



Periodic Variation of Anomalous Cosmic Ray Oxygen During Solar Cycles 23 and 24

Pieter Kotzé¹ · Kalevi Mursula²

Received: 5 August 2024 / Accepted: 19 December 2024
© The Author(s) 2025

Abstract

We investigate the evolution of the Rieger periodicity at 152–156 days, the 27-day synodic rotation period as well as the 13.5- and 9-day harmonic periodicities in anomalous cosmic ray (ACR) oxygen (O) fluxes at the energy range between 8–25 MeV/n observed by the *Advanced Composition Explorer* (ACE) satellite during Solar Cycles 23 and 24. The ACR oxygen flux data is analysed using the Lomb–Scargle periodogram and Morlet wavelet spectral analysis techniques. Daily mean oxygen fluxes during solar quiet times are used to identify how the ACR oxygen at different energies varies with the Rieger periodicity and the solar rotation periodicities in each year. This is the first investigation of the periodicity evolution of ACR oxygen ions. Previous investigations have mostly concentrated on the spectral behaviour of GCR particles during various solar cycles of opposite polarities, in particular the 27-day and 13.5-day periodicities. Our analysis revealed a significant temporal and energy dependence in the spectral behaviour of ACR oxygen during both cycles. An important finding of this investigation, not reported before in the literature, is the significant increase in the power of the different ACR oxygen periodicities during the minimum of Cycle 24/25 (characterised by a positive solar polarity) in comparison to the minimum of Cycle 23/34 (dominated by a negative solar polarity).

1. Introduction

Anomalous cosmic ray (ACR) particles are high first-ionization-potential (FIP) neutrals, such as oxygen, that have their origin outside the solar system and drift inwards towards the Sun. In the heliosphere, they become singly ionized ions that have a typical energy in the range of 5–50 MeV/n (Klecker et al. 1998; Potgieter 2013a; Giacalone et al. 2022). Temporal variation of cosmic ray particles correlates closely with solar activity at different timescales (Potgieter 2013b), with the 11-year solar sunspot cycle being the most dominant long-term variation. On the other hand, shorter-period variations like the 27-day synodic rotation and the first harmonics of this period, the 13.5-day and 9-day periodicities, correlate with the passage of co-rotating interaction regions which have their origin in solar coronal holes (Sabbah and Kudela 2011; Kotzé 2020; Modzelewska and Gil 2021). Solar activity

✉ P. Kotzé

¹ Centre for Space Research, North-West University, Potchefstroom, South Africa

² Space Climate Group, Space Physics and Astronomy Unit, University of Oulu, Oulu, Finland

variations within the 0.3–2 year periodicity timescale, which includes the Rieger period (150–160 days), have recently been attributed to magnetic Rossby waves (Korsós et al. 2023). Dikpati et al. (2018) reported that Rossby waves provide evidence of magnetic patterns around the solar tacholine, the region where the solar magnetic field is accumulated. A recent study by Gurgenchvili et al. (2016) showed that the Rieger period has a strong dependence on solar activity level, and Feng et al. (2017) showed that these periodicities in sunspot indices have a strong correlation with the solar magnetic field.

The modulation of cosmic ray (CR) particles in the heliosphere is influenced by properties of the solar wind as well as the orientation of the solar magnetic field and solar activity level. Around solar minima CR modulation is predominantly driven by drifts, while around solar maximum it is affected by enhanced diffusion resulting from a complex magnetic structure (Potgieter 2013b). Drift effects are also responsible for the 22-year cycle in CR modulation, as CR ions are sensitive to the polarity of the solar magnetic field. Particularly, positively charged particles drift inward along the near-equatorial heliospheric current sheet (HCS) when the solar magnetic field is negatively orientated ($qA < 0$ minima), e.g., during the minimum of solar cycle 23/24 (SC23/24), while these particles drift outward along the HCS during positively oriented solar magnetic fields ($qA > 0$ minima), e.g., during the minimum of solar cycle 24/25 (SC24/25). Solar activity levels were anomalously low during both the minima of SC23/24 and SC24/25, resulting in much lower than usual interplanetary magnetic field strengths which was accompanied by unusually small tilt angle values of the heliospheric current sheet. In fact, during the minimum of SC24/25 the tilt angle was more than 50% lower than during the minimum of SC23/24 (Rankin et al. 2022). This resulted in the highest recorded levels of GCR intensities (Rankin et al. 2022) as observed by both spacecraft and ground-based neutron monitors (NM). A recent study by Rankin et al. (2022) of CR oxygen particles, using the Parker Solar Probe, revealed that the ACR component is remarkably similar across the minima of Solar Cycle 23/24 and Solar Cycle 24/25.

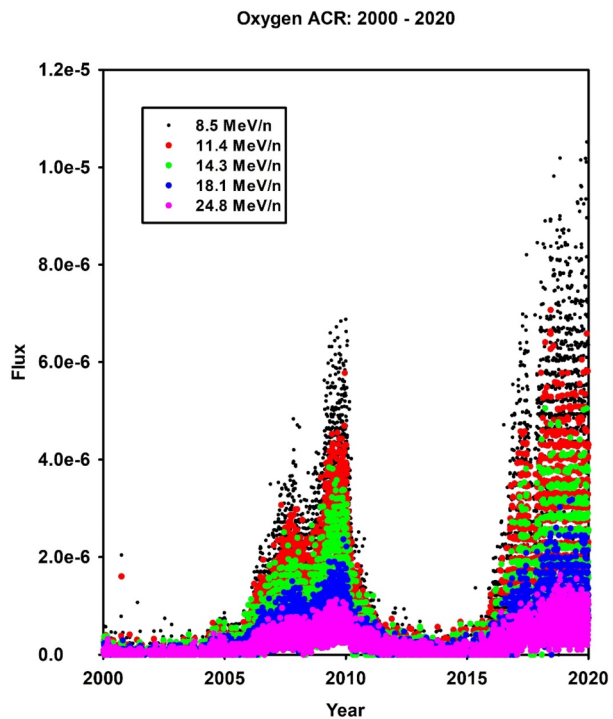
The periodicity behaviour and modulation, particularly, of GCR's has been a topic of investigation for several decades, using both ground-based NM data (Gil and Mursula 2017; Kotzé 2020) as well as space-based satellite data using, e.g., the Advanced Composition Explorer (ACE) satellite (Leske et al. 2010; Kotzé 2021). A recent study by Kotzé (2023) found an energy and solar-polarity dependence for the 27-day and 13.5-day periodicities of proton, carbon, and oxygen GCR particles observed by ACE/CRIS and SOHO/EPHIN spacecraft during SC23 and SC24. Larger powers of these periodicities were observed during positive polarity intervals ($qA > 0$; SC24) than negative polarity ($qA < 0$; SC23).

The different characteristics between the minima of SC23/24 and SC24/25, combined with opposite drift patterns, provide a unique opportunity to investigate the periodicity behaviour of, particularly, ACR oxygen ions, and to compare their variation to the periodicity behaviour of GCR particles during the same time interval (Kotzé 2023). Previous studies (Fu et al., 2021, 2023) indicated that oxygen energy spectra below about 30 MeV/n are dominated by ACRs, in contrast to the GCR components that occur at higher energies.

2. Data Selection and Analysis

Low-energy (less than about 35 MeV/n) oxygen ion data as measured by the Advanced Composition Explorer / Solar Isotope Spectrometer (ACE/SIS) between 2000 and 2020 were utilized in this investigation. The main purpose of the ACE/SIS instrument (Stone et al. 1998), located at the L1 point in space, is to measure the isotope composition of energetic particle nuclei from He to Ni in the energy range between about 10 and 100 MeV/n. Daily

Figure 1 Quiet-time daily mean (flag = 0) ACR oxygen flux observations at 8.5 MeV/n, 11.4 MeV/n, 14.3 MeV/n, 18.1 MeV/n and 24.8 MeV/n by ACE/SIS during Solar Cycles 23 and 24.



mean Level-2 verified data were downloaded from the ACE website https://izw1.caltech.edu/ACE/ASC/level2/lvl2DATA_SIS.html for further study. In general, low-energy CR particle data can be contaminated by solar energetic particles (SEPs) originating in solar eruptions. Daily solar activity levels have been flagged by the ACE Science Centre (ASC) together with the Level-2 verified particle flux data. The general rule applied by ASC was that if the 3.43–7.29 MeV/n He flux exceeds 1.0×10^{-4} particles/(cm² Sr sec MeV/n), the flag is set to 1 (active period), and otherwise it is set to 0 (quiet period). All oxygen particle data were selected here according to this criterion (flag = 0) to ensure the cleanest possible ACR data for this study. Figure 1 shows a plot of the selected ACE/SIS oxygen quiet-time daily mean fluxes as observed at energies below 30 MeV/n during SC23 and SC24. Figure 1 also clearly shows that the highest daily mean fluxes are observed at 8.5 MeV/n during SC24.

Figure 1 shows that the 8–25 MeV/n ACR oxygen flux (particles/(cm² Sr sec MeV/n)) during the SC24/25 minimum increased by an average of $49 \pm 17\%$ in comparison to the minimum of SC23/24. This is in a good agreement with results found by Fu et al. (2023), who obtained an increase of $48 \pm 12\%$ for ACR oxygen in the energy range of 6–13.4 MeV/n during the same time interval using WIND satellite data. A clear energy dependence can also be observed in Figure 1, with distinct differences in profiles between lower and higher energies. In addition, the sharp peaked profiles during SC24 are in sharp contrast to the flat profiles of oxygen GCR, as reported by Fu et al. (2021). This indicates a distinct difference between the modulation of ACR and GCR particles.

We use the Lomb–Scargle (Lomb 1976; Scargle 1982) periodogram spectrum analysis technique to determine the behaviour of the roughly 155-day Rieger periodicity and 27-day, 13.5-day and 9-day solar rotation periodicities for each energy level and for every year in the time interval between 2000 and 2020. The Interactive Data Language (IDL) Mor-

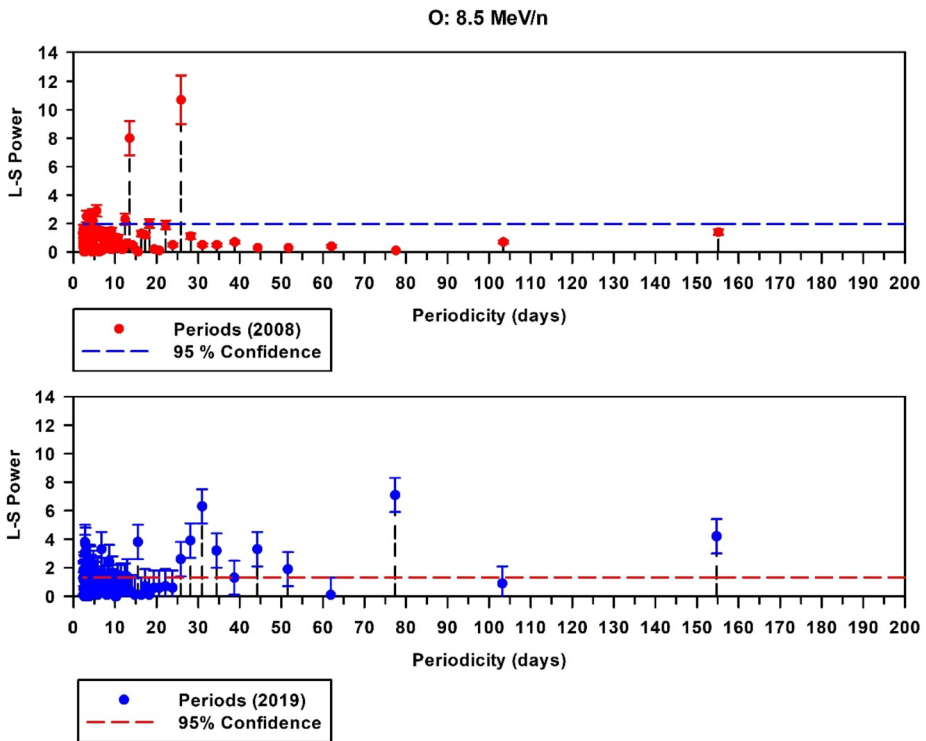


Figure 2 Lomb–Scargle power (L–S power) of 8.5 MeV/n oxygen ions for different periodicities in 2008 (top) and 2019 (bottom). The 95% confidence levels (dashed horizontal lines) denote the error.

let wavelet applet (https://www.l3harrisgeospatial/docs/wv_applet.html) was used to calculate the wavelet spectral analysis from the daily fluxes of ACR oxygen and to generate the wavelet contour plots for each year. The energies reported and utilized in this study are the means of the energy intervals measured by ACE/SIS. Only results complying with a 95% confidence level are used and reported in this study.

3. Results

The main aim of this investigation is to determine whether the 155-day Rieger, and the 27-day, 13.5-day and 9-day periodicities of ACR oxygen ions exhibit any energy or time dependencies during SC23 and SC24, particularly around the respective minima after these solar cycles. A Lomb–Scargle spectral analysis was performed for each energy range of O ions measured by the ACE/SIS instrument (Stone et al. 1998) separately in each year from 2000 to 2020. As an example, the Lomb–Scargle periodograms of 8.5 MeV/n ACR oxygen ions in 2008 and 2009 are displayed in Figure 2.

Figure 2 shows that the annual mean power of statistically significant periodicities differed quite substantially between the two sunspot minima. It is also evident that the power of the Rieger periodicity and its harmonic during the SC24/25 minimum are much higher than during the SC23/24 minimum. Rieger periodicity is below the 95% CL in 2008, the deep minimum of SC23/24, but appears strongly in 2019 during the minimum of SC24/25.

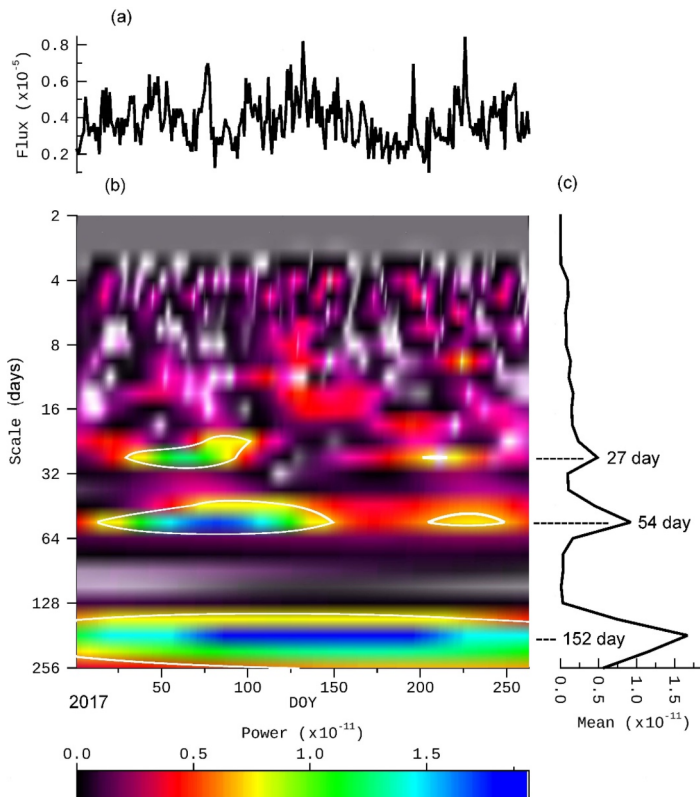


Figure 3 Morlet wavelet spectrum (b) of daily fluxes of 8.5 MeV/n ACR oxygen ions in 2017 (a) as a function of the day of the year, showing the 27-day solar rotation period, the 54-day period and the Rieger period at 152 days. Vertical axis represents the scale (period) in days. White contour lines represent the 95% confidence level. Global wavelet spectrum (c) shows the relative integrated power of periodicities in 2017.

Morlet wavelet analysis confirmed the Lomb–Scargle periodogram analysis. Figure 3 shows, as an example, the Morlet wavelet spectrum analysis of 8.5 MeV/n oxygen ions in 2017. Figure 3c shows that the power of the Rieger period is largest in 2017, exceeding, e.g. that of the 27-day periodicity.

Figure 4a shows the ACR oxygen Lomb–Scargle power at the Rieger period of approximately 155 days as a function of time (x-axis) from 2000 to 2020 and energy (y-axis) from 5 to 25 MeV/n. Figure 4a shows that the Rieger periodicity in ACR oxygen ions exhibits a strong energy and temporal dependence. The strongest power occurs during the late declining phase of both SC23/24 (2006–2007) and SC24/25 (2015–2017), respectively. In addition, it also appears that in SC23, the Lomb–Scargle maximum power is at slightly higher energies (about 8–12 MeV/n) compared to SC24, where the maximum power is at about 6–9 MeV/n.

Figure 4b depicts the behaviour of the 27-day rotational periodicity in the same way and for the same time interval as Figure 4a shows the Rieger periodicity. Figure 4b shows that the strongest power of the 27-day rotational periodicity is centred around the 8.5 MeV/n energy during the late declining to minimum phase (2007–2008) of SC23, and (2017–2018) of SC24. This gives further evidence for the fact that the strongest periodicities in ACR oxygen

Figure 4a Power (in colour) of Rieger periodicity of ACR oxygen ions calculated by the Lomb–Scargle periodogram method annually from 2000 to 2020 as a function of energy (5–25 MeV/n).

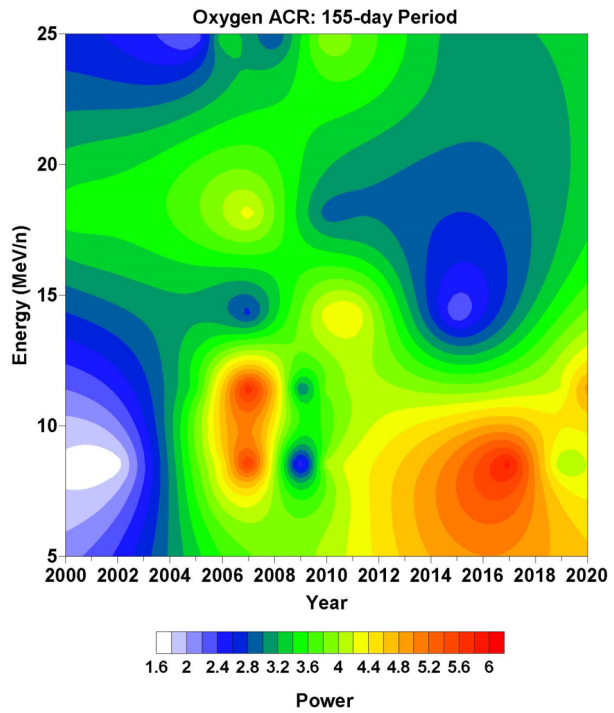


Figure 4b Lomb–Scargle periodogram for the 27-day rotational period in similar presentation as Figure 4a for the Rieger periodicity.

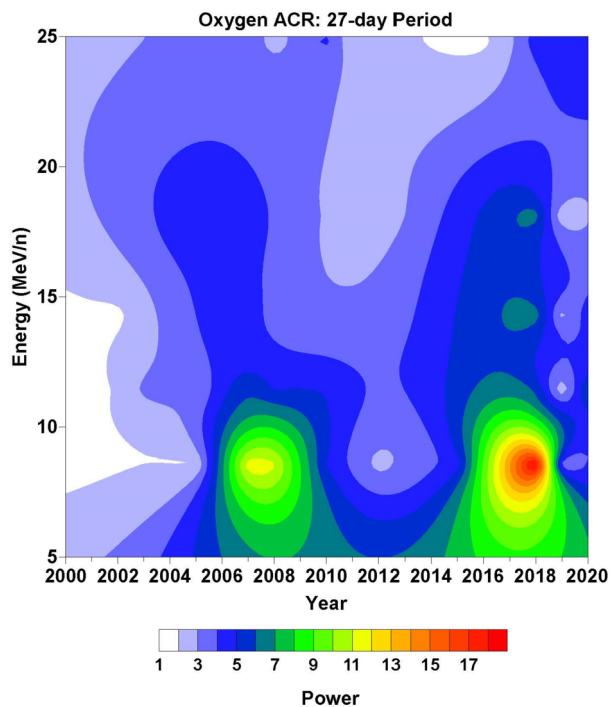
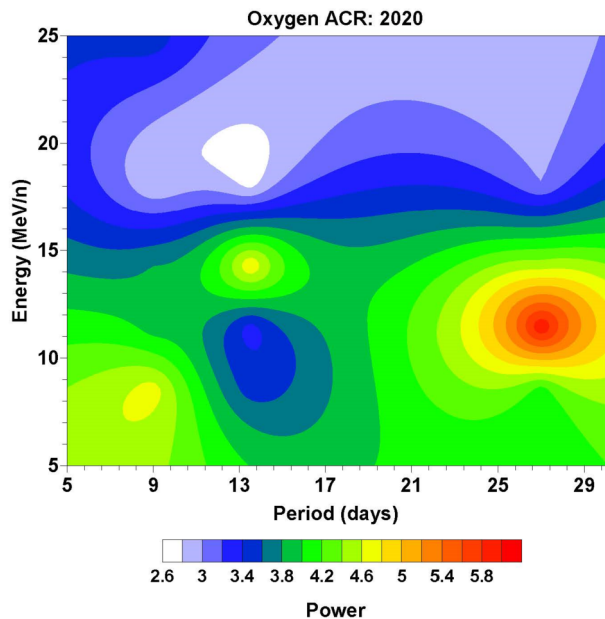


Figure 5 Power (in colour) of solar rotation periodicities in ACR oxygen ions in 2020 as a function of period (x-axis) between 5–30 days and particle energy between (y-axis) from 5 to 25 MeV/n.



ions occur in the late declining to minimum phase of the solar cycle and are limited to energies below 15 MeV/n. Note also that a clearly larger power is found during SC24 than SC23.

A further investigation into the evolution and relative strength of the 27-day, 13.5-day and the 9-day solar rotation periodicities around the minima of SC23/24 (2007, 2008, 2009) and SC24/25 (2018, 2019, 2020) was conducted using Lomb–Scargle periodogram analysis.

As an example, Figure 5 depicts the power of periodicities in ACR oxygen ions between 5 and 30 days in 2020 as a function of energy. The strongest rotational periodicities occur at particle energies below 15 MeV/n. The 27-day period has its strongest activity centred at about 11.5 MeV/n, while the 13.5-day period peaks around 14.5 MeV/n and the 9-day period exhibits its strongest power around 8.5 MeV/n. Figure 5 also shows that the power of the 27-day periodicity exceeds the power of the 13.5-day and the 9-day period. We note that the power is considerably reduced above some 15–17 MeV/n for all periods. This is likely due to the fact that the relative fraction of GCR starts increasing at this energy range (Leske et al. 2013), which dilutes the observed periodicities.

We have also calculated the difference of solar rotation periodicities between the SC23/24 minimum and the SC24/25 minimum. For this purpose, the average power for each period at each energy level for the 3-year interval 2007–2009 was calculated and subtracted from the corresponding average for 2016–2020. The results for the percentage differences for the Rieger, 27-day, 13.5-day and 9-day period are shown in Figure 6.

Figure 6 shows that the Lomb–Scargle power of the four periodicities at the different energies between 5 and 25 MeV/n during the minimum of SC24/25 exceed the corresponding power during the minimum of SC23/24, except in the case of the Rieger periodicity at 11.5 MeV/n when the power is 21% higher during SC23/24 than during SC24/25. Only results that are statistically significant above the 95% confidence level are displayed in Figure 6. In the case of the 155-day Rieger period, the maximum difference occurs at 8.5 MeV/n (8%). In contrast, the 27-day period exhibits the strongest difference (36%) at 18 MeV/n.

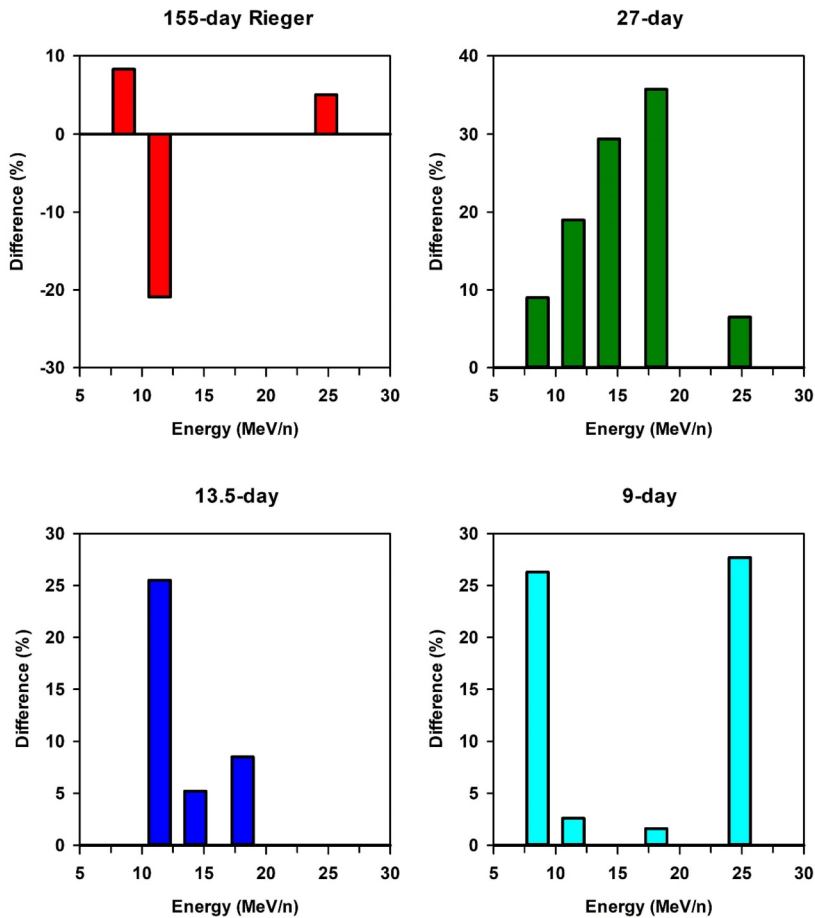


Figure 6 Percentage differences between the minima of SC23/24 and SC24/25 for the 155-day Rieger, 27-day, 13.5-day and 9-day periodicities of ACR oxygen ions at various energy levels.

The 13.5-day period, on the other hand, experiences its greatest difference (25.5%) at 11.4 MeV/n. The 9-day period is the only periodicity that shows its maximum difference (28%) at the highest energy of 24.8 MeV/n.

4. Discussion and Conclusions

We have used the Lomb–Scargle periodogram and a Morlet wavelet spectral method to investigate the energy and time-dependence of the 155-day Rieger, and the 27-day, 13.5-day and 9-day solar rotation periodicities in anomalous cosmic ray oxygen fluxes as measured by the ACE/SIS instrument on board the ACE satellite during SC23 and SC24. Particular attention has been paid to the late declining to minimum phases of SC23/24 (2006–2009) and SC24/25 (2017–2020). Previous investigations of the evolution of ACR oxygen ions in the energy range from 6.0 to 13.4 MeV/n observed by the WIND satellite (Fu et al. 2023) revealed a clear increase in particle flux during SC24 in comparison to SC23. In contrast to

this finding, a study by Rankin et al. (2022) on ACR oxygen particles in the energy range 6.7 to 27 MeV/n observed by Parker Solar Probe at 0.1 AU revealed no observable difference between the minima of SC23/24 and SC24/25. Results obtained in this study (Figure 1) using ACR oxygen data measured by ACE/SIS in the energy range between 8.5 and 24.8 MeV/n showed that the flux during SC24/25 increased by an average of $49 \pm 17\%$ compared to the minimum of SC23/24.

Spectral analysis results obtained in this investigation show both an energy dependence (between 8.5 and 24.8 MeV/n) and a solar polarity dependence of the Rieger, 27-day, 13.5-day and 9-day periodicities for ACR oxygen ions. A recent investigation (Kotzé 2023) revealed a particularly strong time- and energy-dependent behaviour of both 27-day and 13.5-day periodicities in GCR fluxes observed both by spacecraft and ground-based neutron monitors. Periodicities of GCR fluxes observed during the minimum of SC24/25 (when $q_A > 0$) were larger than during the minimum of SC23/24 (when $q_A < 0$).

Lomb–Scargle periodogram results for the Rieger, 27-day, 13.5-day and 9-day periodicities obtained in this investigation for ACR oxygen ions show that these periods exhibit more power in general during the minimum of SC24/25 than during the minimum of SC23/24. An exception however has been observed at 11.5 MeV/n for the Rieger periodicity, which forms part of a strong energy dependence, as displayed in Figure 6.

The recent minimum of SC24/25 forms a part of the weakest solar cycle (SC24) in the history of space age with 77% spotless days observed during 2019 compared to 73% observed during 2008. The slightly lower level of turbulence and weaker heliospheric magnetic field (Rankin et al. 2022) resulted in an estimated 10% increase in cosmic particle mean free path compared to 2009. In addition, a change in the solar magnetic field during this time interval can possibly serve as a signal of increasing solar activity towards the next Gleissberg cycle, the Future Grand Maximum (Mursula 2023). According to a study by Moraal and Stoker (2010), ACR particles, like GCRs, were therefore subjected to less modulation during SC24/25 than during the previous solar minimum. These differences, together with opposite drift patterns during SC23/24 and SC24/25, provide an explanation for the behaviour of the different periodicities revealed in this study. In the case of the Rieger periodicity, an enhanced generation of Rossby waves during the increasing solar activity in SC24/25 after the centennial low point in SC23/24 (Mursula 2023) could be the reason for the larger power of this periodicity during the minimum of SC24/25 compared to SC23/24. The larger power of rotational periodicities (27-day, 13.5-day, 9-day) during SC24/25, an interval of positive solar polarity, indicates that large-scale drift effects play an important role in the behaviour and modulation of ACR cosmic particles.

Acknowledgments The Surfer (www.goldensoftware.com) contour software was used to produce Figures 4a, 4b and Figure 5, while the SigmaPlot (www.systat.com) plotting package was used to produce Figures 1, 2, and 6 in this manuscript. The wavelet contour plot (Figure 3) was generated using the Interactive Data Language (IDL) (<http://www.exelisvis.com/ProductsServices/IDL.aspx>) wavelet applet. The ACE/SIS instrument team and the ACE Science Centre are acknowledged for making the calibrated ACE data available.

The authors are especially grateful for constructive comments by an anonymous reviewer.

Author contributions Pieter Kotzé did the data analysis, made all the figures, while both authors drafted the manuscript.

Funding Open access funding provided by North-West University. No funding has been received to conduct the research for this manuscript.

Data Availability Daily mean Level-2 verified data were downloaded from the ACE website https://izw1.caltech.edu/ACE/ASC/level2/lv2DATA_SIS.html for further study.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Dikpati, M., Belucz, B., Gilman, P.A., McIntosh, S.W.: 2018, Phase speed of magnetized Rossby waves that cause solar seasons. *Astrophys. J.* **862**, 159. DOI.
- Feng, S., Yu, L., Wang, F., Deng, H., Yang, Y.: 2017, Midterm periodicity analysis of the Mount Wilson magnetic indices using the synchrosqueezing transform. *Astrophys. J.* **845**, 11. DOI.
- Fu, S., Zhang, X., Zhao, L., Li, Y.: 2021, Variations of the galactic cosmic rays in the recent solar cycles. *Astrophys. J. Suppl.* **254**, 37. DOI.
- Fu, S., Zhang, Z., Zhao, L., Wang, M., Shang, W., Luo, P.: 2023, Measurements of anomalous cosmic rays from the WIND spacecraft over 1994–2021. *Mon. Not. Roy. Astron. Soc.* **518**, 4832. DOI.
- Giacalone, J., Fahr, H., Fichtner, H., Florinski, V., Heber, B., Hill, M.E., Kóta, J., Leske, R.A., Potgieter, M.S., Rankin, J.S.: 2022, Anomalous cosmic rays and heliospheric energetic particles. *Space Sci. Rev.* **218**, 22. DOI.
- Gil, A., Mursula, K.: 2017, Hale cycle and long-term trend in variation of galactic cosmic rays related to solar rotation. *Astron. Astrophys.* **599**, A112. DOI.
- Gurgenashvili, E., Zaqarashvili, T.V., Kukhianidze, V., Oliver, R., Ballester, J.L., Ramishvili, G., Shergelashvili, B., Hanslmeier, A., Poedts, S.: 2016, Rieger-type periodicity during solar cycles 14–24: estimation of dynamo magnetic field strength in the solar interior. *Astrophys. J.* **826**, 55. DOI.
- Klecker, B., Mewaldt, R.A., Bieber, J.W., Cummings, A.C., Drury, L., Giacalone, J., Jokipii, J.R., Jones, F.C., Kranev, M.B., Lee, M.A., Le Roux, J.A., Marsden, R.G., McDonald, F.B., McKibben, R.B., Steenberg, C.D., Baring, M.G., Ellison, D.C., Lanzerotti, L.J., Leske, R.A., Mazur, J.E., Moraal, H., Oetliker, M., Ptuskin, V.S., Selesnick, R.S., Trattner, K.J.: 1998, Anomalous cosmic rays. *Space Sci. Rev.* **83**, 259. DOI.
- Korsós, M.B., Dikpati, M., Erdélyi, R., Liu, J., Zuccarello, F.: 2023, On the connection between Rieger-type and magneto-Rossby waves driving the frequency of the large solar eruptions during solar cycles 19–25. *Astrophys. J.* **944**, 180. 1–10. DOI.
- Kotzé, P.B.: 2020, Fourth harmonic behaviour of the 27-day periodicity in galactic cosmic rays during different solar magnetic polarity intervals. *Solar Phys.* **295**, 158. DOI.
- Kotzé, P.: 2021, Spectral analysis of rieger periodicity behaviour in O and Fe galactic cosmic particles observed by ACE in solar cycles 23 and 24. *Solar Phys.* **296**(12), 177. DOI.
- Kotzé, P.: 2023, Behaviour of 27-day and 13.5-day periodicities in galactic cosmic particles as observed by spacecraft and neutron monitors during different solar polarity cycles. *Solar Phys.* **298**, 107. DOI.
- Leske, R.A., Mewaldt, R.A., Mason, G.M., Cohen, C.M.S., Cummings, A.C., Labrador, A., W., Stone, E.C., Wiedenbeck, M.E.: von Roseninge, T.T.: 2010, STEREO and ACE observations of energetic particles from corotating interaction regions. *AIP Conf. Proc.* **1216**, 379. DOI.
- Leske, R.A., Cummings, A.C., Mewaldt, R.A., Stone, E.C.: 2013, Anomalous and galactic cosmic rays at 1 AU during the cycle 23/24 solar minimum. *Space Sci. Rev.* **176**, 253. DOI.
- Lomb, N.R.: 1976, Least-squares frequency analysis of unequally spaced data. *Astrophys. Space Sci.* **39**, 447. DOI.
- Modzelewska, R., Gil, A.: 2021, Recurrence of galactic cosmic-ray intensity and anisotropy in solar minima 23 = 24 and 24 = 25 observed by ACE/CRIS, STEREO, SOHO/EPHIN and neutron monitors. *Astron. Astrophys.* **646**, A128.
- Moraal, H., Stoker, P.H.: 2010, Long-term neutron monitor observations and the 2009 cosmic ray maximum. *J. Geophys. Res.* **115**, A12109. DOI.
- Mursula, K.: 2023, Hale cycle in solar hemispheric radio flux and sunspots: evidence for a northward shifted relic field. *Astron. Astrophys.* **674**, A182. DOI.

- Potgieter, M.S.: 2013a, Cosmic rays in the inner heliosphere: insights from observations, theory and models. *Space Sci. Rev.* **176**, 165. [DOI](#).
- Potgieter, M.S.: 2013b, Solar modulation of cosmic rays. *Living Rev. Solar Phys.* **10**, 3. [DOI](#).
- Rankin, J.S., McComas, D.J., Leske, R.A., Christian, E.R., Cohen, C.M.S., Cummings, A.C., et al.: 2022, Anomalous cosmic-ray oxygen observations into 0.1 au. *Astrophys. J.* **925**, 9. [DOI](#).
- Sabbah, I., Kudela, K.: 2011, Third harmonic of the 27-day periodicity of galactic cosmic rays: coupling with inter-planetary parameters. *J. Geophys. Res.* **116**, A04103. [DOI](#).
- Scargle, J.D.: 1982, Studies in astronomical time series II, - statistical aspects of spectral analysis of unevenly spaced data. *Astrophys. J.* **263**, 835. [DOI](#).
- Stone, E.C., Cohen, C.M.S., Cook, W.R., Cummings, A.C., Gauld, B., Kecman, B., et al.: 1998, The cosmic-ray isotope spectrometer for the advanced composition explorer. *Space Sci. Rev.* **86**, 285. [DOI](#).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.