TEMPORAL VARIATIONS OF THE SOLAR CORONA ROTATION

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ABSTRACT

The analysis of the solar corona rotation was performed using our own database (1939-2001) on the brightness of the coronal green line Fe XIV 530.3 nm. It is shown that the velocity of differential rotation of the corona is cycle-dependent. At the descending branch the differentiality of rotation is reduced. A higher differentiality of rotation (though still lower than that measured at the photosphere) appears at the ascending branch, immediately before the cycle maximum and, sometimes, during the maximum itself. The coronal rotation rate can be expressed by a sum of two modes (slow and fast) of rotation. The above results indicate that the whole structuralism of the velocity field in the convective zone should be necessarily time-dependent, as well. The forthcoming helioseismic measurements are of capacity to verify this opinion.

Key words: coronal green line brightness; differential rotation of the Sun; bimodal rotation.

1. INTRODUCTION

The differential rotation of the Sun is a fundamental problem of astrophysics. It is considered to be a necessary condition for operation of the dynamo mechanism. The solar rotation data must be taken into account when developing theories of evolution, time variation, and periodicity of the solar activity. The particularities of rotation of various features in the solar atmosphere can be interpreted as manifestation of the rotation velocities at certain depths where the fields of different scales are rooted. The solar corona reflects the rotation of the deepest subphotospheric layers.

Helioseismic measurements provide a general pattern of the angular rotation rate of the Sun and its dependence on depth and latitude. It enables a better understanding of the mechanisms of differential rotation and generation of the toroidal magnetic field on the basis of nonlinear interactions in the convection zone. Recently, a certain progress has been made in studying the mechanism of differential rotation Kichatinov (2004), but exact quantitative investigation of it is a task for the future. Thus, a comparison of the rotation parameters of different tracers with helioseismic data may contribute significantly to the solution of this challenging problem.

In this paper, the rotation characteristics of the solar corona have been studied using measured brightness of the coronal green line Fe XIV 530.3 nm. Cyclic variations in the latitude-time dependence of the coronal rotation period have been considered for the interval from 1939 to 2001. Our own database has been used (for description see Sýkora, 1971a; Storini & Sýkora, 1997).

2. LATITUDE-TIME DEPENDENCE OF THE ROTATION OF THE SOLAR CORONA

Badalyan & Sýkora (2004, 2005) studied the rotation of the solar corona using the method of the spectral-variation analysis. The method consists in applying the Fourier expansion into harmonic functions in a moving time window. In (Badalyan et al., 2005) and in the present work, we are using a modified version of this method - a periodogram analysis, which allows better resolution of the period. For the time window of a chosen length, we calculate the correlation between the daily values of the green-line brightness in a given latitude zone and the test harmonic function with period T. If there are pronounced variations with a period T in the window under examination, the correlation coefficient will be maximum at t = T. After that, the window is shifted in time and the whole procedure repeats. The sequences obtained in such a way are used to plot a general map of amplitudes in the time-period coordinates. In this work, the length of the window is assumed to be equal to 1095 days (3 years) and its shift, to 81 days.

The spectral analysis was performed separately for all latitudes over the time interval under consideration (1939-
rotation period increases gradually (i.e., the rotation rate decreases) to reach 29 days or more. Above $45^\circ - 50^\circ$, the rotation rate does not practically change with latitude. Fig. 3 provides an idea of some mean parameters of the differential rotation of the solar corona.

Once the distributions of $T$ at all latitudes are known, we can plot a general distribution diagram in the latitudetime coordinates. To plot this diagram, a filtration procedure was applied. The sequence of $n$ values of the period $T$ at all northern and southern latitudes was expanded into Fourier series of $n/2$ terms, after which the inverse summing was performed with a smaller number of the harmonics. Restricting the number of the harmonics in inverse summing allows us to cut off the noise component. We summed up the first ten harmonics to cut off the harmonics with the oscillation periods less than 6 years. The filtration was performed for all latitudes in both hemispheres.

As a result, a map of the periods $T$ was obtained (Fig. 3, upper panel). The lower panel shows the monthly mean Wolf numbers, for reference. The map reveals a cyclic variations of the period $T$. In the ascending branch of the activity cycle, the coronal rotation period at high latitudes increases. In the descending branch, the rotation rates at high latitudes and at the equator do not differ significantly, and, in general, a near rigid rotation is observed.

It means that, in the periods close to the activity maximum, the $b$ index characterizing differentiability of the coronal rotation in Equation 1 increases ($\omega$ is the angular rotation rate and $\varphi$ is the heliographic latitude):

$$
\omega = a + b \times \sin^2 \varphi
$$

(1)

The latitude dependence of $\omega$ and its time variation allow
us to study the cyclic variation of the index $b$ in Equation 1. Fig. 4 represents the cyclic variation of the coronal differential rotation as a function of the cycle phase defined by Equation 2:

$$\Phi = (\tau - m)/(|M - m|)$$  \hspace{1cm} (2)

Here, $\tau$ is the current time and $M$ and $m$ are the times of the nearest maximum and minimum of the 11-year cycle, respectively. According to Equation 2, the phase of the cycle is zero at the minimum, positive on the ascending branch, and negative on the descending branch. Fig. 4 illustrates the values of $b$ averaged over all cycles under consideration and over both hemispheres (for more detail see Badalyan et al., 2005). As seen from the plot, $b$ changes during a cycle. In the descending branch, $b$ is close to zero; i.e., the rotation of the corona is quasi-rigid. In the ascending branch, the differential rotation becomes most pronounced; i.e., $b$ reaches the greatest (negative) value.

It follows from Fig. 4 that the quasi-rigid rotation is observed at the phase $\Phi = -0.5$, i.e., on the descending branch, about three years before the minimum. Here, a quasi-rigid rotation is identified quite reliably and corresponds to approximately the same $\Phi$ in all cycles under investigation. The differential rotation is most pronounced on the ascending branch (sometimes, at the maximum) of the activity cycle and is usually observed at $\Phi = +0.5$ about 1.5 years before the maximum. In each particular cycle, the time of the maximum differentiality is fixed quite precisely, but its location on the ascending branch differs in different cycles. That is why we see a certain plateau of high $b$ values in Fig. 4. The formal error of $b$ in this plot is about 0.5° per day; however, taking into account the difference between the cycles, the true error is smaller.

Thus, the quasi-rigid rotation of the solar corona in the descending branch of the activity cycle turns gradually into the rotation with more pronounced differentiality. It can be suggested that, in the ascending branch, some slowly rotating elements appear in the corona at high latitudes resulting in the observed increase of the period $T$.

3. TWO ROTATION MODES OF THE SOLAR CORONA

Many particularities of the latitudinal and time dependence of the coronal rotation period suggest that the observed rotation of the corona is a superposition of two components or modes (see Badalyan & Sýkora 2004, 2005; Badalyan et al., 2005). The probability of coexistence of two modes (quasi-rigid and slightly differential ones) in the rotation of the Sun was explored by many authors (e.g., Sýkora, 1971b; Antonucci & Svalgaard, 1974; Stenflo, 1977; Mouradian et al., 2002).

The general problem of decomposition of the coronal rotation into two modes is not unambiguous. Therefore, its solution requires some additional conditions. We have set the separation boundary between the two modes at 29 days. In each window, the maximum period of the fast mode in the range of the periods not exceeding 29 days was found. As for the slow mode, since it is only detected at some time intervals, its period must be determined only at those particular intervals. Fig. 5 shows how the mean periods of the fast and slow modes change with latitude. One can see that the fast mode is weakly differential, and its period ranges from 27 to 28 days. The mean period of the slow mode ranges within 30.5-31.5 days.

Once the periods of both modes are known at every time and at all latitudes, the contribution of each mode in the latitude-time coordinates can be plotted. Let us denote the relative contribution of the fast mode to the total rotation rate of the corona as $D$. Then, the contribution of the slow mode will be $1 - D$, and the observed angular rotation rate of the corona $\omega$ will be expressed as:

$$\omega = \omega_1 \times D + \omega_2 \times (1 - D),$$  \hspace{1cm} (3)

where $\omega_1$ and $\omega_2$ are the angular velocities of the fast and slow rotation modes, respectively. This equation allows us to determine the relative contribution of both modes as a function of time and latitude. For calculations by Equation 2, the distribution of the rotation periods of the fast mode was obtained as described above (see also Badalyan et al. (2005)), and the mean period of the slow mode was
Figure 6. Contribution of the slow mode 1 – D to the total rotation rate of the corona.

assumed to be equal to 31 days. Fig. 6 illustrates the contribution of the slow mode 1 – D. It is readily seen that the contribution of the slow mode is, naturally, significant at those latitudes and times where and when large rotation periods are observed. At some instants, the contribution reaches 100%. At lower latitudes, the fast mode prevails and its contribution to the total rotation is dominating at the descending branch of activity.

4. CONCLUSIONS

The spatial and temporal rotation characteristics of the solar corona have been studied in detail using a periodogram analysis of the coronal brightness in the green line FeXIV 530.3 nm for approximately six activity cycles (1939-1991). The following results have been obtained:

1) The periodogram analysis of the integral (i.e., averaged over the time interval under consideration) rotation characteristics of the solar corona has revealed the synodic rotation period at low latitudes close to 27 days. Above ±15°, the rotation period increases gradually the values somewhat greater than 29 days. Above 45° – 50°, the rotation rate does not change significantly.

2) A more detailed analysis shows that the velocity of differential rotation of the corona changes with time. This variability has a periodic character and is associated with the 11-year activity cycle. At the middle of the descending branch, the differentiality of rotation is weakly pronounced, and the corona rotates almost rigidly. During the ascending branch (sometimes, including the maximum), the differentiality increases (still remaining lower than in the photosphere). The greatest differentiality index b is observed approximately at the middle of the ascending branch.

3) The total rotation rate of the corona can be represented as a superposition of two rotation modes (a fast and a slow ones). A method is proposed for separating these modes. It is shown that the synodic period of the fast mode in the vicinity of the equator is approximately 27 days and somewhat changes with time. The fast mode exists at all times and all latitudes. It is weakly differential, and its period at high latitudes may reach 28 days. Approximately at the middle of the descending branch, the fast mode is best pronounced. The slow mode is only noticeable at high latitudes at the ascending branch of activity. Its synodic period is close to 31 days.

4) The obtained space-time distribution of the rotation periods of both modes is used to calculate the relative contribution of each mode to the total rotation velocity. This contribution is shown to depend both on time and on heliographic latitude. At low latitudes, the rotation of the corona is determined almost completely by the fast mode. This mode also prevails at the middle of the descending branch of the activity cycle. The slow mode is dominant at higher latitudes at the ascending branch of the activity cycle.

5) Our results agree with the helioseismic model (Schou et al., 1998) (see Badalyan & Sýkora 2004, 2005; Badalyan et al., 2005) However, this model was developed by Schou et al. (1998) for the ascending branch of cycle 23. According to our results, this is the time interval when two rotation modes co-exist in the corona. In the descending branch, a different model, with low differentiality at all latitudes, is necessary to describe the rotation in the convection zone. This conclusion can be verified by helioseismic investigations.

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REFERENCES

Antonucci E., Svalgaard L., 1974, Sol. Phys. 34, 3
Kichtinov L.L., 2004, Astron. Zh. 81, 176
Stenflo J.O., Astron. and Astrophys., 1977, 61, 797