



Hydrogen Lyman-Alpha Periodicity Behaviour During Various Solar Cycles

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Abstract

The temporal behaviour of various periodicities of hydrogen Lyman-alpha ($\text{Ly-}\alpha$) between 1950 and 2020 have been analysed using Lomb-Scargle and Morlet wavelets spectral analysis techniques. Daily mean values of $\text{Ly-}\alpha$ radiance (https://lasp.colorado.edu/lisird/data/composite_lyman_alpha/) for each individual year were used in this investigation to obtain the temporal behaviour of particularly the Rieger periodicity (150–180 days), the synodic solar rotation periodicity (≈ 27 days) as well as the elusive 13.5-day periodicity. Results obtained showed that the Rieger periodicity dominates at solar maximum during strong solar cycle conditions (Cycles 19, 21, 22, and 23), while the ≈ 27 -day periodicity is in most cases dominant during solar minima. On the other hand, the 13.5-day periodicity only appears above the 95% statistical confidence level during solar maxima of Cycles 19, 21, 22 and 24. Contrary to all previous Cycles since 1950, the 13.5-day periodicity appears exceptionally strong and above the 95% confidence level during the downward and minimum phases of Cycles 23 (2006) and 24 (2016) when its power exceeds that of the 27-day periodicity. This peculiar behaviour of the 13.5-day periodicity in $\text{Ly-}\alpha$ can probably be attributed to the anomalous asymmetrical structure of the solar magnetic field during Cycles 23 and 24.

Keywords Solar cycle · Lyman-Alpha · 27-day periodicity · Rieger periodicity · Asymmetric solar magnetic field

1 Introduction

The hydrogen Lyman-alpha ($\text{Ly-}\alpha$) line at 121.567 nm is the strongest solar vacuum ultraviolet emission line and the main excitation source for atomic hydrogen resonant scattering in cool material in the solar system. During quiescent solar conditions, the wings of the $\text{Ly-}\alpha$ line are formed in mid-chromosphere, whereas the core is formed higher up at the base of the transition region from where it is radiated into the upper chromosphere, playing an important role in the radiative energy transport of a cool star like the Sun. Energy losses through the $\text{Ly-}\alpha$ emission are the most important radiative losses in the lower transition region, where the approximate temperature ranges from 8000 K to 30 000 K. The spectral irradiance behaviour of $\text{Ly-}\alpha$ is therefore im-

portant to characterise dynamic processes occurring in the solar atmosphere, particularly solar flares (Fontenla et al. 1988; Milligan and Chamberlin 2016; Milligan et al. 2020). It is important to note that $\text{Ly-}\alpha$ radiation can vary quite substantially during a solar cycle. A study by Woods et al. (2000) reported that the mean variability of $\text{Ly-}\alpha$ due to the 27-day solar rotation across Solar Cycles 18–22 was 5% at solar minimum which increased to 11% at solar maximum.

Studies focussing on the identification and behaviour of periodicities in solar indices and observational data (Pap et al. 1990; Zou and Li 2014) has been of high interest for several years to understand solar variability and space weather. A long-term analysis of solar activity led e.g. to the identification of the well-known 11-year sunspot and 22-year magnetic cycles (Hale 1924). Solar activity is to a large extent modulated by the ≈ 27 -day Carrington rotation together with its different harmonics (e.g. 13.5-day 2nd harmonic). During a solar cycle lasting ≈ 11 years, solar behaviour is predominantly driven by changes in the solar magnetic dynamo (Solanki et al. 2006). The Rieger periodicity (Rieger et al. 1984), first detected in solar flares at ≈ 155 days, has since been observed in several solar activ-

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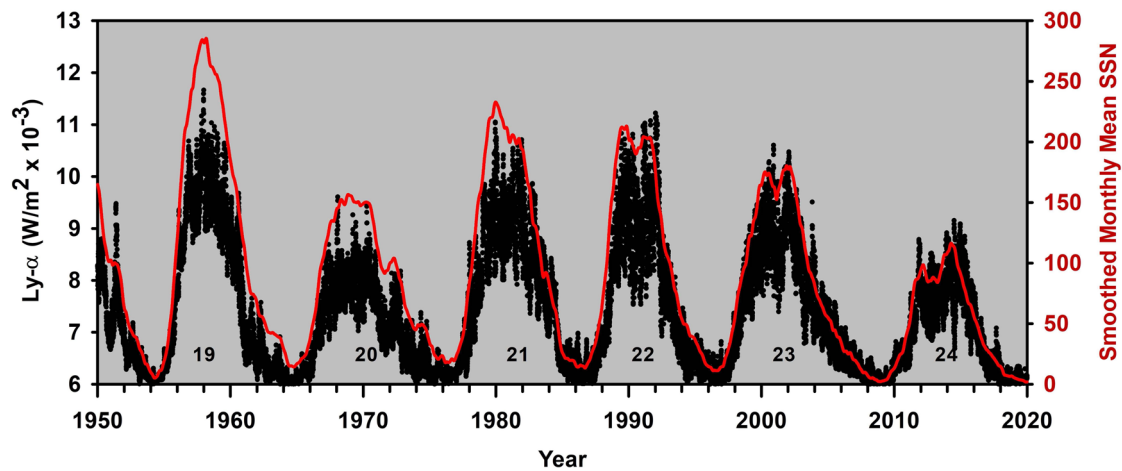


Fig. 1 A combined plot of Ly- α and smoothed monthly mean sunspot values (SSN) between 1950 and 2020. The respective solar cycle numbers are also shown

ity indices, e.g., Mg II (Kotzé 2020). A wavelet investigation of sunspot data by Krivova and Solanki (2002) revealed that the power at the 1.3 year and the Rieger periodicity at 156 days fluctuates approximately in phase, correlating with the strength of a solar cycle as determined by the number of sunspots. This finding led to the conclusion that the 1.3-year solar dynamo period (Richardson et al. 1994; Mursula and Zieger 2000), as well as the Rieger period have a strong underlying common magnetic origin, most probably at the bottom of the solar convection zone.

Several studies have shown that periodicities can vary in strength and amplitude during various phases of a solar cycle and that the ratio of powers can also indicate the dominance of a certain period during e.g., solar maximum or solar minimum. Solar cycles 23 and 24 were characterised by extremely low solar activity levels. During 2008 the number of sunspot-less days were 268 (73%), while during 2019 it was 281 (77%) days (<https://www.spaceweather.com/>). In addition, an anomalously weak and asymmetric solar dynamo (Love et al. 2012) resulted in unusual behaviour of several periodicities and harmonics of the synodic solar rotation period as observed across a wide range of geomagnetic and solar parameters (Chowdhury et al. 2015). Mursula and Zieger (1996) made a detailed analysis of the 13.5-day periodicity of the solar chromosphere, the near-Earth solar wind, interplanetary magnetic field and geomagnetic activity during solar cycles 20, 21 and 22 and concluded that the 13.5-day periodicity is a real quasi-periodicity whose amplitude varies substantially with time, sometimes reaching values larger than the amplitude of the 27-day synodic rotation periodicity.

In this article we report how the Rieger, 27-day as well as the 13.5-day periodicities in solar Ly- α vary with time during various solar cycles since 1950. In the past the Rieger period has been identified in the range 150–180 days, while in

this study it is detected between 152–155 days. In particular, the focus will be placed on the behaviour of these periodicities during solar cycles 23 and 24 when the solar dynamo showed anomalous (fewer sunspots during 2008 than in any year since 1913) and asymmetric characteristics. These results for the solar hydrogen Ly- α spectral line have not been reported before in the literature.

2 Data analysis

The Ly- α line is produced in the solar transition region and radiated into the upper chromosphere (Vernazza et al. 1981). It has been observed that this spectral line not only varies quite substantially over a 27-day period, but its variability over a solar cycle is about a factor of 2 (Woods et al. 2000). Since the first composite compilation of a Ly- α data set (Woods and Rottman 1997; Woods et al. 2000), several upgrades with improvements have been published. The latest version 4 of the Ly- α composite (Machol et al. 2019) addressed several of the discrepancies in previous versions. This data set and has been downloaded from the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) Interactive Solar Irradiance Data Centre (https://lasp.colorado.edu/lisird/data/composite_lyman_alpha/) for the purposes of this investigation. Figure 1 above shows a combined plot of the Ly- α data and smoothed monthly mean sunspot data (<https://www.sidc.be/silso/datafiles>, SILSO data Version 2.0, Royal Observatory of Belgium, Brussels) for the time interval 1950–2020.

Both the Lomb-Scargle (Lomb 1976; Scargle 1982; Press et al. 1992, Chap. 13.8) periodogram method and the Morlet (Morlet et al. 1982; Torrence and Compo 1998) wavelet approach have been employed to conduct a spectral analysis

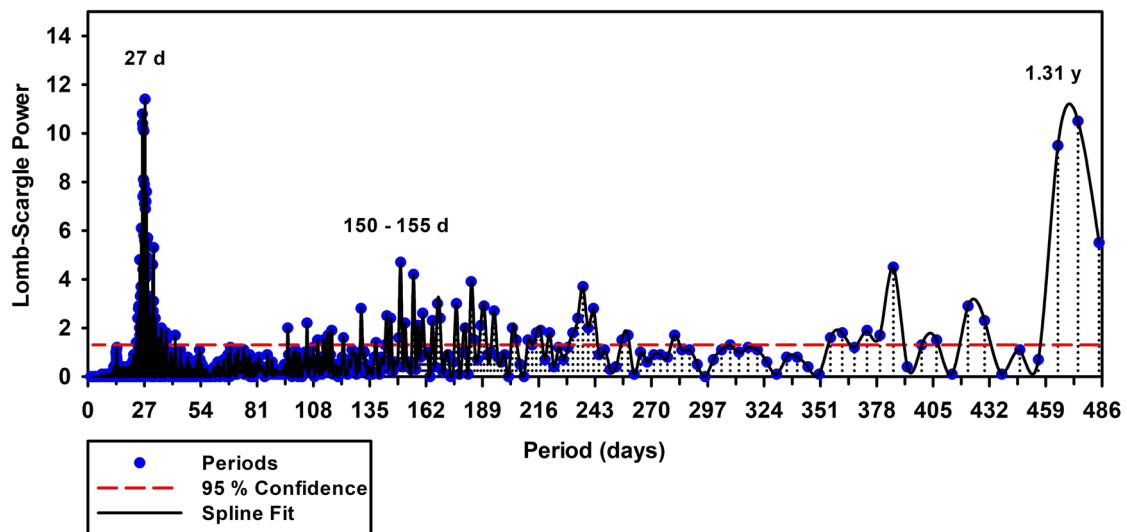


Fig. 2 A Lomb-Scargle periodogram of Ly- α for the time interval from 1950 till 2020. The ~ 27 -day solar rotation period, the Rieger period at ~ 155 days as well as a periodicity at 1.31 years are clearly visible above the 95% confidence level

of Ly- α time series behaviour during various stages of solar cycles between 1950 and 2020. Employing 1-year intervals, consisting of daily mean values in previous studies investigating higher harmonics of the ≈ 27 -day synodic period in geomagnetic time series (Love et al. 2012; Kotzé 2015, 2016) as well as the Rieger periodicity in Mg II (Kotzé 2021) has been proven to provide statistically significant results at the 95% confidence level. The Morlet wavelet, consisting of a plane wave modulated by a Gaussian, utilises wavelets characterized by scale (frequency) and position in time to analyse a time series that contains non-stationary power at different frequencies (periods). The Morlet transform has therefore been the preferred choice in our wavelet analysis as it is a proven and well-established wavelet function for revealing the temporal behaviour of periodicities of space and geophysical parameters in previously published results (Kotzé 2015, 2016, 2021). Global wavelet spectra provided additional information on the presence of dominant periodicities in the Ly- α time series. Both spectral analysis methods were able to identify periodicities in the annual Ly- α time series ranging between 2 days and 365 days, taking into account only those periods complying with a 95% confidence level.

3 Results obtained and discussion

A Lomb-Scargle power spectrum analysis of the complete Ly- α time series from 1950 till 2020 revealed not only a very strong 27-day periodicity, but also the presence of the Rieger period at ≈ 155 days as well as a strong 1.31-year period above the 95% confidence level, as shown in Fig. 2.

It is interesting to notice that the Rieger periodicity appears in Fig. 2 as a double peak at 152 and 155 days. This can most probably be attributed to peaks originating at various epochs of solar activity, a feature that has been observed from our Lomb-Scargle analysis of individual years where the Rieger period varies between 152–155 days. This is similar to our previous analysis of Mg II (Kotzé 2021). The 13.5-day period is just visible above the 95% confidence level, which is an early indication that this period does not appear on a regular basis in annual Ly- α time series. Another interesting feature of the periodogram in Fig. 2 is the unusual power of the 1.31-year periodicity which compares favourably with the 27-day periodicity. The strong presence of the 1.31-year period is in line with the wavelet spectral analysis of sunspot observations by Krivova and Solanki (2002), who concluded that this periodicity as well as the Rieger period has a common origin in the solar dynamo.

A Lomb-Scargle periodogram analysis of each individual year from 1950 to 2019 revealed varying powers of the Rieger periodicity, the ~ 27 -day synodic period as well as the elusive 13.5-day period. The ratio of Rieger periodicity (152–155 days) power to 27-day periodicity power, when observed above the 95% confidence level, can be seen in Fig. 3.

Figure 3 clearly reveals that the Rieger periodicity exceeds the power of the 27-day period during the maximum of the strong solar cycles 19, 21, 22 and 23. During the maximum of the weaker solar cycles 20 and 24, the power of the Rieger period is equal to or below the power of the 27-day periodicity. Contrary to the behaviour during previous cycles, the Rieger periodicity appears exceptionally strong in comparison to the 27-day period during the minima of SC23/24 (2009 and 2010) and SC 24/25 (2019). These two

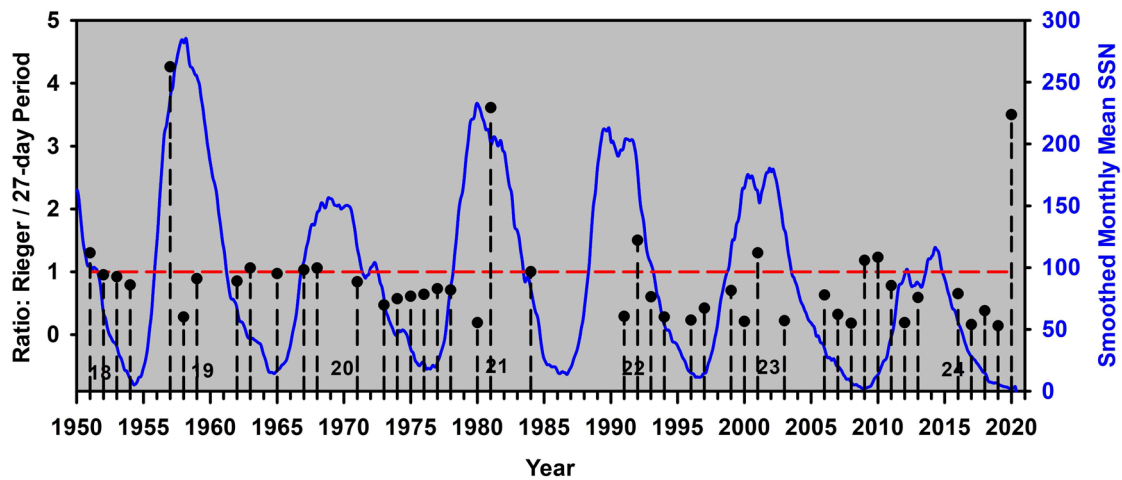


Fig. 3 Lomb-Scargle power ratio of Rieger to synodic periodicities (represented by the black dots) between 1950 and 2020 for each individual year subjected to a 95% statistical confidence level. The red

dashed line indicates equal powers for both periodicities. Superimposed is a plot of smoothed monthly mean sunspot numbers (represented by the blue spline fit) together with the solar cycle numbers

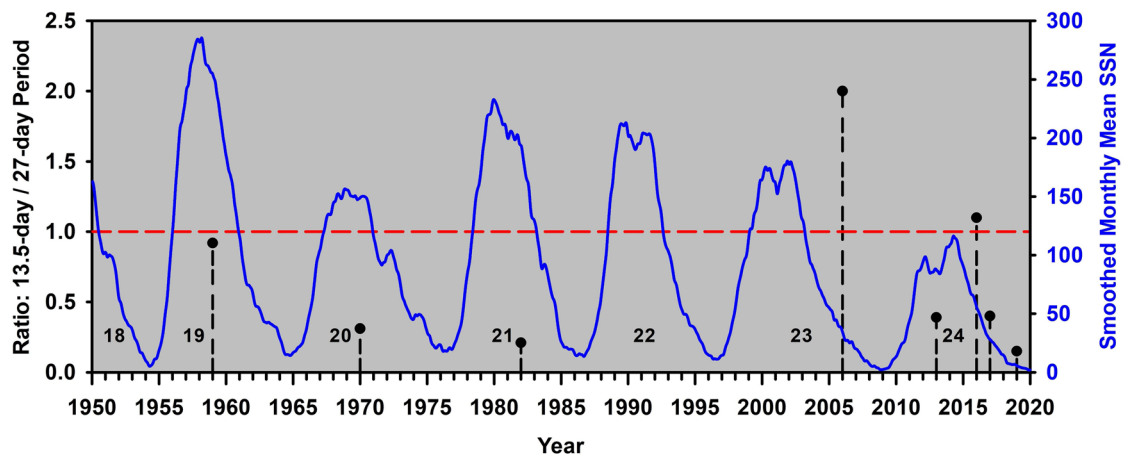


Fig. 4 Ratio of 13.5-day power to 27-day power as obtained by a Lomb-Scargle periodogram analysis of Ly- α between 1950 and 2020 as shown by the black dots above the 95% statistical confidence level.

The red-dotted line is where both powers have equal values, while the blue spline fit represents smoothed monthly mean sunspot numbers. Solar cycle numbers are also provided

solar cycle minima are also characterised by an anomalous behaviour of the axial symmetric spherical harmonic solar dipole coefficient g_1^0 (see Fig. 3, Obridko et al. 2021), the dominant axisymmetric magnetic field harmonic at solar minima. This anomalous behaviour can therefore be regarded as a direct indication of extremely low solar activity levels observed during SC23/24 and SC24/25.

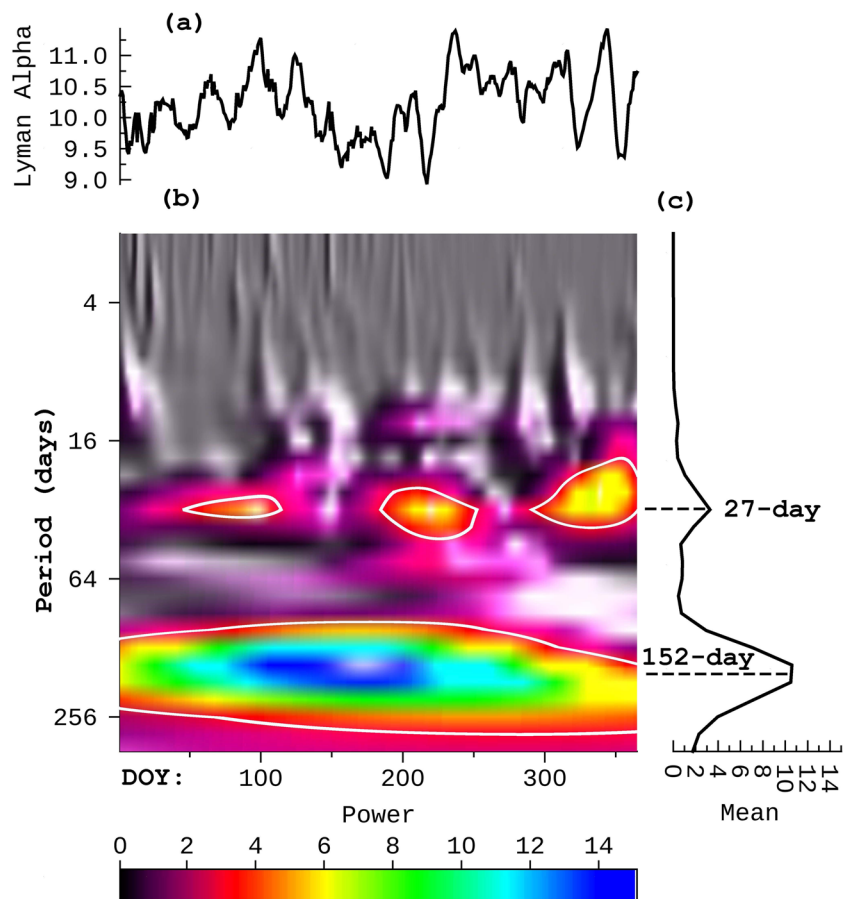
The power ratio of the 13.5-day period to the 27-day period can be seen in Fig. 4 above.

The first observation from Fig. 4 is that the 13.5-day period appears with varying powers between 1950 and 2020. During solar cycles 19, 20, 21 and 24 it can be observed at solar maximum above the 95% confidence level, but weaker than the 27-day periodicity. No 13.5-day period could be observed above the 95% confidence level during Cycles 22 and 23. During 2006 (cycle 23) and 2016 (cycle 24), how-

ever the 13.5-day periodicity dominates the 27-day period. This is also when the solar dynamo experienced an anomalous behaviour characterised by unusually low values of the axial symmetric spherical harmonic coefficient g_1^0 .

An investigation to determine the time-periodicity relationship of each annual Ly- α interval which is compiled of daily mean values was subsequently done using a Morlet wavelet power spectrum analysis. This was done to determine the possible presence of various periodicities as well as their relative powers with respect to each other in these time series. No reference to similar previous studies could be found for Ly- α , this was indeed a new study with the possibility to reveal results not previously published. Application of the wavelet transform to the annual Ly- α time series with a daily cadence enables the identification of periods between 2 days and 365 days. An example of a Morlet

Fig. 5 A Morlet wavelet power spectrum (b) of Ly- α observations during 1981 (a) showing the ≈ 27 -day solar rotation period as well as the Rieger period at ≈ 152 days as a function of the day of the year. The vertical axis represents the scale (period) in days, while the white contour lines represent the 95% confidence level. The global wavelet spectrum (c) shows the relative integrated powers of the observed periodicities



wavelet power spectrum of Ly- α observations for 1981 during the maximum of solar cycle 21 can be seen in Fig. 5.

Figure 5 clearly shows that the power of the Rieger period substantially exceeds that of the 27-day periodicity during 1981. This is in line with our Lomb-Scargle results for 1981.

4 Conclusions

In this study a spectral analysis has been made of solar Ly- α observations using both Lomb-Scargle and Morlet wavelet techniques. The most prominent periodicities identified using daily mean values at each annual interval between 1950 and 2020 included the Rieger periodicity at 152–155 days, the 27-day synodic rotation period as well as the 13.5-day period. From Fig. 2 we observe that the Rieger periodicity appears as a double peak at 152–155 days. This can most probably be attributed to contributions from several individual years, corresponding to different epochs of solar activity, as can be confirmed by results obtained from annual daily mean Lomb-Scargle periodogram analysis, revealing that these periodicities appear with varying powers during this interval since 1950. A comparative analysis of the relative powers of both the Rieger (Fig. 3) as well as the 13.5-day

period (Fig. 4) to the 27-day period showed that the powers of these periodicities are sometimes greater or less than the power of the 27-day period. In particular, this study shows that the power of the Rieger periodicity is exceeding the 27-day power during the maximum of cycles 19, 21, 22 and 23, while during the maxima of cycles 20 and 24, the 27-day periodicity dominates. On the other hand, the Rieger periodicity dominates during the minima of Cycle 23 (2009, 2010) and Cycle 24 (2019). These two cycles are characterised by anomalously low axial symmetric spherical harmonic components of the solar magnetic field (Obridko et al. 2021). Previous studies (Krivova and Solanki 2002; Oliver et al. 1998) linked the Rieger periodicity to the behaviour of the solar dynamo. Similar results have been obtained in a previous investigation of chromospheric Mg II behaviour (Kotzé 2021), supporting results of this study.

In contrast to the Ly- α Rieger periodicity, the 13.5-day period only appears above the 95% confidence level during the maxima of cycles 19, 20 and 21 where it is dominated by the 27-day period. During Cycle 22 it could however not be observed. During 2006 (Cycle 23) and 2016 (cycle 24) the power of the 13.5-day period exceeds the power of the 27-day periodicity, the only time that this happens between 1950 and 2020. A study by Mursula and Zieger (2002) on the variability of the 13.5-day period in solar chromospheric

variables during Cycles 20, 21 and 22, concluded that the largest enhancements of this periodicity occur around solar maximum due to the presence of two solar active longitudes. Results obtained in this investigation seem to follow the same tendency for cycles 19, 20 and 21. As it is well-known that the axisymmetric component of the solar magnetic field dominates during minima (Obridko et al. 2021), we speculate that a possible explanation for the behaviour of the 13.5-day periodicity during 2006 and 2016 is the all-time anomalously weak axial symmetric g_1^0 coefficient. A recent study by Chowdhury et al. (2022) on the behaviour of Ca II K (393.34 nm) spectral line concluded that currently no physical model exists to explain the origin and behaviour of mid-term periodicities like the Rieger periodicity. A study by McIntosh et al. (2015) provided evidence that Rieger-type periodicities have a magnetic origin located deep inside both the Northern and Southern solar hemispheres.

Results obtained from our spectral analysis of the solar Ly- α time series between 1950 and 2019 show that the power of both the Rieger and the 13.5-day periodicities fluctuate substantially with time in comparison to the 27-day period, particularly during the recent weak and deep minima of solar cycles 23 and 24. A possible explanation for these peculiar behaviours is the anomalous behaviour of the solar dynamo during this time interval. This manuscript provides to the best of our knowledge the first evidence that the powers of the Rieger as well as the 13.5-day periodicity variation with respect to the 27-day period in Ly- α are dependent on solar cycle behaviour.

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The sunspot data used in this study have been obtained from SILSO, Royal Observatory of Belgium.

Author contributions Pieter Kotzé did the data analysis, made all the plots and figures and drafted the manuscript.

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Data Availability Data used in this study are freely available by the author on request by email.

Declarations

Competing interests The authors declare no competing interests.

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