Postprint: Overall Rotation Evolution of Coronal Green Line Radiation During Solar Cycles 18-24

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Abstract

Solar rotation plays an important role in the conversion between poloidal and toroidal magnetic fields and constitutes a key foundation for revealing the origin and evolution of solar magnetic fields; however, research on the long-term evolutionary patterns of coronal rotation has yet to reach definitive conclusions. Using Ensemble Empirical Mode Decomposition and wavelet analysis, this study investigates coronal green line radiation intensity from January 1, 1939 to December 31, 2023. The results include: (1) The significant periods identified in coronal Fe XIV green line radiation intensity are 15.64;d, 27.99;d, 70.37;d, 162.79;d, 314.50;d, 1.89;yr, 10.30;yr, and 11.04;yr, with the first three periods being closely related to coronal rotation; (2) Within solar cycles 18–24, the period length of coronal rotation exhibits a decreasing trend, indicating a continuously accelerating coronal rotation speed; (3) Variations in coronal rotation period length are closely correlated with the Rieger period, quasi-biennial oscillation, and quasi-six-year oscillation.

Full Text

Preamble

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Global Rotation Evolution of Coronal Green Line Radiation during Solar Cycles 18-24

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Abstract

Solar rotation plays a crucial role in the conversion between poloidal and toroidal magnetic fields and serves as a fundamental basis for revealing the origin and evolution of solar magnetic fields. However, the long-term evolutionary patterns of coronal rotation remain inconclusive. This study investigates the intensity of coronal green line radiation from January 1, 1939, to December 31, 2023, using ensemble empirical mode decomposition and wavelet analysis. The findings include: (1) The significant periods of coronal Fe XIV green line radiation intensity are 15.64 d, 27.99 d, 70.37 d, 162.79 d, 314.50 d, 1.89 yr, 10.30 yr, and 11.04 yr, with the first three periods being closely related to coronal rotation; (2) Across solar cycles 18–24, the period length of coronal rotation exhibits a decreasing trend, indicating that coronal rotation is accelerating; (3) The variation in coronal rotation period length is closely associated with the Rieger period, quasi-biennial oscillation, and quasi-six-year oscillation.

Keywords: Sun: activity, Sun: corona, methods: statistical
Classification codes: P182; Document code: A

Introduction

The corona, as the outermost layer of the solar atmosphere, exhibits both differential and rigid rotation like other atmospheric layers. Coronal rotation can be studied through various methods, including white-light observations [1-3], coronal green line (530.3 nm Fe XIV line) [4-6], soft X-rays [7-8], and radio frequencies [9]. Research on the overall coronal rotation and its variation across activity cycles has attracted considerable attention from solar physicists.

Numerous researchers have employed different analytical methods to study coronal rotation, revealing its close relationship with latitude, altitude, and density, though many patterns remain to be uncovered. Previous studies on coronal rotation have primarily focused on three aspects: (1) differential coronal rotation; (2) temporal variation of coronal rotation; and (3) differences between coronal rotation and rotation in the lower atmosphere.

Studies of differential coronal rotation have utilized several tracers: white light, coronal green line, radio emissions, and soft X-rays. Hansen et al. [1] applied autocorrelation analysis to white-light observations to establish a function of annual mean coronal rotation velocity varying with latitude and altitude, demonstrating the existence of differential rotation. Similar conclusions were reached by Fisher et al. [2], Nash [10], Lewis et al. [11], and Lewis and Simnett [3], confirming that coronal rotation is indeed differential. In contrast, Sime et al. [4]

and Wang et al. [5] concluded from coronal green line analysis that coronal rotation is rigid, a finding also supported by Aschwanden et al. [9]. Regarding the specific latitudinal variation, most researchers agree that coronal rotation is faster in equatorial regions and gradually slows with increasing latitude toward the poles.

Despite extensive research, the long-term activity and periodic variations of the corona remain unclear. Sime et al. [4] and Altrock [12] found that the corona exhibits rigid rotation during solar activity minima and differential rotation during maxima. Rybák [13] studied coronal rotation from 1964–1989 and found no significant solar cycle variations. Tlatov [14] discovered that the coronal rotation period at low and mid-latitudes becomes longer (i.e., slower) during solar maxima. Harvey and Sheeley [15] identified periods of 28–29 d at high latitudes and 27 d at low latitudes. Giordano and Mancuso [16] determined an average rotation period of approximately 27.5 d in the equatorial region. Mouradian et al. [17] reported coronal periods of 25.4 d during solar maxima and 30 d during minima. Chandra et al. [18] found a relationship between coronal rotation and the 22 yr Hale cycle. However, Li et al. [19] argued that coronal rotation shows no statistically significant Schwabe cycle, while Li et al. [20] found that coronal activity is synchronized with solar wind acceleration. These differing conclusions likely arise from different time ranges and research methodologies.

Many researchers propose that the corona has two rotation modes: fast and slow. Antonucci and Svalgaard [21] identified both long-lived and short-lived features. Badalyan and Sykora [22] revealed that overall coronal rotation results from a combination of fast and slow modes. Shnirman et al. [23] found coronal rotation periods concentrated in the ranges of 25–27.3 d and 27.3–31 d. Badalyan [24] suggested that the corona rotates in fast mode at low latitudes and slow mode at high latitudes. The temporal variation of coronal rotation is complex, and its relationship with solar activity remains unclear and requires further investigation. Studying temporal variations in coronal rotation can provide important information for understanding solar cycle mechanisms. This paper analyzes nearly 85 years of coronal index data to explore the temporal variation patterns of coronal activity.

2.1 Data

The coronal green line exhibits periodic behavior ranging from days to decades, making it ideal for studying solar activity cycles. The original Coronal Index (CI) was derived from ground-based measurements of the 530.3 nm coronal green line intensity. Lyot invented the coronagraph in 1939 [25], enabling observations of full-disk 530.3 nm coronal green line intensity variations that reflect the total irradiance of the corona at this wavelength. This measurement was defined as the coronal index of solar activity. The CI can reflect solar activity changes over extended periods (monthly means from 1939 and daily measurements from 1943). However, due to decreasing numbers of observation sites and weather fluctuations, this solar activity index has some data gaps. Consequently, Rybák et al. [26] introduced the Modified Coronal Index (MCI) to replace the original CI, minimizing weather-related measurement impacts. MCI data from 1947-1995 were directly converted from the original CI, while data from 1996 onward were obtained from SOHO (Solar and Heliospheric Observatory) CELIAS (Charge, Element, and Isotope Analysis System) measurements using approximate relationships, with adjustments for certain solar eruptive events.

Daily MCI values from January 1, 1939, to December 31, 2023, are shown in Figure 1 [Figure 1: see original paper]. The data can be downloaded from the website of the Slovak Central Observatory in Hurbanovo[1], with units of 10^{-6} $\mathrm{W \cdot m^{-2}}$.

[1] www.kozmos-online.sk

Figure 1 presents the time series of coronal index values. Vertical dashed lines indicate solar activity minima, while solid lines indicate maxima. The coronal index variations generally align with solar cycle changes, though differences exist in detail. The slanted dashed line shows the linear regression result for the coronal index, revealing an overall declining trend in intensity from 1939 to 2023.

2.2 Methods

This study employs EEMD (Ensemble Empirical Mode Decomposition) and Continuous Wavelet Transform (CWT) to analyze MCI data.

2.2.1 EEMD Method

Empirical Mode Decomposition (EMD) is an advanced time-frequency analysis technique that decomposes original signals into a series of Intrinsic Mode Functions (IMFs). It has been widely applied in periodic analysis of solar magnetic activity. However, EMD suffers from mode mixing, where signals of different periods become aliased. This manifests in two ways: (1) signals with different characteristic scales appear in the same IMF component, and (2) signals with the same characteristic scale are distributed across different IMF components. To address this issue, Wu and Huang [27] proposed EEMD, which adds noise to the original signal, performs multiple decompositions, and uses the average of these decompositions to replace the original result, thereby avoiding mode mixing. The specific principles and procedures of EEMD can be found in Wu and Huang [27].

2.2.2 Continuous Wavelet Transform (CWT)

Continuous wavelet transform is a time-frequency analysis method proposed by Torrence and Compo [28]. Based on wavelet properties, projecting a function into the wavelet transform domain facilitates extraction of its essential features. From a time-frequency perspective, the relationship between frequency and power can be obtained, and periods can be calculated from frequency. This yields the relationship between period and power, with peaks above the confidence line identified as the signal' s periods. Continuous wavelet transform is widely used in periodic analysis of solar magnetic activity, particularly for studying solar atmospheric rotation patterns [29-32].

3 Analysis and Discussion

First, EEMD is applied to decompose the daily Modified Coronal Index (MCI), after which continuous wavelet transform is used to calculate the period of each IMF component. Then, CWT is performed separately on MCI data for each activity cycle from 18-24 to calculate the rotation period and its length variation trend for each cycle. Finally, we obtain the overall variation trend of coronal rotation and the Period Length of Coronal Rotation (PLCR).

3.1 Comparison of Coronal Index and Solar Activity Trends

Figure 1 shows a declining trend in the coronal index over the considered time range. Li [33] found an increasing trend in daily sunspot area from May 9, 1874, to February 28, 2010. Similarly, Li et al. [30] found an increasing trend in solar faculae from 1849-2010. The distribution of these tracers is consistent with the distribution of solar activity maxima and minima during the considered periods. The observed increasing and decreasing trends may be related to different observation time intervals.

3.2 EEMD Analysis of Coronal Index

Figure 2 [Figure 2: see original paper] shows the EEMD decomposition of the coronal index into 11 IMFs and a residual term. The residual reveals the long-term trend of the coronal index series, showing a declining trend over the considered time interval (January 1, 1939-December 31, 2023), consistent with the linear decline in Figure 1. Li et al. [30] applied CWT to sunspots and found that since the Maunder Minimum, particularly from cycle 6 onward, the cycle amplitude of sunspots has been steadily increasing, termed the "long-term trend" [34]. Notably, Figure 1' s result comes from linear analysis reflecting the overall decline of the modified coronal index. Using nonlinear tools like EEMD, we further find that MCI showed a slow upward trend from 1939-1957, followed by a rapid decline from 1973 onward.

Next, continuous wavelet transform is applied to each IMF. Based on the global wavelet power spectrum, the relationship between period and frequency is obtained, yielding the periods of each component, as shown in Table 1 . For long timescales, particularly IMF11, the lack of oscillatory variation results in very few degrees of freedom, making the corresponding correlation coefficients potentially misleading; therefore, these can be ignored.

IMF1 and IMF2 have relatively small periods and can be considered noise.

IMF3, IMF4, and IMF5 are closely related to rotation signals. IMF3 represents the second harmonic of rotation, while IMF5 represents the half harmonic [19]. Similarly, Joshi et al. [35] also found a 63 d period. For the rotation signal (IMF4 with a period of 27.99 d), we obtain the synodic period (Psynodic) of the corona, which relates to the sidereal period (Psidereal) as:

$$P_{\text{sidereal}} = \frac{365.26 P_{\text{synodic}}}{365.26 + P_{\text{synodic}}}$$

Thus, the sidereal period corresponding to IMF4 is 25.998 d. The 27.99 d period is close to the accepted solar rotation period, with many previous studies showing rotation periods around 27 d. For example, Rybák [13] analyzed Fe XIV 5303 Å coronal green line radiation (1964-1989) and found an overall rotation period of (28.18 ± 0.12) d and a synodic period of (27.65 ± 0.13) d near the \$±\$30° latitude band. Mouradian et al. [17] analyzed 10.7 cm (2800 MHz) radio flux from the Dominion Radio Astrophysical Observatory [36], finding rotation periods of 25.4 d during solar maximum, 30 d during minimum, and 32 d during quiet periods. Harvey et al. [15] reported solar cycle periods of 28-29 d at high latitudes and 27 d at low latitudes.

The 162.79 d period also has similar findings. Carbonell et al. [42] analyzed daily sunspot area data (1878-1982) and found a period of about 155 d. The Rieger period of solar flares is 154-158 d, with energy closely matching phase variations of the 1.28 yr period. Based on this, Krivova et al. [43] proposed that the Rieger period is the third harmonic of the 1.3 yr period (3 × 156 d = 1.28 yr). Kılıç [44] used Date Compensated Discrete Fourier Transform (DCDFT) to obtain a period of 133.6 d for the solar flare index.

The 314.50 d period is close to twice the Rieger-type period and may be influenced by both differential rotation magnetic fields and toroidal magnetic fields, being closely related to magnetic flux emergence processes. Similarly, Li et al. [19] found a period of (390.6 ± 22.3) d.

The 688.30 d period likely originates from the Quasi-Biennial Oscillation (QBO), considered a fundamental mode of low-latitude solar magnetic activity involving dynamical processes and magnetic field interactions in the solar interior. Similarly, Chowdhury et al. [40] obtained a 1.24 yr period by analyzing coronal soft X-rays from January 2004 to December 2008. Javaraiah et al. [45] and Javaraiah and Bertello [46] studied daily equatorial rotation rates from Mount Wilson Doppler velocity measurements and sunspot group numbers, finding periods of 1.47 yr and 1.4 yr, respectively.

For the well-recognized Schwabe period (11 yr cycle), Xie et al. [31] used autocorrelation function analysis to find a significant 10.1 yr period. Javaraiah [47] performed Fourier transforms on sunspot groups from 1879-1976 and found an 11 yr period. Brajša et al. [48] also analyzed sunspot groups from 1874-1981 and obtained an 11 yr period. Tlatov [14] studied coronal green line data from

1939-2004 and found an 11 yr period. Our decomposition of daily coronal index from 1939-2023 yields periods of 3761.00 d (10.30 yr) and 4030.94 d (11.04 yr), confirming the existence of the 11 yr cycle in solar rotation.

3.3 Rotation Variations from Cycle 18 to Cycle 24

Based on the previous analysis, we extract rotation-related signals (IMF3, IMF4, and IMF5), sum them to obtain a new rotation signal, and conduct subsequent studies. Figure 3 [Figure 3: see original paper] shows this extracted rotation signal. In Figure 3, the x-axis represents time and the y-axis represents index magnitude. Since the original data were standardized before EEMD, the extracted rotation signal is similarly distributed around zero, which does not affect subsequent analysis. Dashed lines indicate solar cycle minima, while solid lines indicate maxima. The coronal index shows weak periodic variations during activity minima but strong variations near maxima.

Deng et al. [32] and Xie et al. [31] comprehensively discussed coronal index using continuous wavelet transform. This study similarly applies CWT to analyze the coronal rotation signal, beginning with each activity cycle. Figures 4 [Figure 4: see original paper]-10 [Figure 10: see original paper] show the wavelet power spectra for cycles 18-24 (1944-2019). Taking Figure 4 as an example, the upper panel shows the local wavelet power spectrum with the x-axis representing years and y-axis representing period. Black contours indicate the confidence interval, and the red curve shows the cone of influence. Due to time length limitations, periods outside the cone of influence are not considered. The lower panel shows the global wavelet power spectrum, where the blue curve represents power at each period and the red dashed line is the 95% confidence level. Peaks above this line represent the cycle' s period. As shown, cycle 18 has a period of 27.99 d (synodic period). Figures 6 [Figure 6: see original paper]-10 [Figure 10: see original paper] show power spectra for cycles 20-24.

The periods for each cycle are summarized in Table 2 . Column 1 shows the cycle number, column 2 the years, column 3 Psynodic, and column 4 Psidereal.

Table 2 Rotation periods from the 18th to 24th solar cycles

Solar Cycle	Time Interval	Psynodic (d)	Psidereal (d)
18	1944-02-1954-04	27.99	26.00
19	1954-04-1964-10	28.45	26.51
20	1964-10-1976-03	28.23	26.34
21	1976-03-1986-09	27.47	25.67
22	1986-09-1996-08	27.29	25.50
23	1996-08-2008-12	27.12	25.34
24	2008-12-2019-12	26.59	24.85

Wavelet analysis of coronal index for each activity cycle reveals that the period length increased from cycle 18 to 19, then decreased continuously from cycle 19 through cycle 24. This trend is consistent with MCI variations. Li et al. [49] analyzed daily sunspot area from May 9, 1874, to February 28, 2010, and found a long-term trend in solar rotation speed: gradually slowing from 1874-1950, then accelerating from 1950 onward. In other words, the rotation period became longer during 1874-1950 and shorter after 1950, consistent with our conclusions.

3.4 Variation of Coronal Rotation Period Length

This study investigates the periodicity of coronal rotation signals using continuous Morlet wavelet transform [29], obtaining the daily coronal index period length at each time point within the considered time range. The results are shown in Figure 11 [Figure 11: see original paper], with the PLCR time series smoothed over 1 yr. Figure 11 shows a weak declining trend. To study the long-term trend of PLCR, linear regression analysis was performed. The regression line (solid blue line) is shown in the figure, with red dashed lines indicating the 95% confidence interval. Since the error values are very small relative to the rotation period length, the red dashed lines nearly coincide with the blue line. The relationship between rotation period length and time can be described as:

$$p(t) = -4.80 \times 10^{-6} \cdot t + 26.57$$

where t is time (in years, with start time set to 0 and end time set to the series length of 31,046), and $p(t)$ is the rotation period length varying with t. Linear regression indicates that the rotation period length decreases linearly from (26.57 ± 0.026) d to (26.42 ± 0.026) d, a difference of (0.15 ± 0.052) d, with a slope of -4.80×10^{-6} d/d. A goodness-of-fit test at 95% confidence shows excellent fit quality, with errors approaching zero. Therefore, overall, coronal rotation speed is increasing (i.e., period length is decreasing) during the studied time interval (1939-2023), though the change is small.

The long-term declining trend in our rotation period length time series is consistent with Heristchi and Mouradian [50], Chandra and Vats [18], Li et al. [19], and Xie et al. [31]. Overall, cycles 18-24 show a decreasing trend, though the specific trend for individual cycles may depend on solar activity levels and related dynamical characteristics. Jin et al. [51] divided the solar magnetic field into active and quiet regions, further subdividing quiet regions into four zones with different phase relationships based on magnetic flux magnitude. Interactions among these zones may affect rotation speeds in certain cycles, potentially making cycle 18 rotate faster than cycle 19. Li et al. [52] decomposed total solar irradiance (TSI) when investigating solar constant variations across cycles. Notably, all these studies used 10.7 cm radio flux to reveal coronal rotation behavior. Since both 10.7 cm radio flux and Fe XIV coronal green line reflect global coronal features, the long-term trends in rotation period length obtained from both indicators are similar. Li et al. [30] studied rotation period length of sunspot area from 1849-2010 and estimated photospheric magnetic activity, reaching similar conclusions. They found a long-term decreasing trend in photospheric rotation period length, with a linear decrease of about 0.47 d over the observed time range. Our rotation period difference is 0.15 d, about one-third of Li et al.' s value. This discrepancy may arise from different time ranges: Li et al. [30] studied sunspots from January 1, 1849, to February 28, 2010 (162 yr), while our MCI data span 85 yr. Similarly, Heristchi and Mouradian [50] calculated sunspot rotation periods for 1849–2004 (156 yr) and obtained a value of 0.66 d. Thus, period differences among studies result from rotation period uncertainties, but the consistent trend is noteworthy. Therefore, from current and previous work, we infer that within the studied time range (1939–2023), rotation periods of sunspot activity, coronal index, and coronal green line all show similar long-term decreasing trends.

Next, wavelet analysis of PLCR yields the local wavelet power spectrum (Figure 12 [Figure 12: see original paper]) and global wavelet power spectrum (Figure 13 [Figure 13: see original paper]). Figure 12 shows PLCR' s local wavelet power spectrum, with x-axis representing years, y-axis representing period, black contours indicating the 95% confidence interval, and the red curve showing the cone of influence. Periods outside the cone are not considered due to time length limitations. Figure 13 shows the global wavelet power spectrum, where the curve represents power at each period and the dashed line is the 95% confidence level. Peaks above this line represent significant periods: 253.69 d, 785.19 d, 1348.28 d, and 2057.82 d.

Kılıç [44] used DCDFT to analyze sunspot numbers and flare indices for cycle 23 (August 23, 1997–December 31, 2005), finding a significant periodicity at 220.0 d for sunspot numbers, similar to our 253.69 d period. Kane [53] analyzed multiple solar indices and found periods ranging from 5.1 to 28.0 months, including one at 7.6 months similar to our 253.69 d period.

The 785.19 d (2.15 yr) period corresponds to the QBO. Deng et al. [32] used synchrosqueezing wavelet transform to identify QBO as a significant periodic scale for high-latitude solar magnetic activity. Through flux transport dynamo model simulations, Inceoglu et al. [54] analyzed sunspot groups and found quasi-biennial oscillation behavior in low-latitude regions, showing that solar QBO appears across the entire solar disk and in sunspot zones of both hemispheres.

The 1348.28 d (3.69 yr) period was also found by Knaack et al. [55], who analyzed Kitt Peak synoptic Carrington maps of photospheric magnetic field (1975–2003) and monthly mean sunspot area (1874–2003), obtaining a (3.6 ± 0.3) yr period. Deng et al. [56] studied sunspot zones for cycles 9–24 and found similar periods.

Whether solar rotation temporal variations exhibit an 11 yr cycle warrants further investigation. Chandra and Vats [18] analyzed 2.8 GHz solar radio flux and found no significant 11 yr period in coronal rotation variations, suggesting weak or no correlation between coronal rotation and solar activity. Li et al. [19] similarly concluded that long-term variations in coronal rotation period length lack an 11 yr cycle. However, Xie et al. [31] used continuous wavelet transform and autocorrelation analysis to show that long-term coronal rotation variations should relate to the 11 yr Schwabe cycle, as the smoothed coronal rotation period is 10.3 yr. Javaraiah [47], Obridko and Shelting [57], Brajša et al. [48], and Xie et al. [58] studied rotation characteristics of Greenwich sunspot groups, spectroscopic velocity data, large-scale magnetic fields, and photospheric magnetograms, finding quasi-11 yr rotation variations. Our study also finds no 11 yr period, possibly due to time range limitations.

Coronal rotation is one of the most significant motions in the solar atmosphere, essential for understanding solar structure and dynamics, as well as planetary environments and Earth' s climate. Using daily MCI from January 1, 1939, to December 31, 2023, this study combines EEMD and CWT methods to analyze nearly 84 years of MCI rotation periods. The novel methodology and extensive time span yield the following results: (1) Coronal activity intensity shows a declining trend from 1939-2023; (2) EEMD decomposition of coronal index reveals periods of 15.64 d, 27.99 d, 70.37 d, 162.79 d, 314.50 d, 1.89 yr, 10.30 yr, and 11.04 yr; (3) Rotation signal analysis shows average sidereal periods for cycles 18-24 of: 26.00 d, 26.51 d, 26.34 d, 25.67 d, 25.50 d, 25.34 d, and 24.85 d; (4) Within the studied time range, average period length first increased then decreased; (5) Continuous wavelet transform of periodic signals reveals coronal rotation periods of 253.69 d, 785.19 d, 1348.28 d, and 2057.82 d.

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Note: Figure translations are in progress. See original paper for figures.