Rotational velocity of the solar corona versus solar activity

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Abstract: The contribution summarizes the results of determining the rotational speed of the solar corona in the period of 2011 - 2022. The authors published already the method of input data selection and the results for the period of 2011 - 2018 in Dorotovič and Rybanský (2019). This extended analysis takes into account temporal variations in the speed of rotation of the solar corona in the period of 2011 - 2020 depending on (a) the heliographic latitude in the range of (-65°, +65°) and (b) on the level of solar activity.

Keywords: Sun: corona; Sun: rotation; Cross-correlation

1. Introduction

The problem of temporal changes in the rotation of the solar corona (angular rotational velocity ω) and other layers of the solar atmosphere can still be considered open, unexplored. The reason is a large variance of the measured velocities, while the small contribution of changes in ω (if any exist) is overlapped with the scatter of the measured values of ω. Main objective of the study is to investigate eventual relationship between the rotational velocity of the solar corona and the level of the solar activity, *i.e.* the phase of the solar cycle) .

2. Input data, method of data selection and results

Monthly average values of ω for the period of 2011–2018 are published in Dorotovič and Rybanský (2019). In that paper were determined first daily values of coronal rotational speed in °/day using cross-correlation between two SDO/AIA 21.1 nm images with a time lag of 30 minutes and in this work additional values of the rotational speed for the years 2019 and 2020, respectively, were determined. Similarly as in the cited paper, only the areas ± 6° in the heliographic length around the central meridian and ± 70° in the heliographic latitude around the equator were compared in the cross-correlation process. Such way we obtained a time series of 120 months. Spatial resolution was 0.05° in both heliographic coordinates. Intensity data were transformed into a matrix of 241 rows x 2761 columns.

Then monhtly averages of ω were calculated from daily values, fulfilling certain defined criteria. It has to be noted that we divided the resulting monthly data into two groups. If there was a bright coronal bright point (CBP) at a certain row, then it served as a tracer, otherwise the role of a tracer was taken over by an intensity coronal structure. In the first case we denote the time series as ω_p, in the second case as ω_n. As we will see later, time series of ω_n correlates well with solar activity indices and, on the contrary, the correlation of time series of ω_p is low. The obtained time series have a variance at the equator ($\omega \cong 14$°/day) of about 3°/day. As the latitude increases, the variance increases and at a heliographic latitude of about 50° it is already about 5°/day for the value of ω about 12°/day. In order to reduce the variance for the further analysis, we selected in the time series only those data that differ from the average by less than in ± σ and we averaged the data in the latitudinal range from –35° to +35°.

Within this range, there are 21,000 measurements per an average month, and about half of them meet the required criteria. In this way, the variance in the time series of monthly averages of ω was reduced to a level below 0.05°, which can also be seen in Figure 1.

3. Comparison with solar activity

We characterize the level of solar activity by different indices derived from the observations of its various manifestations. For comparison, we used monthly averages of the Wolf number (W), the level of solar radio flux at 2800 MHz (IR) and the coronal index (CI), and these values were correlated with ω_p and ω_n.

CI is derived from ground-based observations of the green corona emission line at 530.3 nm above the solar limb. Rybanský (1975) and Rybanský et al (2005) showed that it is possible to determine from these observations the total radiated power in this line (in units of 10^{16} W/sr) at a distance of 1 au from the Sun.

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Those observations were later replaced by corona observations from satellites in the XUV region of the spectrum (Lukáč and Rybanský, 2010). For this purpose, we currently use observations of the SDO/AIA instrument at a wavelength of 21.1 nm.

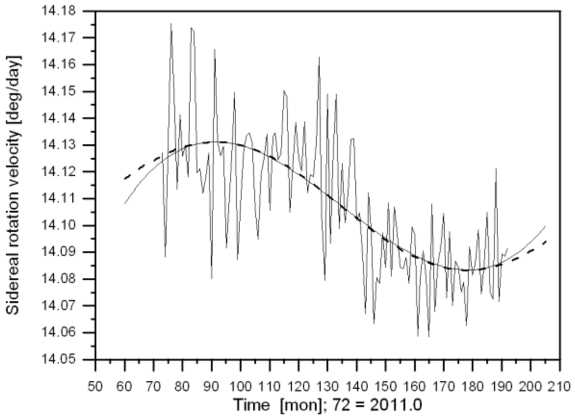

Figure 1. Time series graph of monthly averages of ω_n ; cubic parabola approximation (thin solid line): y = 14.123 + 8.93.10^{-4} t – 2.73.10^{-5} t^2 + 1.45.10^{-7} t^3, where t is time in months; sinusoidal approximation (thick dashed line): y = 14,1072 + 0,02388.sin((t +24).2π/173,8).

We calculated the monthly averages from the indices W, IR and CI and then we correlated these with the monthly averages of ω_n and ω_p. The results are shown in Table 1

Table 1: Correlation coefficients between the activity indices and the rotational speed ω_n and ω_p, respectively.

	ωn	**ωp**
W	0.678	0.188
IR	0.692	0.183
CI	0.752	0.215

We can see from the table that the best correlation is between the datasets of CI and the ω_n. Further, we will analyze the course of the dataset of ω_n, which is shown in Figure 1, indicated by a thin solid line. The values of ω_n decrease in the studied period. When approximating the course by a line:

$y = 14.1387 - 5.085\ 10^{-4}t$ (1)

where *t* is the time in months, whereas January 2011 ≅ 1, the sum of squares of deviations has the value of $\Sigma\varepsilon^2 = 0.0462$.

When approximating by a cubic polynomial:

$y=14.123 + 8.93\ 10^{-4}t - 2.73\ 10^{-5}t^2 + 1.45\ 10^{-7}t^3$ (2),

the value of $\Sigma\varepsilon^2 = 0.0434$. Course of this approximation is shown in the figure by a thin line.

Between the maximum (91.3) and the minimum (178.3) is a distance of 87 months (7.25 years). This interval is close to the mean length of the descending phase of a solar activity cycle. In this part of the course of the ω_n we can replace the approximation (2) with a sinusoidal approximation:

$y = 14.1072 + 0.02388 \sin((t + 24)2\pi/173.8)$ (3).

Course of this approximation is shown in the figure by a dashed line.

3.1. Model of an average solar cycle

According to the equation (3) we create a corresponding model of an average solar cycle. The sinusoidal period from this approximation in Figure 1 is 173.8 months, *i.e.* 14.48 years.

The length of the descending phase of the cycle is 7.24 years. Ratio between the ascending and the descending phase of a cycle is 4:7 and from this ratio the ascending phase lasts 4.14 years, *i.e.* 49.68 months. Then the whole cycle would have the length of: 173.8/2 + 49.68 = 136.58 months, *i.e.* 11.39 years. Range of the sinusoid is 2 x 0.02388°/day and the rotational speed rate varies in the equatorial regions of the Sun by 6.4 m/s.

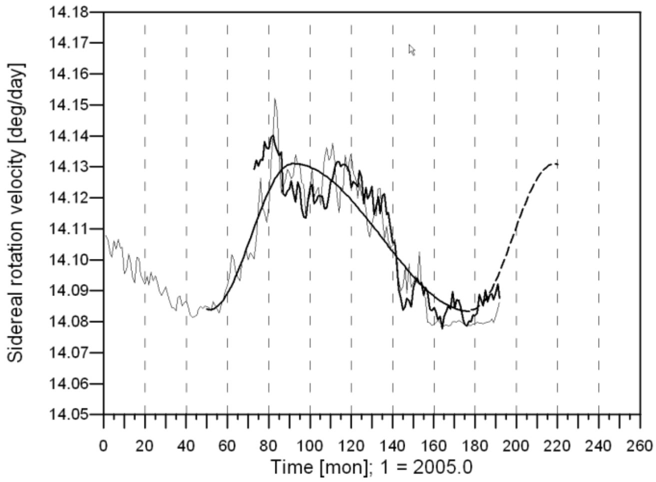

Figure 2. Graphs of monthly averages of CI (thin gray line), running mean of monthly averages of ω_n (thick black solid line) and model of solar activity cycle according to the sinusoidal approximation of evolution of the rotational speed of the solar corona (solid+dashed line).

4. Summary and Conclusions

- The mean coronal rotation rate (monthly averages of the time series of ω_n) in the observed period correlates well with the level of solar activity, while for CI the coefficient is r = 0.752.

The dependence can be expressed by the line: $\omega = 14.08 + 0.0227$ CI.

The course of monthly average of CI values for the period 2005 –2020 is shown in Figure 2 with a thin solid line. The thick solid line shows the moving average (from 7 points) of the time series of ω_n for the period 2011 - 2020. The model of the course of the solar cycle

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obtained according to the method described above is indicated by a thick line as well.

- According to the constructed hypothetical solar cycle model, the dates of minima are 2009.2 and 2019.6, respectively; the dates of activity maxima are 2012.4 and 2023.2, respectively.
- We know that it is too early to definitively confirm the hypothesis. We would need a longer time series with the necessary resolution, i. at least about 0.05°/day.

Perhaps observations of other space instruments could also be used, *e.g.* on the SOHO satellite, or to propose terrestrial observations of various tracers for this purpose.

- We do not know any theoretical explanation for the relationship between the coronal rotation speed and the phase of the solar activity cycle. However, if this hypothesis would be confirmed, its explanation will appear in the theory of solar activity cycles.

- We cannot explain the difference between the behavior of datasets of ω_n and ω_p.

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