Postprint of Solar Differential Rotation Study Based on SDO/AIA Ultraviolet Images

Authors: Zeng Shuguang, Jin Hanle, Deng Linhua, Wu Qianrui, Zeng Xiangyun, Zheng Sheng, Huang Yao, Liu Dejian

Date: 2026-03-03T15:53:35+00:00

Abstract

The solar differential rotation is a key mechanism for converting the poloidal magnetic field into a toroidal magnetic field. In this study, the differential rotation was investigated using the flux modulation method applied to full-disk solar ultraviolet images from bands such as 1600 Å of the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO). First, the full-disk images were preprocessed and divided into different latitudinal zones. Then, flux time series for each latitudinal zone were obtained through data processing. Finally, autocorrelation analysis was performed on the flux time series of each latitudinal zone to derive the rotation periods and angular velocities at various latitudes. The research results indicate that within the latitude range of 80°S to 80°N, the solar rotation angular velocity is a function of latitude. Across different AIA wavelengths, the solar equatorial rotation angular velocity increases with altitude, while the degree of differential rotation weakens. Furthermore, the average rotation angular velocity near the equator and the degree of differential rotation show no significant correlation with the solar cycle.

Full Text

Preamble

Vol. 67, No. 1

2026 年 1 月

ACTA ASTRONOMICA SNICA Vol. 67 No. 1 Jan., 2026 doi: 10.15940/j.cnki.0001-5245.2026.01.004

Study of Solar Differential Rotation Based on SDO/AIA Ultraviolet Images

ZENG Shuguang[1,2], JIN Hanle[1,2], DENG Linhua[3], WU Qianrui[4], ZENG Xiangyun[1,2†], ZHENG Sheng[1,2], HUANG Yao[1,2], LIU Dejian[1,2]

([1] Center for Astronomy and Space Science, China Three Gorges University, Yichang 443002) ([2] College of Science, China Three Gorges University, Yichang 443002) ([3] School of Mathematics and Computer Science, Yunnan Minzu University, Kunming 650504) ([4] South-Western Institute for Astronomy Research, Yunnan University, Kunming 650500)

Abstract

Solar differential rotation is a fundamental characteristic of solar dynamics and plays a crucial role in the generation and evolution of the solar magnetic field. In this study, we utilize high-resolution ultraviolet (UV) images obtained by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) to investigate the characteristics of solar differential rotation. By applying automated feature tracking and correlation tracking methods to various UV wavelengths, we derive the rotation profiles of the solar atmosphere at different heights. Our results indicate that the rotation rate varies significantly with latitude and shows subtle dependencies on the specific wavelength observed, reflecting the complex plasma dynamics across different layers of the solar atmosphere. These findings provide observational constraints for solar dynamo models and contribute to our understanding of the transport of angular momentum within the Sun.

Key words: Sun: rotation; Sun: UV radiation; Sun: activity; Methods: data analysis

1 Introduction

The Sun does not rotate as a solid body; instead, it exhibits differential rotation, where the rotation rate varies with both latitude and depth. This phenomenon is a cornerstone of solar physics, as it is intimately linked to the solar dynamo process, which generates the 11-year solar activity cycle. Understanding

摘要太阳的较差自转是将极向磁场转化为环向磁场的关键机制．采用通量调制法对太阳动力学观测台

This study investigates solar differential rotation using full-disk solar ultraviolet images from the 1600 Å and other bands captured by the Atmospheric Imaging

Assembly (AIA) onboard the Solar Dynamics Observatory (SDO). First, the full-disk images were preprocessed and divided into distinct latitudinal zones. Next, data processing was performed to extract flux time series for each latitudinal region. Finally, an autocorrelation analysis was applied to these time series to determine the rotation periods and angular velocities across different latitudes. The results demonstrate that within the latitude range of 80°S to 80°N, the solar angular velocity is a function of latitude. Across different AIA wavelengths, the equatorial angular velocity increases with height, while the degree of differential rotation weakens. Furthermore, the average equatorial angular velocity and the degree of differential rotation show no significant correlation with the solar cycle.

Keywords: Sun: rotation, Sun: activity, Sun: UV radiation, Methods: data analysis, Autocorrelation
PACS/CLC Codes: P182; **Document Code:** A

1 引言

Introduction

The differential rotation of the Sun provides a crucial dynamical foundation for solar dynamo theory and plays a key role in the transformation of the magnetic field structure within the solar interior. The interaction between solar differential rotation and magnetic fields influences solar activity and its various manifestations [?].

Investigating the patterns of variation in differential rotation can also provide a theoretical basis for studying the solar activity cycle and the mechanisms generating differential rotation. Furthermore, researchers have identified a close relationship between solar rotation and terrestrial atmospheric ozone, which aids in better understanding the impact of solar activity on the Earth [?].

To date, various methods have been employed to study the angular velocity of solar rotation. The earliest method used for this purpose was the tracer method [?], which determines rotation speed by observing the positional changes of features with slowly evolving structures. Howard [?] and Arevalo et al. [?] conducted long-term studies on solar differential rotation by observing sunspots. In addition to sunspots, other solar features such as faculae, plaques, and filaments can also serve as tracers to calculate the solar rotation angular velocity [?]. Another approach is the spectroscopic method, which determines the angular velocity based on the Doppler shift of spectral lines [?]. Livingston [?] utilized spectroscopic methods to determine the differential rotation of the outer solar atmosphere and found that differential rotation increases with altitude. While the tracer method is suitable for studying differential rotation at latitudes where magnetic structures emerge, the spectroscopic method is more effectively applied to high-latitude regions [?]. In recent years, the flux modulation method has been widely adopted in the field of solar rotation research [?]. This method is highly sensitive and capable of detecting subtle changes in solar surface brightness, making it applicable to observational data across different wavelengths. By extracting flux information from solar images and performing autocorrelation analysis on the resulting flux time series, the solar rotation period can be determined.

Chandra et al. [?] utilized the flux from full-disk solar images to study the rotation speed of the corona. Sharma et al. [?] employed flux data from the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) to investigate solar rotation periods at different coronal layers, finding that these periods decrease as temperature (or altitude) increases. Li et al. [?] used the flux modulation method to study the rotational characteristics of the chromosphere, demonstrating that the degree of differential rotation intensifies as magnetic field strength increases.

The Sun is a star composed of plasma, and its angular velocity of rotation varies not only across different latitudes on the surface but also with altitude (or temperature) [?]. Using solar filament observation data from 1929 to 1941 provided by the Geophysical and Astronomical Observatory of the University of Coimbra (OGAUC), Wan et al. [?] found that in low-to-mid latitude regions, the rotation angular velocity of filaments in the upper chromosphere is greater than that in the photosphere and the lower-to-mid chromosphere. Sharma et al. [?] utilized high-resolution 19.3 nm observation data obtained from SDO/AIA between 2011 and 2021, discovering that the coronal rotation angular velocity varies with latitude; specifically, the average angular velocity in the equatorial region of the corona is higher than that in the photosphere, chromosphere, and transition region. Sharma et al. [?] utilized Extreme Ultraviolet (EUV) 304 Å images from the Solar Terrestrial Relations Observatory (STEREO), obtaining the rotation profile coefficients for the transition region and found that its equatorial rotation angular velocity is faster than that of the corona, although the absolute value of the rotation velocity gradient in the transition region is smaller than in the corona. Similarly, Wu et al. [?] conducted a study using SDO/AIA 304 Å images, revealing that the rotation angular velocity at the equator of the solar transition region is lower than that observed in the corona and chromosphere. Kharayat et al. [?] studied solar rotation from 1907 to 1996 using digitized Ca-K images from the Kodaikanal Observatory; using plaques, they determined the equatorial rotation angular velocity to be $13.98^\circ \cdot \mathrm{d}^{-1}$, with a decreasing trend in angular velocity observed from 0° to 80° latitude.

The correlation between solar rotation angular velocity and the solar activity cycle remains inconclusive. Studying the variations in solar rotation during the activity cycle helps us understand the mechanisms underlying the solar cycle [?]. Some researchers argue that changes in solar rotation are synchronized with the solar cycle [?]. However, Chandra et al. [?] pointed out that while the equatorial rotation angular velocity of the corona shows systematic variations relative to the annual mean International Sunspot Number (SSN), its gradient is anti-correlated with the SSN. Li et al. [?] observed a negative correlation between long-term periodic changes in sunspot activity and solar equatorial rotation, suggesting that a faster equatorial rotation angular velocity corresponds to lower levels of sunspot activity.

In this paper, we investigate the differential rotation characteristics of the Sun using SDO/AIA image data from 2011 to 2023 via the flux modulation method. Section 2 provides the data description and preprocessing steps. In Section 3, we introduce the autocorrelation method used to obtain the rotation periods. Section 4 discusses the results, focusing on three aspects: the solar differential rotation profile, the variation of rotation angular velocity with altitude across different wavelengths, and the relationship between rotation angular velocity and the solar activity cycle. Finally, Section 5 provides a summary and discussion.

2.1 数据来源

SDO was launched in February 2010 and began returning scientific data in May of the same year. The AIA instrument consists of four telescopes capable of observing solar images across 10 channels, with wavelengths ranging from 94 Å to 4500 Å. These channels correspond to heights ranging from the photosphere to the corona [**?**]. The temperature coverage spans from 5000 K to 20 MK, capturing emissions from various ions such as C IV, Fe XVI, He II, and Fe IX. The data utilized in this study consist of images from SDO/AIA at 1600 Å, 1700 Å, 304 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, and 94 Å. Among these, the 1600 Å and 1700 Å channels belong to the ultraviolet (UV) band, while the other wavelengths are in the extreme ultraviolet (EUV) range. The 1600 Å images represent the solar transition region and upper photosphere [**?**]; their imaging spectrum is primarily composed of the double lines emitted by C IV ions, the continuum, and numerous other chromospheric lines, with a characteristic emission temperature of approximately 10^5 K [**?**]. The EUV bands, such as 211 Å, primarily consist of spectral lines formed by various ions of Fe.

Observation and imaging within this spectral range constitute an important and effective method for acquiring solar physical information and characteristics. We downloaded observational images at nine wavelengths with a resolution of 1024 × 1024 from the official SDO website, covering the period from 2011 to 2023. One image was selected daily at approximately the same time, resulting in a total of over 42,000 images used as the experimental data for this study.

2.2 数据预处理

As the observed solar images appear slightly dimmer at the edges than at the center, Zeng Shuguang et al. conducted a study on solar differential rotation based on SDO/AIA ultraviolet images. The solid black line in [Figure 2: see original paper] shows the original flux time series, where significant fluctuations in the mean of the raw data can be observed; specifically, the overall flux between 0 and 150 days is relatively high. To prevent trend variations in the mean flux from affecting subsequent periodicity analysis, it is necessary to process the flux time series to eliminate these trends. First, the original flux time series was fitted using an 8th-order polynomial, and the mean of the original series was calculated. Then, a smoother time series was obtained by subtracting the mean from the original data and adding the fitted values. In [Figure 2: see original paper], the dashed black line represents the flux time series obtained through polynomial fitting, with the horizontal axis representing time. [Figure 3: see original paper] displays the detrended flux time series. Compared to the curves in [Figure 2: see original paper], the mean of the curve in [Figure 3: see original paper] no longer exhibits significant trend variations.

This limb-darkening effect may affect experimental results [**?**]. Therefore, it is necessary to remove this effect from the images. The specific processing steps are as follows: First, an edge detection algorithm (such as the Canny operator) is used to fit the solar disk contour, accurately calculating the center coordinates and radius of the solar disk. Then, the image is transformed from the Cartesian coordinate system to a polar coordinate system with the solar center as the origin. In the polar coordinate system, the radial profile values at each angle constitute a radial profile curve. The profile curves of the entire image are then replaced by a median profile curve smoothed over a 360° range. After converting back to the Cartesian coordinate system, a quiet background image is obtained.

Finally, by subtracting the background image, a high-quality image with the limb-darkening effect removed is obtained [**?**]. After performing brightness equalization on the image, the solar disk is extracted from the full-disk image. Next, the solar disk from 80°S to 80°N is divided into 16 latitude bands. Due to the 7.2° angle between the solar equatorial plane and the ecliptic plane, it is necessary to transform the solar image coordinates into heliographic coordinates. Using latitude as an index, the flux within the corresponding latitudinal regions is extracted at 10° intervals. As shown in [Figure 1: see original paper], the elliptical curves provide a schematic representation of the latitude band division for the 1600 Å images; each 10° interval from the equator to the poles constitutes a latitude band. The regions beyond 80° in the Northern and Southern Hemispheres are very narrow and contain few informational features, and are therefore not considered. Finally, the average ultraviolet flux within each small latitude band is extracted to obtain the average flux time series for each band.

[Figure 2: see original paper] The original flux series and its fitted curve. [Figure 1: see original paper] Schematic diagram of the full-disk latitude band division of the Sun in SDO/AIA 1600 Å. [Figure 3: see original paper] The flux series after detrending. By performing a Fourier transform on the flux series shown in [Figure 3: see original paper], the amplitude spectrum is obtained as shown in [Figure 4: see original paper]. As can be seen from the figure, the extracted flux time series contains multiple frequency components. A Butterworth bandpass filter is applied to the amplitude spectrum to remove noise components. The passband range of the filter corresponds to a period of 10–50 days. An inverse Fourier transform is then performed on the filtered amplitude spectrum to obtain the band-pass filtered time series, as shown in [Figure 5: see original paper]. Compared to [Figure 3: see original paper] before filtering, the curve becomes smoother and contains less noise.

[Figure 4: see original paper] Amplitude spectrum of the flux time series after Fourier transform. [Figure 5: see original paper] The flux series after band-pass filtering.

3 分析方法

The Autocorrelation Function (ACF) describes the degree of correlation between different time points of a random signal, which is instrumental in identifying repetitive patterns within the signal. For a discrete time series y_t (where $t = 0, 1, 2, 3, ...$), a lag value can be set to calculate its autocorrelation coefficient. In an autocorrelation plot, the lag value corresponding to the first secondary peak represents the solar rotation period [?]. The formula for calculating the autocorrelation coefficient is:

$$\mathrm{ACF}(h) = \frac{\mathrm{Cov}(y_t, y_{t-h})}{\mathrm{Var}(y_t)} \tag{1}$$

where $\mathrm{ACF}(h)$ represents the autocorrelation coefficient of the time series at time lag h, $\mathrm{Cov}(y_t, y_{t-h})$ represents the covariance between the time series at time t and time $t-h$, and $\mathrm{Var}(y_t)$ represents the variance of the time series at time t.

The autocorrelation coefficients were calculated for the preprocessed average flux time series, with the lag value set to vary within the range of 0–150 days. [Figure 6: see original paper] displays the autocorrelation plot for 50°S in the Southern Hemisphere for the year 2022, where the horizontal axis represents the number of days and the vertical axis represents the corresponding autocorrelation coefficient.

[Figure 6: see original paper] Fig. 6 Autocorrelation plot of flux at 50°S in 2022

The autocorrelation plot at 50°S reveals several distinct peak structures, each corresponding to a different period on the lag axis. As shown in the figure, the first secondary peak is higher than the subsequent peaks and possesses a larger correlation coefficient, indicating its statistical significance and suggesting the presence of a stable cycle [?]. To obtain a more precise period value, Gaussian fitting was applied to the first secondary peak. The Gaussian function effectively describes the shape of the autocorrelation peak, and its center position corresponds to the statistically optimal estimate of the rotation period, allowing for a more accurate determination of the solar rotation period. The Gaussian fitting formula is:

$$f(x) = ae^{-\frac{(x-b)^2}{c^2}} \tag{2}$$

In this equation, b is the center of the Gaussian function, which determines the position of the peak and corresponds to the rotation period; a is the amplitude of the Gaussian function, and c is the standard deviation. In [Figure 7: see original paper], the black line represents the fitting curve obtained using this Gaussian function for the 50°S latitude data in 2022, the triangular points represent the original data points, and the vertical dashed line corresponds to the center value of the Gaussian function. In [Figure 7: see original paper], the goodness-of-fit (R^2) for the 50°S latitude data in 2022 is 0.99, and the rotation period corresponding to the peak is 27.31 days, which is also known as the solar synodic period. The synodic period cannot be used directly to calculate the solar angular velocity; it must be converted into the sidereal rotation period. The relationship between the solar angular velocity ω and the solar sidereal rotation period is as follows, where 365.26 is the orbital period of the SDO satellite [**?**].

[Figure 7: see original paper] Fig. 7 Gaussian fit plot at 50°S for the year 2022

It is well known that the solar rotation angular velocity is closely related to latitude. Traditional measurements of rotation angular velocity utilize polynomial fitting; the velocity decreases as latitude increases, reaching its maximum at the equator.

Chandra et al. [**?**] proposed a relationship based on the square of the sine of the latitude, namely:

$$\omega(\phi) = A + B \sin^2 \phi$$

where the variable ϕ represents the solar latitude, A represents the rotation angular velocity at the solar equator, and B represents the degree of latitudinal differential rotation.

4.1 自转轮廓曲线

In this study, we calculated the annual rotational angular velocity across different latitudes using the flux modulation method based on SDO/AIA images from nine wavelengths. Using Equation (5), we obtained fitting results for a 13-year period spanning from 2011 to 2023. presents the annual fitting results for the 1600 Å wavelength, where SE (Standard Error) represents the standard error of the estimates. The Sunspot Number (SSN) data were sourced from the World Data Center SILSO (Sunspot Index and Long-term Solar Observations) at the Royal Observatory of Belgium [**?**] (https://www.sidc.be/SILSO/datafiles).

The final row of the table displays the fitted values and associated SE for the annual average rotation coefficients A and B. Between 2011 and 2023, the average rotation profile coefficients fluctuated, with A values ranging approximately from 14.01 to 14.84, and B values varying between -1.32 and -3.24.

After calculating the 13-year average of the rotation periods for each latitude band from 2011 to 2023, the mean rotational angular velocity was determined. By fitting these data, the average differential rotation coefficients for this 13-year period were found to be $A = 14.33 \pm 0.07$ and $B = -2.12 \pm 0.12$.

[Figure 8: see original paper] illustrates the profile of the rotational angular velocity as a function of latitude for the year 2022. In this figure, the horizontal axis represents latitude, while the vertical axis represents the rotational angular velocity. The black scattered points with error bars denote the measured rotational angular velocity, and the solid black line represents the fitted differential rotation profile. As shown in the figure, the rotational angular velocity decreases from the equator toward the poles.

Using the same analytical methodology, we calculated the differential rotation profile coefficients for the other eight wavebands, the results of which are summarized in . In this table, the second column lists the primary emission ions, the third column provides the height above the photosphere along with its associated error, and the fourth and fifth columns present the average differential rotation coefficients A and B, respectively, including their error margins. The heights above the photosphere are cited from existing literature. For the 131 Å and 94 Å bands, specific heights have not yet been established in the literature and are therefore indicated by horizontal dashes.

[Figure 9: see original paper] displays the average differential rotation profiles for all nine wavebands, with latitude on the horizontal axis and rotational angular velocity on the vertical axis. The figure reveals that the differential rotation profiles across the nine wavelengths are qualitatively similar: the rotational angular velocity peaks near the equator and diminishes as latitude increases. Notably, the differential rotation profiles for the 1700 Å and 1600 Å wavelengths exhibit the steepest decline with latitude, indicating that the differential rotation is most pronounced in these two wavebands.

Table 1: Fitted A and B values and their standard errors (SE) for different years

$A \pm SE$ / $[(^\circ) \cdot \mathrm{d}^{-1}]$	$B \pm SE$ / $[(^\circ) \cdot \mathrm{d}^{-1}]$
14.84 ± 0.22	-2.57 ± 0.41
14.72 ± 0.30	-3.24 ± 0.55
14.01 ± 0.18	-1.53 ± 0.33
14.42 ± 0.22	-3.12 ± 0.40
14.07 ± 0.19	-2.80 ± 0.35

The relationship between the synodic rotation period (T_{synodic}) and the sidereal rotation period (T_{sidereal}) can be expressed as:

$$T_{\mathrm{sidereal}} = \frac{365.26 \times T_{\mathrm{synodic}}}{365.26 + T_{\mathrm{synodic}}} \tag{3}$$

The sidereal angular velocity (ω) is then calculated as:

$$\omega = \frac{360^\circ}{T_{\text{sidereal}}} \tag{4}$$

For a sample calculation where $T_{\text{synodic}} = 27.31$ days, the fitting yields an R-square value of 0.9901.

[Figure 8: see original paper] **Fig. 8 The rotation profile for the year 2022**

The solar differential rotation law is typically described by the following formula, where $\omega(\phi)$ represents the angular velocity at latitude ϕ:

$$\omega(\phi) = A + B\sin^2\phi \tag{5}$$

Table 1 Continued

$A \pm SE$ / $[(^\circ) \cdot \mathrm{d}^{-1}]$ | \$

4.2 自转速度随高度变化

In a recent study, Rao et al. [?] utilized Dopplergrams from the Chinese $H\alpha$ Solar Explorer (CHASE), focusing on the Si I (6560.58 Å), $H\alpha$ (6562.81 Å), and Fe I (6569.21 Å) wavelengths with a spectral resolution of 0.024 Å to obtain rotation profile curves for different layers of the solar photosphere and chromosphere. Their study concluded that the solar angular velocity tends to increase from the photosphere to the chromosphere. Sharma et al. [?] investigated the rotation of the solar corona at various wavelengths using multi-band data from the Atmospheric Imaging Assembly (AIA), including 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å. The present work utilizes SDO/AIA data at 1700 Å, 304 Å, 1600 Å, 171 Å, 211 Å, 193 Å, and 335 Å. Table 2 presents the average rotation profile coefficients for each wavelength channel from 2011 to 2013. Correlation analyses were performed between the rotation profile coefficients A and B obtained for each wavelength channel and their corresponding heights. Figure 10 [Figure 10: see original paper] and Figure 11 [Figure 11: see original paper] illustrate the relationship between the rotation profile coefficients A and B and height, respectively. In these figures, points of different shapes represent different wavelength channels; the horizontal axis represents the height above the photosphere (derived from various literature sources) in km, and the vertical axis represents the coefficient A, which denotes the solar angular velocity at the equator. Red line segments represent error bars, with vertical segments indicating errors in the vertical axis and horizontal segments indicating errors in the horizontal axis. Based on the observed trends, both rotation profile coefficients A and B generally show an upward trend as height increases. To further investigate the relationship between angular velocity and height, the Pearson correlation coefficient was introduced. The Pearson correlation coefficient is a statistical measure of the degree of linear correlation between two continuous variables, comprising two parameters: ρ and p. The value of ρ ranges from

-1 to 1, where a larger value indicates a stronger correlation; 1 represents a perfect positive correlation, -1 represents a perfect negative correlation, and 0 indicates no linear correlation. A smaller p-value indicates higher statistical significance, with $p < 0.05$ typically considered significant. The calculated Pearson correlation coefficients between height and coefficients A and B are 0.828 ($p = 0.021$) and 0.728 ($p = 0.064$), respectively. This suggests a positive correlation between the solar equatorial angular velocity and the height of the solar layers, while the degree of differential rotation weakens as height increases.

The average angular velocity A and the degree of differential rotation B were compared with the annual mean sunspot number, as shown in Table 1. This period can be divided into two phases: 2011 to 2018 (the middle and late stages of Solar Cycle 24) and 2019 to 2023 (the beginning stage of Solar Cycle 25).

[Figure 9: see original paper] [Figure 11: see original paper] Figure 12 [Figure 12: see original paper] shows the annual variation of the rotation profile coefficient A for different wavelengths over time. The left axis represents the angular velocity, the right axis represents the annual mean sunspot number, and the horizontal axis represents the year. Figure 13 [Figure 13: see original paper] shows the annual variation curves of the profile coefficient B for different wavelengths. In both figures, the red curves represent the trend of the annual mean sunspot number over time. To more intuitively determine the relationship between the profile coefficients at different wavelengths and the sunspot number, a correlation analysis was performed. As seen from the figures, the relationship between the profile coefficients and the annual mean sunspot number is non-linear. Therefore, the Spearman correlation coefficient, which measures the degree of non-linear correlation, was employed. The Spearman method also includes the correlation coefficient ρ and the p-value, with ρ ranging from -1 to 1. [Figure 10: see original paper]

4.3 太阳自转与太阳活动周之间的关系

To explore the relationship between the solar rotational angular velocity and the solar cycle, a common practice is to use the sunspot number as a proxy for solar activity [**?**]. We analyzed the annual equatorial mean values from 2011 to 2023. In statistical analysis, the closer a correlation coefficient is to 1 or -1, the stronger the monotonic relationship between the two variables; a value near 1 indicates that one variable tends to increase as the other increases, while a negative value indicates a negative correlation, where one variable tends to decrease as the other increases. If the p-value is less than 0.05, the correlation coefficient is considered statistically significant. The calculated Spearman correlation coefficients are presented in . The results show that the ρ values are generally small and the p-values are relatively large, indicating that there is no significant correlation between the rotation profile coefficients and the sunspot number. From this, it can be inferred that there is no obvious correlation between the solar cycle and the solar rotation observed across the nine corresponding wavelengths.

[Figure 12: see original paper] Fig. 12 The relationship between the rotation profile coefficient A and sunspot numbers

[Figure 13: see original paper] Fig. 13 The relationship between the rotation profile coefficient B and sunspot numbers

5 总结与讨论

Based on full-disk solar image data from nine SDO/AIA bands (1700 Å, 1600 Å, 304 Å, 171 Å, 193 Å, 211 Å, 131 Å, 335 Å, and 94 Å), this study investigated solar differential rotation from 2011 to 2023 using the flux modulation method. The following results were obtained:

(1) The average solar differential rotation profiles for each wavelength were determined. The solar angular velocity is highest at the equator and gradually decreases toward the poles. The degree of differential rotation in the ultraviolet bands (1700 Å and 1600 Å) is significantly greater than that in the extreme ultraviolet (EUV) bands.

(2) We examined the relationship between the solar differential rotation profile coefficients and the height above the photosphere across seven SDO/AIA bands (1700 Å, 304 Å, 1600 Å, 171 Å, 211 Å, 193 Å, and 335 Å). The results indicate that as height increases, the equatorial angular velocity (A) increases, while the degree of differential rotation (B) tends to decrease. Sharma et al. [?] utilized AIA 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å data to study rotation periods at different coronal levels, finding that the period decreases with increasing height (temperature), meaning the angular velocity increases with height. Rotation profiles obtained by Rao et al. [?] using Dopplergrams from the Chinese Hα Solar Explorer (CHASE) also demonstrate that the angular velocity increases from the photosphere to the chromosphere. Similarly, research by Vats et al. [?] suggests that the upper corona rotates faster than the lower corona.

(3) The relationship between solar angular velocity and the solar cycle was explored. A correlation analysis was performed between the average equatorial angular velocity (A) and the International Sunspot Number (SSN). A similar calculation was conducted for the relationship between coefficient B and the SSN. The results show that neither coefficient A nor coefficient B exhibits a significant correlation with the SSN. In contrast, Chandra et al. [?] found that the coronal equatorial rotation speed (A) is positively correlated with the annual sunspot number, while the latitudinal differential rotation coefficient (B) is negatively correlated. Furthermore, Sharma et al. [?] reported a positive correlation between the average angular velocity derived from full-disk images of the solar transition region and the solar cycle.

Wu et al. [?] also demonstrated synchronicity between variations in the average angular velocity and the solar cycle. However, Sudjak et al. [?] found a negative correlation between the equatorial angular velocity and the solar cycle. Fei et al. [?] studied the coronal green line emission intensity from January 1, 1939, to December 31, 2023, and observed an increasing trend in coronal angular velocity during Solar Cycles 18-24. Currently, the relationship between solar angular velocity and the solar cycle remains inconclusive and requires further investigation.

致谢　感谢 NASA、SDO/AIA 科学团队提供

…data as well as the annual sunspot numbers provided by the WDC-SILSO, Royal Observatory of Belgium, Brussels.

References Babcock H W. ApJ, 1961, 133: 572 Howard R. ARA&A, 1984, 22: 55 Schroeter E H. SoPh, 1985, 100: 141 Tsiropoula G. JASTP, 2003, 65: 469 Georgieva K, Kirov B, Javaraiah J, et al. P&SS, 2005 Vats H O, Cecatto J R, Mehta M, et al. ApJ, 2001, 548: L87 Sharma J, Brajesh K, Malik A K, et al. MNRAS, 2021, 506: 4952 Chandra S, Vats H O, Iyer K N. MNRAS, 2009, 400:

Chandra S, Vats H O, Iyer K N. MNRAS, 2010, 407:

Sharma J, Kumar B, Malik A K, et al. MNRAS, 2020, 492: 5391 Li K J, Xu J C, Xie J L, et al. ApJ, 2020, 905: L11 Oghrapishvili N B, Bagashvili S R, Maghradze D A, et al. AdSpR, 2018, 61: 3039 Wan M, Li K J. SoPh, 2022, 297: 126 Sharma J, Malik A K, Vats H O, et al. MNRAS, 2023, 521: 1079 Wu Q R, Zheng S, Zeng S G, et al. ApJ, 2023, 954: 20 Kharayat H, Singh J, Priyal M, et al. ApJ, 2024, 968:

Sharma J, Banerjee S K, Singh N K, et al. SoPh, 2024, 299: 90 Li K J, Shi X J, Xie J L, et al. MNRAS, 2013, 433: 521 Li K J, Feng W, Shi X J, et al. SoPh, 2014, 289: 759 Pesnell W D, Thompson B J, Chamberlin P C. SoPh, 2012, 275: 3 Lemen J R, Title A M, Akin D J, et al. SoPh, 2012, 275: 17 Simões P J A, Reid H A S, Milligan R O, et al. ApJ, 2019, 870: 114 Neckel H, Labs D. SoPh, 1994, 153: 91 Lefebvre S, Rozelot J P. SoPh, 2004, 219: 25 Clette F, Svalgaard L, Vaquero J M, et al. SSRv, 2014, 53: 197 186: 35 Gilman P A. ARA&A, 1974, 12: 47 Boerner P, Edwards C, Lemen J, et al. SoPh, 2012, 275:

Balthasar H, Vazquez M, Woehl H. A&A, 1985, 155: 87 Arevalo M J, Gomez R, Vazquez M, et al. A&A, 1982, 111: 266 Glackin D L. SoPh, 1974, 36: 51 Adams W M, Tang F. SoPh, 1977, 55: 499 Belvedere G, Godoli G, Motta S, et al. ApJ, 1977, 214:

Berger P S, Simon M. ApJ, 1972, 171: 191 Livingston W C. SoPh, 1969, 9: 448 Beck J G. SoPh, 2000, 191: 47 Fossum A, Carlsson M. ApJ, 2005, 625: 556 Simon G W, Noyes R W. SoPh, 1972, 22: 450 Simon G W, Seagraves P H, Tousey R, et al. SoPh, 1974, 39: 121 Kwon R Y, Chae J, Zhang J. ApJ, 2010, 714: 130 Rao S, Li C, Ding M, et al. NatAs, 2024, 8: 1102 Ruždjak D, Brajša R, Sudar D, et al. SoPh, 2017, 292:

Solar Differential Rotation Study Based on SDO/AIA Ultraviolet Images

ZENG Shu-guang[1,2], **JIN Han-le**[1,2], **DENG Lin-hua**[3], **WU Qian-rui**[4], **ZENG Xiang-yun**[1,2], **ZHENG Sheng**[1,2], **HUANG Yao**[1,2], **LIU De-jian**[1,2]

[1] Center for Astronomy and Space Sciences, China Three Gorges University, Yichang 443002 [2] College of Mathematics and Physics, China Three Gorges University, Yichang 443002 [3] School of Mathematics and Computer Science, Yunnan Minzu University, Kunming 650504 [4] South-Western Institute for Astronomy Research, Yunnan University, Kunming 650500

Abstract The differential rotation of the Sun is a key mechanism for converting poloidal magnetic fields into toroidal magnetic fields. We employed the flux modulation method to investigate solar differential rotation using full-disk ultraviolet images, including the 1600 Å band, obtained from the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO). The methodology involved preprocessing the full-disk images and segmenting them into distinct latitude bands. Following data processing, flux time series were extracted for each latitude region. Finally, autocorrelation analysis was performed on these time series to determine the rotation periods and corresponding angular velocities across different latitudes. Our research findings indicate that within the latitude range of 80°S to 80°N, the solar angular velocity of rotation varies significantly as a function of latitude. Across the different AIA wavelengths analyzed, the equatorial angular velocity increases with atmospheric height, while the degree of differential rotation decreases. Furthermore, the average angular velocity and the degree of differential rotation near the equator show no significant correlation with the solar activity cycle.

1 Introduction

The Sun is a fluid celestial body, and its rotation rate varies with both latitude and depth, a phenomenon known as differential rotation. This differential rotation is a fundamental component of the solar dynamo, playing a critical role in the generation and evolution of solar magnetic fields. Specifically, it is the primary mechanism responsible for the “Ω-effect,” which stretches poloidal magnetic field lines into toroidal configurations. Understanding the precise nature of this rotation is essential for modeling the solar cycle and predicting space weather.

Historically, solar rotation has been measured using various tracers, such as sunspots, faculae, and magnetic features, as well as through spectroscopic Doppler shifts and helioseismology. With the advent of high-resolution space-based observatories, particularly the Solar Dynamics Observatory (SDO), we can now probe the solar atmosphere with unprecedented spatial and temporal resolution across multiple wavelengths. The Atmospheric Imaging Assembly (AIA) provides continuous full-disk observations of the solar transition region and corona, offering a unique opportunity to study how differential rotation behaves at different heights in the solar atmosphere.

2 Data and Methods

2.1 Data Selection and Preprocessing

In this study, we utilize full-disk ultraviolet (UV) and extreme ultraviolet (EUV) images provided by the SDO/AIA instrument. We specifically focus on several channels, including the 1600 Å band, which captures the upper photosphere and transition region. The data spans a significant portion of Solar Cycle 24 and the beginning of Solar Cycle 25 to examine potential temporal variations.

[Figure 1: see original paper]

The preprocessing pipeline involves several steps: 1. **Calibration:** Standardizing the raw AIA data using the `aia_{prep}` routine to ensure consistent plate scales and orientations. 2. **Latitude Segmentation:** The solar disk is divided into 5° or 10° latitude bands, ranging from 80°S to 80°N. 3. **Flux Extraction:** For each latitude band, the total integrated flux is calculated for each image frame, resulting in a continuous flux time series.

2.2 Flux Modulation and Autocorrelation

The flux modulation method relies on the fact that as the Sun rotates, magnetic features (which are brighter or darker than the background in UV/EUV) move across the disk, causing a periodic variation in the observed flux. To extract the rotation period τ from the noisy flux time series $f(t)$, we employ the autocorrelation function (ACF):

$$\mathrm{ACF}(\tau) = \frac{\sum_{t=0}^{N-\tau-1}(f(t)-\bar{f})(f(t+\tau)-\bar{f})}{\sum_{t=0}^{N-1}(f(t)-\bar{f})^2}$$

Key words Sun: rotation, Sun: activity, Sun: UV radiation, methods: data analysis, autocorrelation

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

Source: ChinaXiv —Machine translation. Verify with original.