solar activity and the large-scale heliospheric magnetic configuration during Solar Cycles 21-25 (1976-2025). Pressure-corrected hourly cosmic-ray intensity data from the Newark and Oulu neutron monitors were analysed using Fourier harmonic analysis to derive the amplitude and phase (time of maximum). Their annual mean values were then examined in relation to solar and heliospheric parameters.*

The diurnal amplitude exhibits a quasi-11-year variation, with generally enhanced values during periods of higher solar activity and reduced values near solar minima. Significant relationships with the 10.7 cm solar radio flux (F10.7) and heliospheric current sheet (HCS) tilt indicate that both solar activity and heliospheric magnetic configuration contribute to the modulation of GCR anisotropy. In contrast, the diurnal phase shows a pronounced approximately 22-year variation, with a tendency toward earlier local times during positive magnetic polarity epochs and later times during negative polarity epochs. The ascending and descending solar cycle trajectories also reveal an odd-even dependence, particularly in the time of maximum.

The SC-24/25 transition is characterised by an exceptionally low diurnal amplitude and an early phase during 2019–2020. Both parameters subsequently show a sustained recovery during Solar Cycle 25 through 2025. Overall, the results demonstrate that long-term GCR diurnal anisotropy reflects the combined influence of solar-cycle activity, heliospheric magnetic-field polarity, and HCS configuration, providing a useful observational measure of long-term cosmic-ray modulation and heliospheric transport.

Keywords: Diurnal anisotropy; Galactic cosmic rays; Neutron monitor; First harmonic; F10.7 solar radio flux; heliospheric current sheet (HCS); HCS tilt; solar magnetic-field polarity; Solar Cycle

I. INTRODUCTION

Galactic cosmic rays originate from interstellar space and enter the heliosphere, where the solar wind and magnetic field modulate them through convection, diffusion in magnetic irregularities, adiabatic energy changes, and gradient, curvature and current-sheet drifts. Because these processes vary with solar activity and with the large-scale configuration of the heliospheric magnetic field, the cosmic-ray intensity observed near Earth carries signatures of both short-term and long-term heliospheric variability, and these transport processes are recognised as the origin of the 11- and 22-year modulation cycles [1].

A key feature of the modulation is its dependence on the polarity of the large-scale HMF. The solar polar magnetic field reverses approximately every 11-years, so the full magnetic cycle is completed in about 22-years, and each reversal reverses the sense of gradient and curvature drifts of charged cosmic rays [1]. Cosmic rays of a given charge



sign therefore follow different trajectories in different polarity epochs, producing a characteristic 22-year variation of the intensity and anisotropy that cannot be explained by the ordinary 11-year variation of solar activity alone [1], [2]. The wavy heliospheric current sheet is an integral part of this modulation, especially near solar minimum, when the global heliospheric configuration becomes relatively well organised [2], [3].

The diurnal variation of the cosmic-ray intensity is one of the most useful ground-based manifestations of the cosmic-ray anisotropy [4]. A near 24-hour periodicity arises because the Earth rotates through an anisotropic cosmic-ray distribution [5] and the observed anisotropy represents the combined effect of the density gradient, diffusion and drift in the HMF, and solar-wind convection [6]. Under equilibrium conditions the Compton-Getting effect places the expected maximum approximately in the corotation direction, near 18 h local time, but the observed phase can depart from this reference direction because the radial and azimuthal components of the anisotropy vary with heliospheric conditions and magnetic-field polarity [7].

Several studies have shown that the diurnal anisotropy varies with the phase of the solar cycle, the polarity of the solar magnetic field, and the characteristics of the observing station [8]. Long-term observations further indicate that the amplitude and phase do not necessarily follow the same periodic behaviour, the amplitude is generally associated with the approximately 11-year solar activity cycle, whereas the phase exhibits a strong Hale-cycle, approximately 22-year variation [4], [5], [9]. Neutron-monitor studies have shown systematic differences in the time of maximum between positive ($qA > 0$) and negative ($qA < 0$) polarity epochs, it shifts to earlier local times during ($qA > 0$) and to later local times during ($qA < 0$) [6], [10], [11] providing an important experimental link between the measured diurnal anisotropy and the theoretical drift description of cosmic-ray modulation [1], [7].

The dependence of the diurnal anisotropy on neutron-monitor (NM) rigidity is also important. Because NMs respond to cosmic rays over rigidity ranges set by their geomagnetic cutoff, stations with high and low cutoffs sample different energy populations of the cosmic-ray spectrum [12]; an investigations have shown systematic changes of the amplitude and phase with cutoff rigidity, latitude and longitude [13], [14], and cosmic rays of different rigidities do not respond identically to the same heliospheric modulation conditions. This provides an additional reason for using neutron monitors at different locations when investigating the long-term anisotropy [15], [16].

The present study is particularly concerned with the HCS, whose wavy structure and tilt vary significantly over the solar cycle, flat and weakly inclined near solar minimum, heavily inclined and complex near solar maximum. The HCS tilt shapes charged-particle drift trajectories and is a central element of modern cosmic-ray transport theory [1], [17]. The 10.7 cm solar radio flux ($F_{10.7}$) serves as the standard continuous index of solar activity for long-term comparisons [18], and comparing the diurnal parameters with $F_{10.7}$ and the HCS tilt reveals how closely the anisotropy follows the solar-activity cycle and the global heliospheric configuration [19].

The recent minimum between Solar Cycles 24 and 25 deserves particular attention. It was associated with exceptionally weak heliospheric magnetic-field conditions, record-high galactic cosmic-ray intensities, low HCS inclination and reduced solar-wind activity [15], making the SC-24/25 transition an especially valuable period for examining whether the diurnal amplitude and phase also behaved unusually [7]. Although several investigations have established the solar-cycle and polarity dependence of the diurnal anisotropy, a long and homogeneous comparison covering several complete solar cycles is still of interest one that examines the amplitude and phase together so as to separate the 11-year variation associated mainly with solar activity from the 22-year variation associated with magnetic polarity, and to relate these behaviours to the HCS tilt [7], [8]. A sufficiently long record also permits direct comparison of corresponding solar-minimum and solar-maximum epochs, and allows one to ascertain whether the recent SC-24/25 minimum is an ordinary extension of previously observed behaviour or a distinctly unusual modulation state [7], [20].

The present work thus studies the long-term variations of the diurnal cosmic-ray anisotropy for 1976-2025, covering Solar Cycles 21-25 and three major HMF polarity reversals. Fourier harmonic analysis is applied to pressure-corrected hourly count rates from the Newark and Oulu neutron monitors to obtain the daily first-harmonic amplitude and phase; the daily values are averaged annually, and the resulting parameters are compared with $F_{10.7}$ and the HCS tilt angle. The study addresses how the diurnal anisotropy relates to the HCS tilt, how it behaves during the ascending and descending



phases of successive cycles, whether the SC-24/25 minimum is anomalous, and how the anisotropy evolves during the recovery and rising phase of Solar Cycle 25 through 2025.

II DATA AND METHODOLOGY

Pressure-corrected hourly cosmic-ray count-rate data from the Newark (vertical cutoff rigidity 2.09 GV; latitude $\approx 39.7^\circ$ N) and Oulu (cutoff rigidity 0.8 GV; latitude $\approx 65.1^\circ$ N) neutron monitors were taken from the IZMIRAN cosmic-ray data archive for 1976–2025, covering Solar Cycles 21–25. The daily diurnal variation was obtained from the 24-hourly count-rate values using first-harmonic Fourier analysis. The first harmonic was represented as

$$I(t) = I_0 + A \cos \left[\frac{2\pi}{24} (t - \phi) \right],$$

where I_0 is the mean daily intensity, A is the amplitude of first-harmonic, and ϕ is the time of maximum of intensity (phase).

The amplitude was expressed as a percentage of the daily mean intensity, while the phase was expressed in local hours (0–24 h). Days with incomplete hourly observations and days strongly affected by transient disturbances, such as Forbush decreases and major geomagnetic disturbances, were excluded from the analysis. The accepted diurnal amplitude and phase values were then averaged annually, and the corresponding standard errors were calculated.

Annual mean $F_{10.7}$ values were derived from the NASA/GSFC OMNI database and the annual mean HCS tilt angles were obtained from the 27-day averaged tilt-angle measurements of the Wilcox Solar Observatory. Pearson correlation coefficients (r) and their statistical significance were calculated in an effort to quantify the linear relationships between the annual harmonic amplitudes and the corresponding $F_{10.7}$ flux and HCS tilt angle. The annual values were also averaged according to ascending/descending solar-cycle phase and according to epochs of SPMF ($qA > 0$) and ($qA < 0$) polarity, and epoch-mean amplitudes and phases were calculated, as well as an event-centred analysis pertaining to the SC-24/25 transition (2019).

III. RESULT AND DISCUSSION

3.1 The diurnal amplitude and the 11-year solar-activity cycle

The annual mean of diurnal amplitude at both stations displays a clear quasi-11-year variation that broadly tracks the sunspot cycle, rising to its largest values near solar maxima and falling to its weakest values at every solar minimum of the record most strikingly in 1996, 2009 and 2019–20 [4], [21]. It is clearly seen from figure (1) that the amplitude of diurnal anisotropy fluctuated randomly during the periods of 1978–84, 1988–94, 2010–15 and 2022–25 for almost both the neutron monitors in this observation which corresponds to the solar maxima. In 1986, 1996 and 2009, the diurnal amplitude dropped significantly and remained low during the solar activity minimum. The SC- 22/23 minimum of 1996 features an abnormally low diurnal amplitude in addition to the solar cycle 24/25 transitions, yet it is larger at the both NM stations. The minimum is precisely the pattern established for the solar diurnal variation over earlier cycles [22].

The overall behaviour is broadly consistent between the two stations, although the magnitude and timing of individual maxima differ somewhat, as expected from their different geomagnetic cut-off rigidities and viewing directions. The diurnal amplitude generally tends to be higher and more variable during periods close to solar maxima, whereas it becomes comparatively lower and more regular near solar minima. The exceptionally low amplitudes observed during the 2019–2020 minimum is notably lower than those recorded during the earlier solar-minimum periods. Superimposed on these long-term variations, a pronounced amplitude enhancement is observed around 1984, particularly during the declining phase of Solar Cycle 21, despite the overall decline in solar activity during this period.

The enhancement in amplitude is seen during the declining phase of Solar Cycle 21 (about 1982–1985), followed by the sharp fall towards the 1986 minimum, is a recurring feature of the record; similar descending-phase enhancements, associated with high-speed solar-wind streams and elevated IMF magnitude, have been reported at several neutron monitors and point to a heliospheric origin of this feature rather than a purely sunspot-related one [22]. The pattern of diurnal amplitude is more scattered near solar maxima and more regular near maxima, may be due to change in interplanetary magnetic field.



Quantitatively, the amplitude correlates positively and significantly with $F_{10.7}$ at both stations (Newark: $r = 0.554$, $p < 0.001$; Oulu: $r = 0.423$, $p < 0.01$), values that bracket the nominal $r = 0.48$ reported for the Deep River diurnal amplitude over 1981–94 [23]. The somewhat stronger correlation at Newark is consistent with its higher effective response rigidity (2.09 GV against 0.80 GV), which samples a portion of the modulated spectrum on which the solar-cycle signature is more pronounced [15], [16]. The relation is a positive long-term association, not an anti-correlation, and confirms that the first harmonic follows the 11-year activity cycle for more than five complete cycles [4].

Long-Term Variation of Diurnal Amplitude with Solar Radio Flux at 10.7

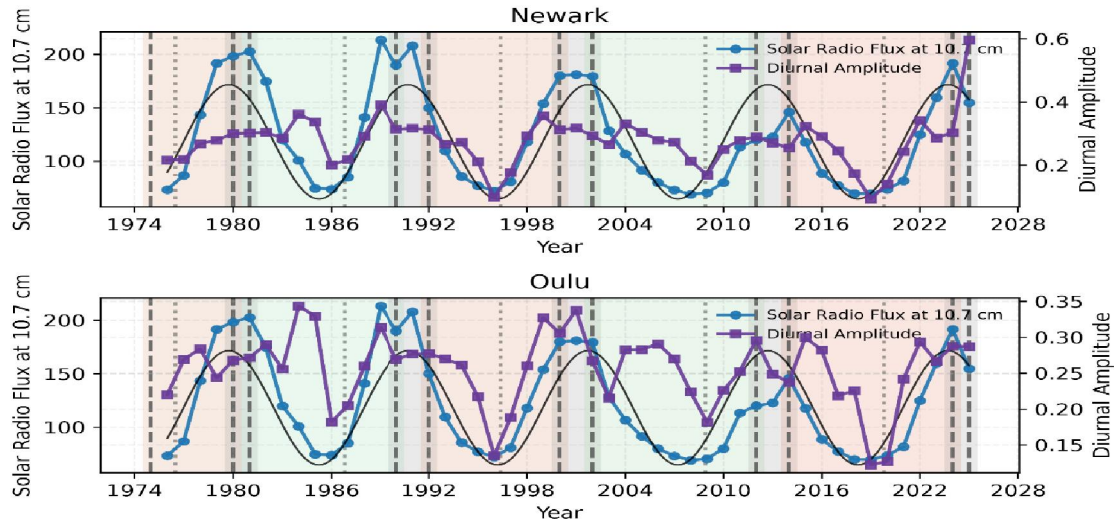


Figure 1. Annual variation of diurnal cosmic-ray amplitude and $F_{10.7}$ solar radio flux at Newark and Oulu neutron monitors during 1976–2025.

3.2 The diurnal phase and the 22-year Hale cycle

The phase behaves in a substantially different way from the amplitude. Instead of the 11-year pattern, the time of maximum shows a pronounced long-term variation related to the 22-year magnetic cycle the phase shifts systematically to earlier hours around the ($qA > 0$) (it is represented in figure 2 by light reddish colour strip) minima of the record (1996 and, 2019–20) and later hours during the positive polarity states, represented by light greenish colour in figure 2 [5], [13]. The phase and $F_{10.7}$ correlation is only moderate (+0.39 at Newark, +0.45 at Oulu), confirming that $F_{10.7}$ i.e. solar activity alone does not control the phase; the directional behaviour of the anisotropy is instead set largely by the large-scale magnetic configuration and polarity-dependent modulation [1], [6]. The generally later phase at Oulu relative to Newark reflects the different directional responses of the two stations [8]. A remarkable excursion of phase around 2005 reaching close to 18 h at Oulu, demonstrating how unpredictable the phase can be and how it can deviate from the simple solar-cycle pattern; comparable excursions have been observed in other long-term phase studies [24], [25].

3.3 The diurnal amplitude and the HCS tilt

The HCS tilt angle (α) varies roughly from 15° near solar minimum to more than 70° near solar maximum, and the diurnal amplitude rises and falls with it on the solar-cycle timescale, higher amplitudes during high-tilt intervals and low amplitudes during the low-tilt, minima obtained at the 1986, 1996, 2009 and at 2019 (figure 3). At both stations the amplitude correlates with the mean HCS tilt angle (Newark: $r = 0.658$; Oulu: $r = 0.499$; $p < 0.001$), and these tilt correlations exceed the corresponding $F_{10.7}$ correlations. This ordering is physically meaningful, the tilt angle (α) determines the structure of the wavy current sheet along which polarity-dependent particle drifts occur, and thereby governs the drift component of the anisotropy more directly than $F_{10.7}$, which is an integrated index of the solar activity level [1].



Long-term Variation Diurnal Phase with Solar Radio Flux at 10.7 cm

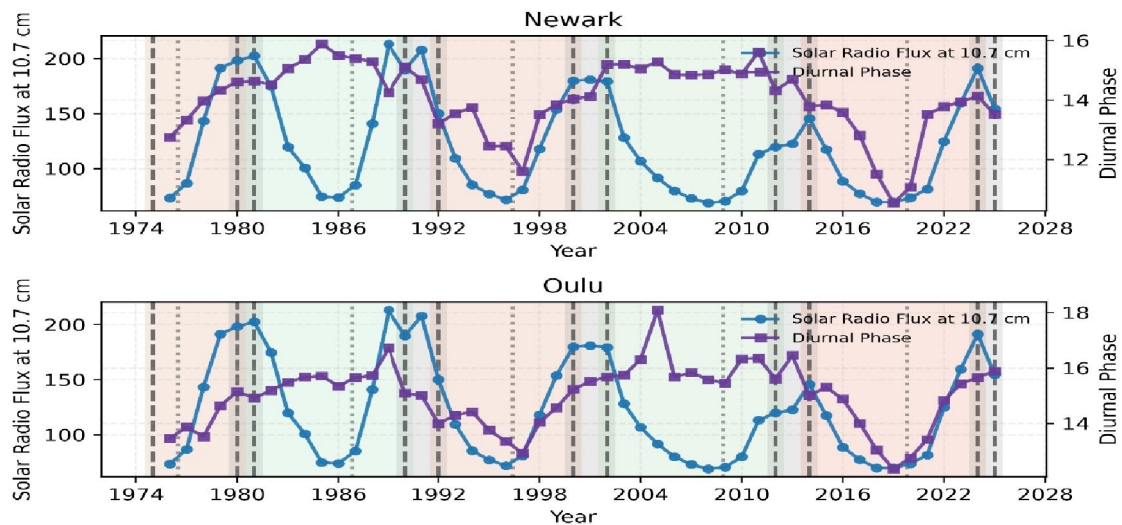


Figure 2. Annual variation of diurnal cosmic-ray phase (time of maximum) and F10.7 solar radio flux at Newark and Oulu neutron monitors during 1976–2025

Long-term Variation of Diurnal Amplitude with Mean HCF tilt alpha

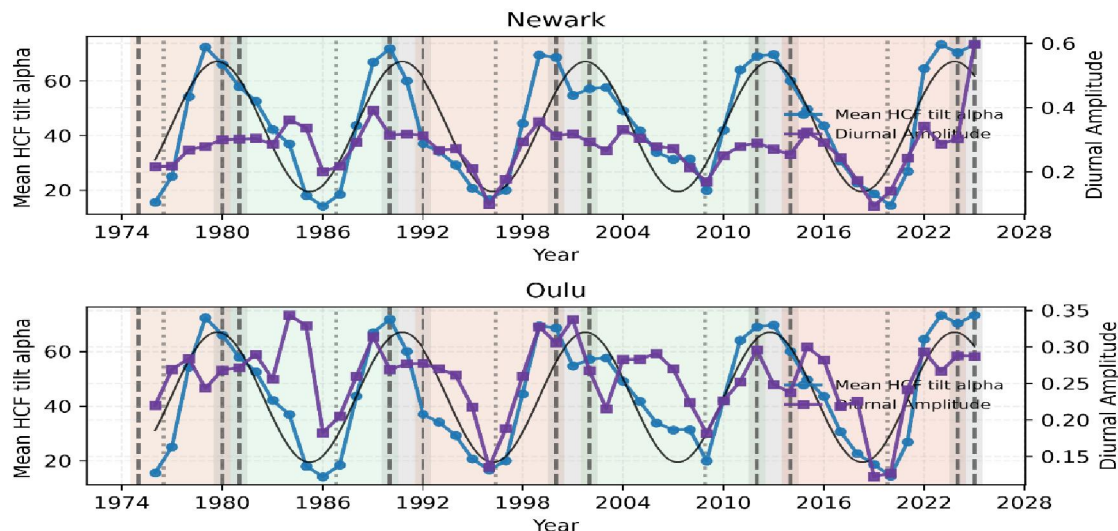


Figure 3. Annual variation of diurnal cosmic-ray amplitude and HCS tilt angle at Newark and Oulu neutron monitors during 1976–2025.

The modulation of cosmic rays by the tilt for both polarity states has long been recognised empirically [26], and the recent record confirms the coupling at its strongest, the drift contribution to the anisotropy near the ($qA>0$) minimum of approximately 2019 reached roughly 40% of the radial anisotropy component, against only about 4% in the ($qA<0$) minimum of 2007–09 [7]. The HCS tilt (α) varies from roughly 15° near solar minimum to more than 70° near solar maximum, and the diurnal amplitude rises and falls with it on the solar-cycle timescale, higher amplitudes during high-tilt intervals and low amplitudes during the low-tilt minima at the 1986, 1996, 2009 and 2019. The diurnal amplitudes, $F_{10.7}$ flux, and HCS tilt angle all show significant variation on about 11-year solar-activity timescale, and the observed



correlation coefficients may be overestimates of the strength of direct physical coupling between the individual parameters. However, the similarity of the correlations independently found at Newark and Oulu suggests that the observed relationships are not just an effect of a station-specific artefact. This interpretation is consistent with the coupled nature of heliospheric cosmic-ray transport, which involves diffusion, convection and drift processes [2].

3.4 The diurnal phase and the HCS tilt

Long-term Variation of Diurnal Phase with Mean HCF tilt alpha

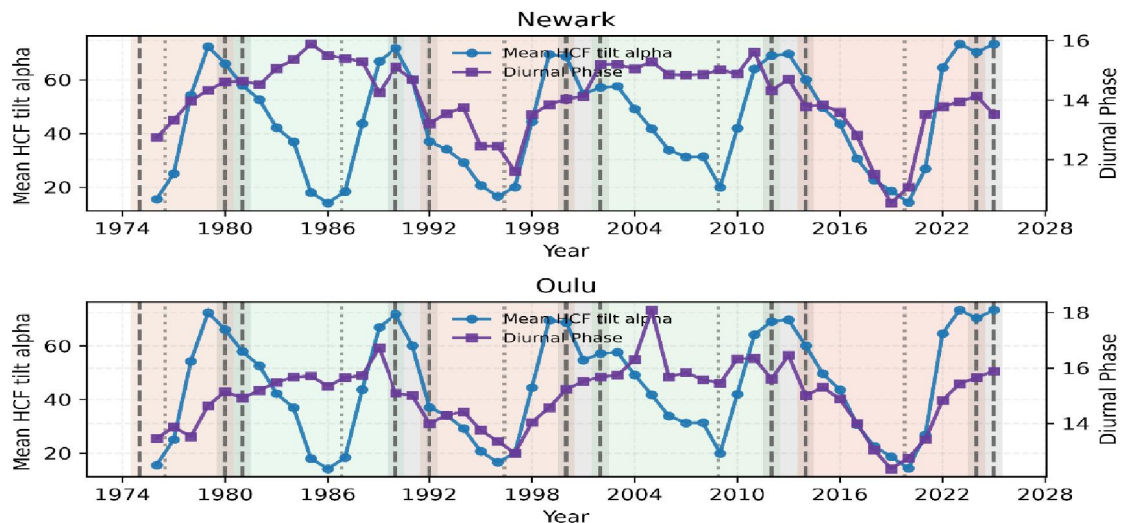


Figure 4. Annual variation of diurnal cosmic-ray time of maximum and HCS tilt angle at Newark and Oulu neutron monitors during 1976–2025.

Unlike the amplitude, the phase has no simple one-to-one relationship with the HCS tilt, figure 4. The clearest connection appears at solar minima during the low-tilt intervals of 1995–1997 and 2018–2020 the phase takes its lowest values (11.5–12 h at Newark and about 13 h at Oulu), and following each minimum it progresses towards later hours as the tilt increases.

But the correspondence is far from complete the strong Oulu phase maximum near 18 h in 2005 occurs at moderate tilt, and some high-tilt intervals at Newark show no corresponding phase maximum at all. The phase therefore carries information about the heliospheric magnetic configuration, and especially its polarity, that the tilt alone cannot capture [1], [2]. Over the record the phase varies over roughly 4–5 h at Newark (about 11.5–16 h) and 5 h at Oulu (about 13–18 h), with Oulu generally later and the two stations tracking each other in the low-phase minima [14], [24].

3.5 Odd–even cycle asymmetry in the ascending/descending-phase trajectories

Figure 5 presents a systematic evolution of the first-harmonic amplitude-phase vectors in the ascending and descending phases of Solar Cycles 21–25. The trajectories at Newark and Oulu show qualitatively similar behaviour implying that the observed variations are not specific to the stations. The phase demonstrates a significant odd-even asymmetry; the descending phases of odd cycles (SC-21 and SC-23) generally the time of maximum of diurnal anisotropy occur later, while even cycles (SC-22 and SC-24) appear comparatively earlier. This behaviour is consistent with the odd-even dependence of cosmic ray diurnal variation reported by [27].



Relative amplitude-phase vector trajectory

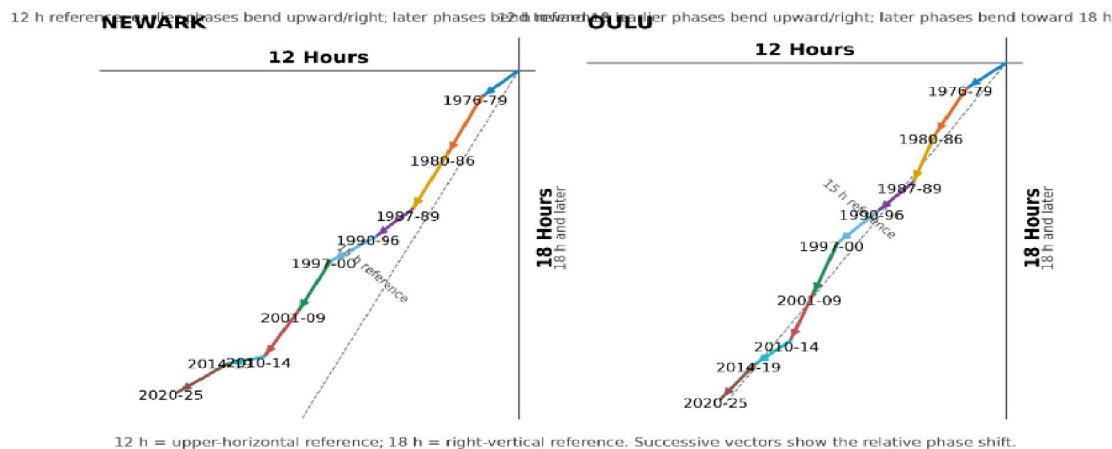


Figure 5. Amplitude-phase vector trajectories at Newark and Oulu obtained from the mean first-harmonic amplitude and phase averaged over the ascending and descending phases of Solar Cycles 21–25.

3.6 SPMF polarity dependence of the phase

Relative amplitude-phase vector trajectory

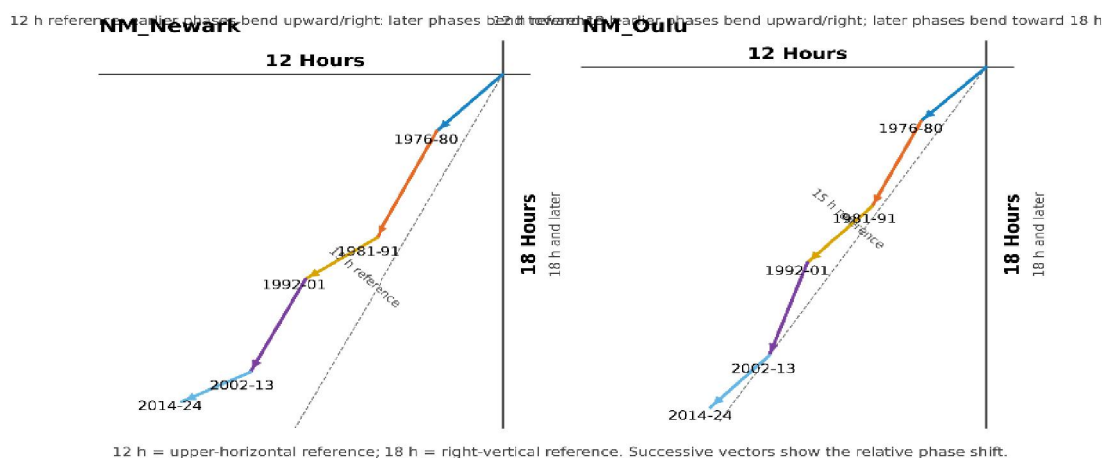


Figure 6. Relative amplitude-phase vector trajectory for diurnal anisotropy at Newark and Oulu, constructed from the mean amplitude and phase over successive SPMF polarity epochs.

Figure 6 presents the relative amplitude-phase vector trajectories of the of the diurnal anisotropy for the Newark and Oulu neutron monitors. The vectors represent the mean amplitude and corresponding mean phase for a given epoch of the Solar Polar Magnetic Field (SPMF), with epochs ordered chronologically from 1976-1980, 1981-1991, 1992-2001, 2002-2013, and 2014-2024. The horizontal and vertical reference directions correspond to 12 h and 18 h phases, respectively. Changes in the length of the vector correspond to changes in the amplitude of the diurnal anisotropy, whereas changes in the direction of the vector correspond to changes in the phase. One of the most remarkable similarities between Newark and Oulu is the systematic offset of vector trajectories from one SPMF polarity epoch to the next. In positive-polarity epochs, especially 1976-1980, 1992-2001, and 2014-2024, the vectors are directed more



toward the early-phase side of the diagram. In the opposite way, during the negative-polarity epochs 1981-1991 and 2002-2013, vectors are shifted toward the latter phase. The same overall polarity dependent behaviour is observed at both stations; however, the magnitude of the displacement and the vector lengths are not the same. So the trajectory is not merely a transition of the amplitude from one polarity epoch to the other. The most obvious systematic change is a rotation or displacement of the vector related to the phase of the diurnal anisotropy. The trajectories at both sites show that the change from positive to negative polarity is associated with a shift to later phase, while the subsequent change back to positive polarity is associated with a shift to earlier phase. This behaviour suggests a persistent polarity dependent modulation of the direction of the diurnal anisotropy.

This pattern is similar to previous long-term studies. [28] using neutron-monitor and muon-telescope observations have shown that the first harmonic of the solar daily variation shows systematic phase shifts related to the reversals of the heliomagnetic polarity and have interpreted these phase shifts in a three-dimensional diffusion-convection model including particle drift. In particular, Sabbah, (2013b) showed that the phase of the diurnal variation is generally earlier for ($qA > 0$) and later for ($qA < 0$) with a clear approximately 22-year variation, which is explained by the effect of solar magnetic polarity on cosmic-ray transport.

The trajectories of the amplitude-phase vectors distinctly demonstrate a modulation of the diurnal anisotropy that is dependent on polarity. In both Newark and Oulu, vectors corresponding to positive SPMF epochs are displaced toward earlier phases, and those corresponding to negative SPMF epochs are shifted toward later phases. This behaviour is consistent with the approximately 22-year Hale-cycle dependence reported in earlier cosmic-ray studies. A three-dimensional diffusion-convection description including the cosmic-ray drift is needed to account for the polarity-associated phase shifts of the first harmonic, as demonstrated by [29]. [10] observed systematically earlier phases in the case of positive polarity, and later phases in the case of negative polarity. Further, Munakata et al., (2014b) show that the diurnal phase tends to shift to earlier hours near solar minima during ($qA > 0$), providing further support for a drift-related interpretation. The fact that a similar behaviour was observed independently at Newark and Oulu, which have different geomagnetic cut-off rigidities, suggests that the polarity-dependent phase shift is a robust heliospheric effect, not a station-dependent effect.

3.7 Consistency between the two stations

The long-term amplitude and phase series at Newark and Oulu are strongly coherent, the cross-station correlation coefficients are $r = 0.80$ for the annual amplitude and $r = 0.86$ for the annual phase. The two stations show the same minima, the same polarity-related phase shifts, and the same odd-even alternation, demonstrating that the principal features of the observed diurnal anisotropy are common to both records and hence of large-scale heliospheric origin rather than local or instrumental [8].

The differences that do appear the stronger late-record enhancement at Newark and the earlier enhancement at Oulu around 2005 are consistent with the different cutoff rigidities (2.09 GV vs 0.80 GV), latitudes (39.7° N vs 65.1° N) and asymptotic viewing directions of the two monitors, which respond to different rigidity ranges and directional samples of the cosmic-ray population [8], [15], [16]

Overall, the Newark-Oulu comparison demonstrates that the long-term variations observed in the present study are not confined to a single neutron-monitor station. The common behaviour supports a large-scale heliospheric origin, while the differences in amplitude and phase reflect the rigidity and geographical dependence of the neutron-monitor response.



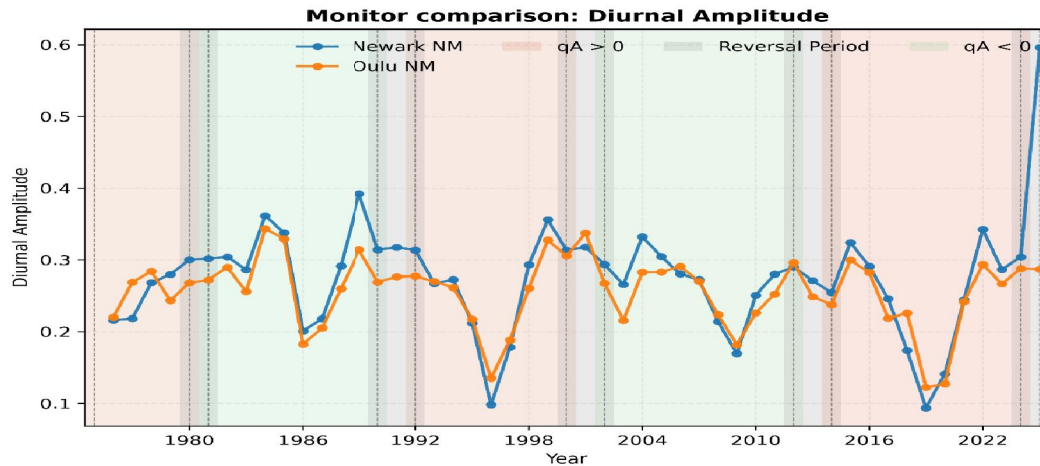


Figure 7. Long-term comparison of the diurnal amplitude at Newark and Oulu neutron monitors for 1976–2025. Shaded regions denote the positive ($qA > 0$), negative ($qA < 0$) and polarity-reversal intervals of the heliospheric magnetic field.

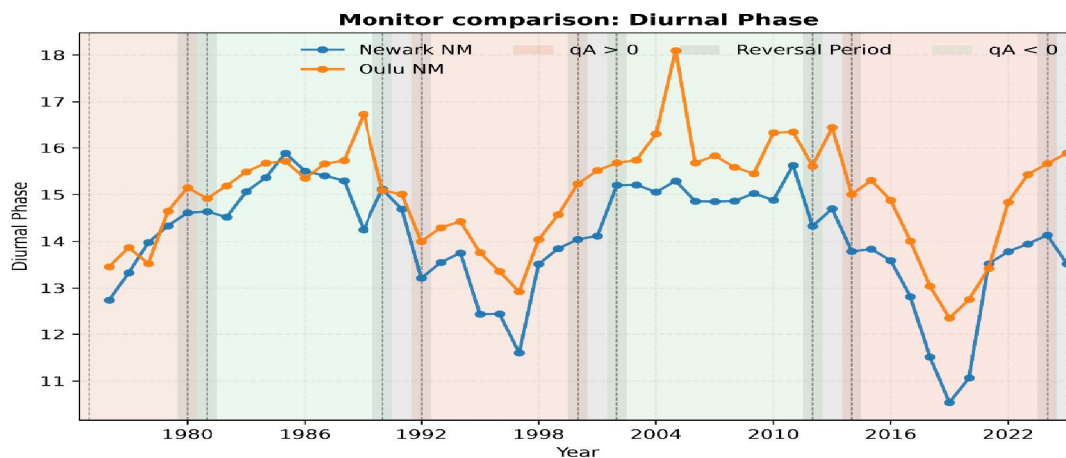


Figure 8. Long-term comparison of the diurnal time of maximum at Newark and Oulu neutron monitors for 1976–2025. Shaded regions denote the positive ($qA > 0$), negative ($qA < 0$) and polarity-reversal intervals of the heliospheric magnetic field.

3.8 The SC-24/25 transition and recovery in Solar Cycle 25

The event-centred analysis represented in figures 9 & 10 makes the exceptional character of the SC-24/25 minimum explicit. At both stations the amplitude declines steadily towards the 2019 transition falling from about 0.32% four years before to 0.09% at the transition at Newark, and from about 0.30% to 0.12% at Oulu and the phase simultaneously shifts to its earliest values (about 10.5 h at Newark, 12.4 h at Oulu), the lowest of the entire study period. Three independent signatures converge at this minimum the weakest amplitude of five decades, the earliest phase, and the weakest solar polar magnetic field of the space age, whose strength reached its lowest recorded level during 2018–2020 [20]. The low amplitude at the onset of Cycle 25 had already been recognised as historically low [21], [31], and the near-40% drift contribution at the transition shows that the anisotropy was then dominated by drift in a weak but unusually well-ordered field rather than by diffusion [7].



Diurnal Amplitude: event-centered comparison - SC24/25 Transition (2019)

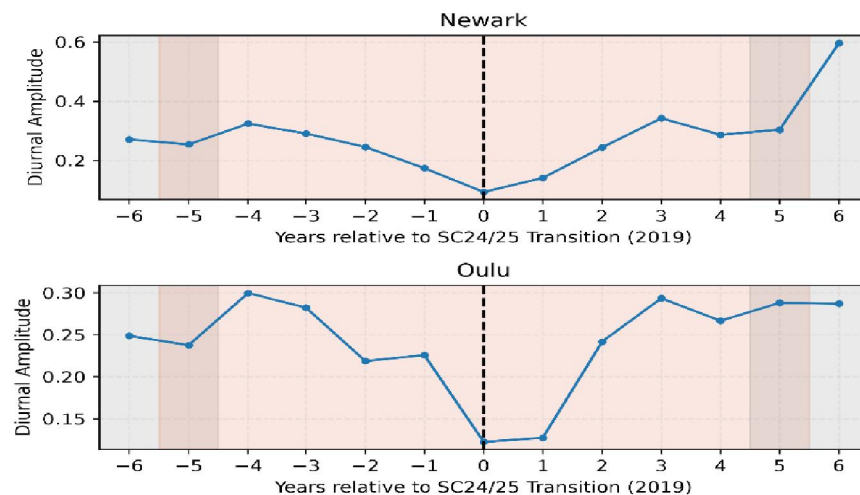


Figure 9. Event-centered variation of diurnal amplitude at Newark and Oulu around the SC-24/25 transition (2019), showing the decline toward the minimum and the subsequent recovery during Solar Cycle 25. Shaded regions indicate the corresponding magnetic-polarity.

Event-Centered Comparison of Diurnal Phase: SC-24/25 Transition (2019)

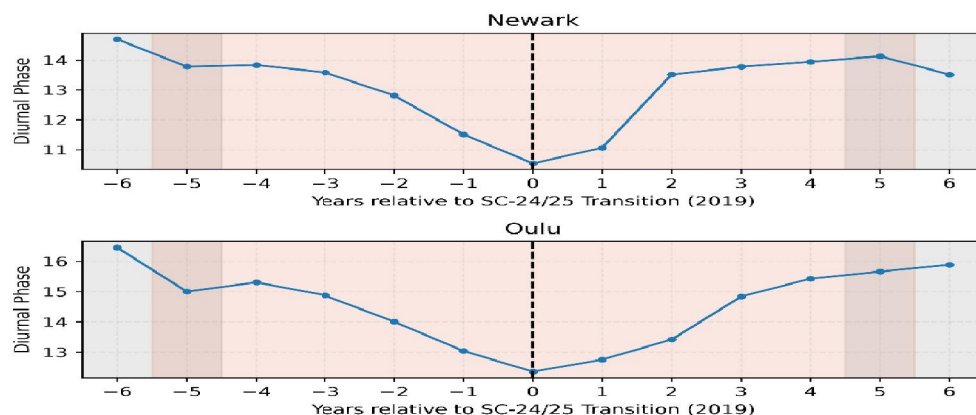


Figure 10. Event-centered variation of diurnal phase at Newark and Oulu around the SC-24/25 transition (2019), showing the decline toward the minimum and the subsequent recovery during Solar Cycle 25. Shaded regions indicate the corresponding magnetic-polarity.

The 24/25 minimum is thus not an ordinary continuation of previous minima but a genuinely unusual modulation state. The recovery during Solar Cycle 25 is equally instructive, and it differs between the stations in a revealing way. Newark shows a deep decline followed by a strong and nearly continuous recovery, reaching record-high values of about 0.5-0.6% by 2025; Oulu recovers more rapidly, returning to about 0.29% within three years of the transition, and then remains comparatively stable. The phases return towards later hours (about 14-15 h at Newark and 15-16 h at Oulu by 2025). The different recovery rates reflect the different rigidity responses and asymptotic viewing directions of the two monitors, and the recovery should not be taken as identical at all stations [8]. In physical terms, the post-transition recovery reads as the re-establishment of the anisotropy as solar activity, the tilt and the accompanying drift conditions rebuilt during the new cycle, the same template seen after earlier ($qA > 0$) minima, where the phase shift to earlier hours persists from the reversal to the minimum and then recovers [13].



Looking ahead, the maximum of Solar Cycle 25 was predicted near 2024 (peak 2024.1 ± 0.8 year) [32], [33] and is now past, so the associated HMF polarity reversal is expected to close the 2014-24 ($qA > 0$) epoch and open a ($qA < 0$) epoch for the declining phase. On the 22-year baseline, the diurnal phase should then drift gradually to later hours, a mirror image of 2019-20 at the next minimum. The secular-minimum scenario allows a less constrained evolution of the amplitude (predicted peak heliospheric field of 5.74 ± 0.80 nT) [20], declining modulation efficiency from cycle 20 to 24 ([34] The anisotropy may still be historically weak, and a stronger than predicted Cycle 25 would bring back typical declining phase amplitudes. The record levels of recovery we see through 2025 at Newark is the first discriminating evidence in favour of the latter interpretation [34].

IV. CONCLUSION

The long-term Fourier analysis of the diurnal cosmic-ray anisotropy at Newark and Oulu over 1976-2025 (Solar Cycles 21-25) leads to the following principal conclusions-

The diurnal amplitude follows the approximately 11-year solar activity cycle, falling to its weakest values at every solar minimum of the record 1996, 2009 and, most profoundly, 2019-20 and correlating significantly with $F_{10.7}$ ($r = 0.554$ at Newark, 0.423 at Oulu) and, more strongly, with the mean HCS tilt angle ($r = 0.658$ and 0.499). The stronger tilt correlation indicates that drift along the wavy heliospheric current sheet is the controlling mechanism, not solar activity alone.

The diurnal phase does not follow a simple 11-year pattern as seen in the amplitude. Conversely, the phase trajectories in the ascending and descending phases of the solar cycles show a strong odd-even dependence. In odd cycles (SC-21 and SC-23) the time of maximum shifts later local times in the descending phases, whereas the corresponding time of maximum shifts earlier local times in the even cycles (SC-22 and SC-24). The resulting bifurcation of the ascending and descending trajectories is mainly in the phase coordinate, showing that the odd-even cycle effect is expressed mainly by the timing of the diurnal anisotropy, not by its amplitude.

The time of maximum shows a true 22-year polarity dependence, it is 1.5-1.7 h later during ($qA < 0$) epochs (15.03 h at Newark, 15.80 h at Oulu) than during ($qA > 0$) epochs (13.34 h and 14.20 h), occurring late at the ($qA < 0$) minima of 1986 and 2008 and early at the ($qA > 0$) minima of 1976, 1996 and 2019 the behaviour expected from charge sign dependent drifts reversing with the solar magnetic field.

The two monitors display coherent long-term variations (cross-station $r = 0.80$ for the amplitude, 0.86 for the phase), confirming the large-scale heliospheric origin of the observed anisotropy; the residual differences reflect their different rigidities, latitudes and viewing directions.

SC-24/25 minimum and recovery in Cycle 25-The 2019-20 minimum is an unusual modulation state the lowest amplitude, the earliest phase, and the weakest polar field of the space era rather than an ordinary continuation of earlier minima. The clear and sustained recovery through 2025, with the Newark amplitude reaching high values and the phase returning to later hours, indicates that the anomaly was a transient state of the prevailing heliospheric conditions and not a permanent change.

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