On the rotation of the solar corona at various stages of the eleven-year cycle of solar activity

© P.B. Dmitriev

Ioffe Institute,
194021 St. Petersburg, Russia
e-mail: paul.d@mail.ioffe.ru

Received May 3, 2024
Revised July 19, 2024
Accepted October 30, 2024

The solar coronal rotation was studied based on the analysis of daily data variations of the solar activity index — the solar radiation flux at a wavelength of 10.7 cm — for six consecutive eleven-year solar cycles (from the 19th to the 24th). Using the calculated time diagrams of the change in the values of the revealed quasi-periods in the time structure of the radio index of each cycle, it was concluded that the corona at different stages of the eleven-year solar cycle can exhibit properties of both differential and „solid-body" rotation.

Keywords: solar activity, photosphere, corona, radio emission, rotation.

DOI: 10.61011/TP.2024.12.60424.398-24

Due to systemic measurements of the radio flux from the Sun full phase performed under the solar activity (SA) radio monitoring program by the National Research Council of Canada since 1947 was able to introduce a new SA index — radio index (RI). This is a daily adjusted radio flux from the Sun full phase at the frequency of 2800 MHz (wavelength of 10.7 cm), which is measured in solar flux units (SFU), and one unit is equal to $10^{-22}\,\mathrm{W\cdot m^{-2}\cdot Hz^{-1}}$. The solar radio emission includes three main components: constant („calm"), due to thermal radiation of the corona and chromosphere, variable — from coronal condensations (consolidations above large groups of sunspots, and more specifically above the arcades of multiple magnetic loops of active regions filled with hot plasma) and short-term bursts with duration from seconds to several hours, which are related to flashes in chromosphere [1]. Therefore, this index reflects the intensity of formation and evolution of active magnetic regions in the atmosphere of the Sun, therefore, its values may be used to research the patterns in the physical properties of the solar chromoshere and corona.

Currently the differential nature of the solar photosphere rotation causes no doubt. Back in the middle of the last century the formula was made based on the sunspot areas for rotation of the horizontal layers of the photosphere depending on the heliolatitude [2], which confirms that the photosphere at the equator rotates much faster than at the poles. As for the corona, the opinion on the nature of its rotation is rather diverse, since the results from the research of its rotation properties first of all depend on the spectral range, where the Sun observations are carried out [3]. Therefore, due to the ground optical observations of the green coronal line intensity (Fe XIV 5303 Å), the source of which is at elevations $\sim 105\,000$ km above the Sun photosphere level, made by the global network of high-altitude observatories from 1939 to 2001. (17–21 SA cycles), it was found that the synodic rotation period of the corona during the SA cycle increases from 27 days on the equator to 29 days at latitudes $\pm 40^\circ$, and starting from the higher latitudes, the differential rotation gradually „fades away", and the corona rotates as a solid body with a period of around 29.5 days at poles [4]. Later, using the same data, the nature of the differential rotation of the corona was established depending on the phase of SA cycle [5], namely during the time of the cycle downtrend there are only minor differences in the rotation, which is similar to the solid body, and during the rise in the cycle activity, directly prior to its maximum, and sometimes in the maximum itself, these differences become more substantial. The differential nature of the corona rotation is confirmed by multiple radio observations of the Sun radiation, too. Thus, for instance, the Sun radio flux data at frequency 2.8 GHz for 22 SA cycle CA (1986–1996) was used with the help of the autocorrelation method of data processing to establish that for the duration of the solar cycle the value of the sideral rotation period of the corona changes from 24.07 to 26.44 days regardless of the number of the sunspots [6]. And during 23 SA cycle for the period from 1999 to 2005 it was found on the basis of the corona observations on radioheliograph Nobeyama at frequency 17 GHz (1.76 cm) that the corona rotates differentially, and its equatorial speed of rotation is comparable to the speed of photosphere and chromosphere rotation [7].

Accordingly, using the RI values measured for quite a long time one may assess the speed of corona rotation, as it is assessed by optically observed coronal „tracers" (line radiation of „pointed" coronal sources), or as the speed of rotation of parallel layers in the solar photosphere is assessed on the visible shift of sunspots. Therefore, in this paper the RI data of the last six SA cycles (from the 19th to the 24th) are used to analyze the rotation of the corona, besides, the time structure of these data is investigated for the presence of quasi-harmonic components using the method developed specifically for such research, which is based on building a „combined" spectral periodogram (CSP) and may be

Table 1. Values of revealed quasiperiods (day) for American version of relative number of sunspots of 19—24 cycles of SA

Cycle of SA		Single rotation		Double rotation		Triple rotation	
		24.9—28.0		49.8—56.0		74.7—84.0	
19	*14*, **22**	**27**	**31**, **33**, 40, 44		62, *68*	**76**	85, **97**
20	17, *22*	*25*, **28**	**31**, *34*	*52, 54*	60, **72**	**75**, 78, *83*	**97**
21		**27**	*33, 37*	52			
22	*18*	**28**	*37, 41*	**54**	61, *65*	*72, 75*	88
23	*18*, 20	**26**	*31*, 36, *44*	*52*	*65*, **73**	**83**	**86**, **94**
24	*16, 18*, 21, **23**	**26**	32, *37*, 45	**53**	**59**, 71	*78, 84*	*93*

briefly described as follows. The main element of CSP is the selective assessment of the normalized spectral density (NSD) [8], calculated for the time series depending not on the frequency, but on the trial period. Besides, the initial time series is exposed to the preliminary high-frequency filtering [9] with the pre-set „cut-off" frequency at the half of the signal power that in the time region is compliant with the value of the „separaging" period T_f. The source data are filtered to remove the trend and more powerful low-frequency components. Then for each parameter T_f of the high frequency component filtered with its specific value, the NSD of the period is again calculated, and all these estimates calculated for the various values of parameter T_f are imposed one onto another in the same field of the curve to form a CSP. The method is described in more detail in paper [10].

To check the suitability of this method for the research of the features in the corona rotation using the radio data, this method was first used to some values of the American version of the relative sunspot number (RA), in order to assess the nature of solar photosphere rotation, the change in the period of rotation of the horizontal layers of which from heliplatitude is known. For this purpose the daily RA data were taken from the server of the World Data Center (WDC) on Solar-Terrestrial Physics at [11], as well as daily RI values at [12] for the time interval covering six SA cycles, from the 19th to the 24th (1954—2019). The results of these data processing using the above method are given in table 1 for RA data and in table 2 for RI values. And CSP curves built for both types of data are only given for the 20th SA cycle (due to the restriction in the volume of this paper) in fig. 1, *a* for RA and in fig. 2, *a* for RI. When the CSP was calculated, the values of the „separating" periodT_f of the high-frequency filter were assumed as follows: $T_f = 7$, 17, 29, 37, 47, 61, 83, 97, 113 and 137 days. Therefore, each peak on CSP „is written" with eleven curves: ten from ten high-frequency components and one more curve from the initial time series. The tables show only those values of the identified quasi-periods, the peaks of which in the periodograms meet the criterion of selection of „random release" at the significance levels: $> 1\sigma$ (figures in the tables are italic), $> 2\sigma$ (figures of regular font) and $> 3\sigma$ (bold figures) — as if all CSP values would be the values of the random value distributed in accordance with the normal law with the mathematical expectation and the standard equal to the sample estimates of these parameters produced for all calculated values of CSP. Fig. 1, *a* and 2, *a* show these significance levels with horizontal lines marked σ, 2σ and 3σ.

Among the table values, one should note the quasi-periods that match the average „life spans" of solar active formations, such as large groups of spots (≈ 45 days) and large faculae (≈ 80 days), which define the changes in the solar activity [2], and also quasi-periods and their groups (duplets and triplets), which fall on the intervals of the „rotation values" of photosphere and corona: single, double and triple rotations (table 1, 2). In the tables these values are located in separate columns, for which the boundaries of the „rotation" intervals of the permissible values for the change in the synodic period of rotation of the Sun from the solar equator (0°) to latitude 45° are set using the data of the papers on the rotation of sunspots and coronal plasma [13]. In CSP these „rotation" intervals include both single peaks and their groups in the form of duplets and triplets. Such structures in CSP may appear, if the period of any single harmonic changes in time, or several harmonics co-exist. To clarify this situation and to analyze the nature of the change in the detected quasi-periods depending on the solar cycle phase, dynamic diagrams were built for the change in the values of the found quasi-periods for the duration of every solar cycle by calculation of NSD for RA and RI data in the sliding time window with width of 731 days. As the example, fig. 1, *b* and 2, *b* shows these diagrams for the 20th SA cycle. From these diagrams it follows that (see the diagrams for the values of quasi-periods in the single rotation values interval) at the solar cycle rise phase (fig. 1, *c* and 2, *c*) includes several quasi-periods, which may indicate various rotation of the several parallel layers of both photosphere (fig. 1, *b*) and corona (fig. 2, *b*), which is the sign of differential rotation. Then at the maximum phase of the cycle the rotation becomes „solid-state" — these values sort of „merge" as one, which, in its turn, at the downtrend phase gradually „rolls over" to the smaller region of values. The similar trend of changes to the values of the identified quasi-periods for the duration of the solar cycle is also observed for other cycles.

Table 2. Values of identified quasi-periods (day) for radio data of 19–24 SA cycles

Cycle of SA		Single rotation		Double rotation		Triple rotation	
		26.1–31.2		52.1–62.3		78.2–93.5	
19	**22**, **25**	**27**, **31**	**38**, 40, 44	51, *53*	*63*, **73**	85	**98**
20	*12*, *17*, 22	**26**, **28**, **31**	*41*	*60*, 62	**75**, **77**	**83**	**97**
21	*17*	*25*, **28**	*37*, *47*	*52*, *60*			
22	*18*, *24*	**26**, **29**, **31**	*36*, *41*, *49*	**54**, *61*	*65*, *72*	86	
23	*12*, **21**	**26**	**31**, **35**, 45	*52*	67, 73	**86**	**94**
24	*20*, 23	**26**	*32*, *44*	53, **60**			*99*

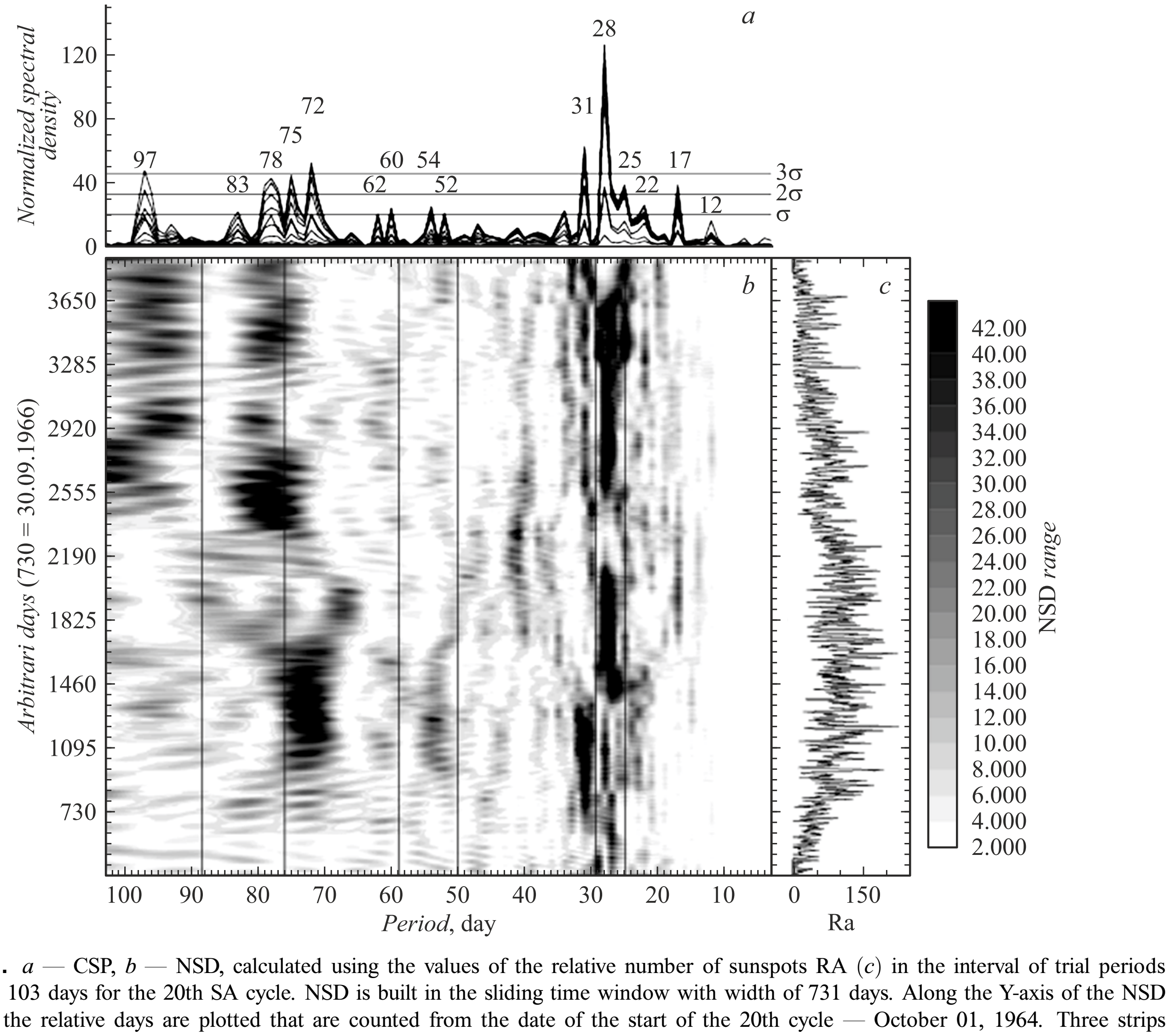

Figure 1. *a* — CSP, *b* — NSD, calculated using the values of the relative number of sunspots RA (*c*) in the interval of trial periods from 3 to 103 days for the 20th SA cycle. NSD is built in the sliding time window with width of 731 days. Along the Y-axis of the NSD diagrams the relative days are plotted that are counted from the date of the start of the 20th cycle — October 01, 1964. Three strips applied on the diagram field from the right to the left indicate accordingly the intervals of the permissible values (from the equator (0°) to the latitude 45°) of the change in the periods of single, double and triple synodic rotation of the Sun.

Therefore, the above diagram in fig. 1, *b* shows that the latitude shift of the spots towards the equator for the duration of the SA cycle their rotation periods decrease, which confirms the differential nature of the solar photosphere rotation. Accordingly, based on the similar effect for the corona radiation sources, when their rotation periods also decrease for the duration of the SA cycle (their values accordingly move from the left to the right inside the

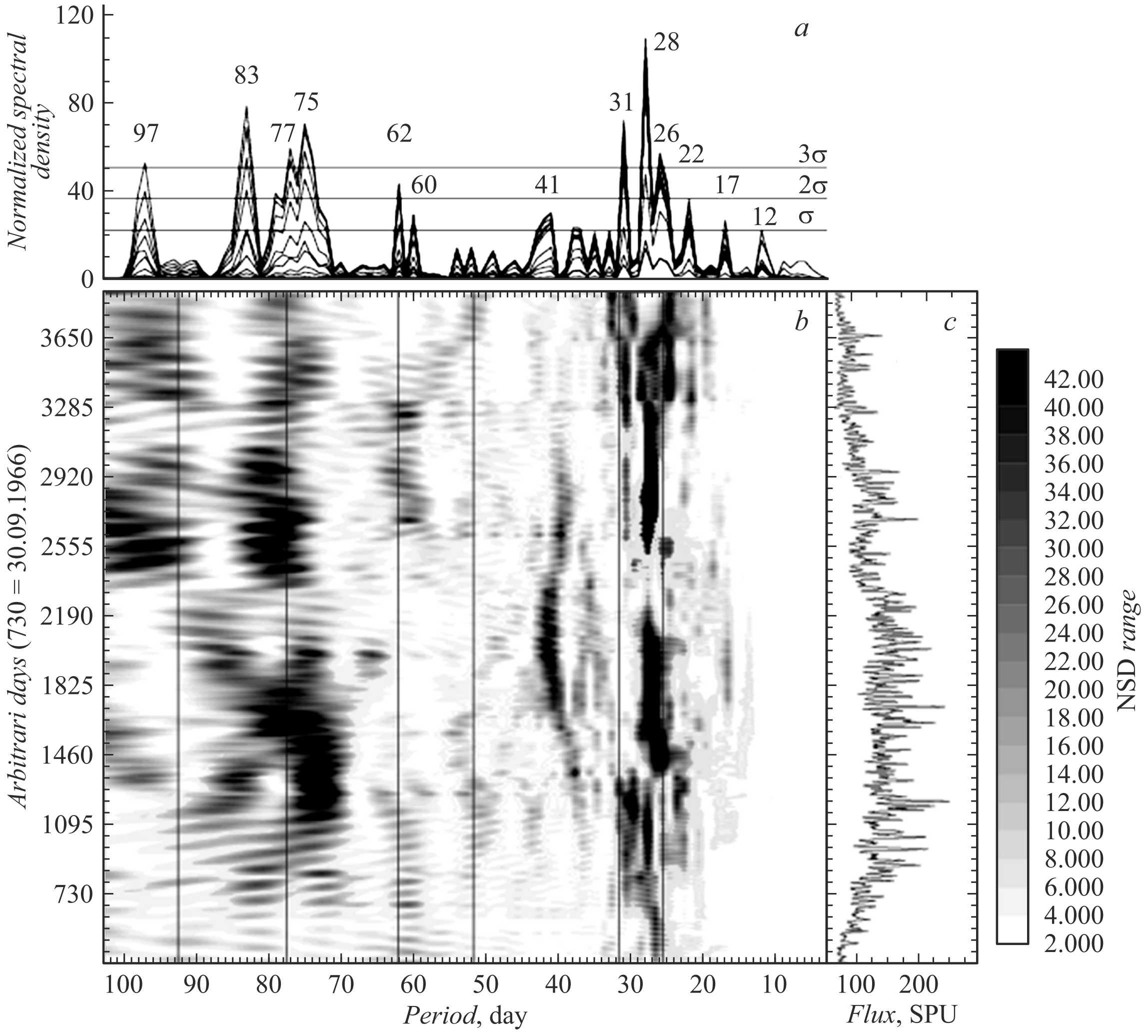

Figure 2. *a* — CSP, *b* — NSD, calculated using the values of the daily radio index (*c*) in the interval of trial periods from 3 to 103 days for the 20th SA cycle. NSD is built in the sliding time window with width of 731 days. Along the Y-axis of the NSD diagrams the relative days are plotted that are counted from the date of the start of the 20th cycle — October 01, 1964. Three strips applied on the diagram field from the right to the left indicate accordingly the intervals of the permissible values (from the equator (0°) to the latitude 45°) of the change in the periods of single, double and triple synodic rotation of the Sun.

dedicated interval of the single rotation (fig. 2, *b*)), one may state that the differential nature of the corona manifests itself clearly at the growth stage of the cycle, in the cycle maximum it is „solid-state" and at the cycle downtrend it again becomes differential.

Conflict of interest

The author declares that he has no conflict of interest.

References

[1] A.D. Fokker. In *Illustrated glossary for solar and solar-terrestrial physics*, ed. by A. Bruzek, C.J. Durrant (D. Reidel Publishing Company, Dordrecht–Hollad/Boston–USA, 1977), v. 11, p. 111–138.

[2] C.W. Allen. *Astrophysical quantities* (Athlone Press, University of London, 1981), v. 9, № 86, p. 180–183.

[3] J. Sharma, B. Kumar, A.K. Malik, H.O. Vats. MNRAS, **506** (4), 4952 (2021). DOI: 10.1093/mnras/stab1959

[4] O.G. Badalyan, J. Sýkora. Contrib. Astron. Obs. Skalnaté Pleso, **35**, 180 (2005).

[5] O.G. Badalyan, V.N. Obridko, J. Sýkora. Astronomy Reports, **50**, 312 (2006). DOI: 10.1134/S1063772906040056

[6] H.O. Vats, M.R. Deshpande, C.R. Shah, M. Mehta. Solar Phys., **181**, 351 (1998). DOI: 10.1023/A:1005070616574

[7] H.O. Vats, S. Chandra. MNRAS, **413**, L29 (2011). DOI: 10.1111/j.1365-2966.2011.18611.x

[8] G.M. Jenkins, D.C. Watts. *Spectral analysis and its application* (Holden-Day, San Francisco, Cambridge, London, Amsterdam, 1969), p. 176.

[9] A.S. Alavi, G.M. Jenkins. J. Royal Statistical Society, Series C (Appl. Statistics), **14** (1), 70 (1965).

[10] M.I. Tyasto, P.B. Dmitriev, V.A. Dergachev. Advances in Space Research, **66** (10), 2476 (2020). DOI: 10.1016/j.asr.2020.08.011
[11] Electronic source. Available at: http://www.wdcb.ru/stp/data/solar.act/sunspot/AAVSO/plt_daily.txt, last accessed July 19, 2024.
[12] Electronic source. Available at: http://www.wdcb.ru/stp/data/solar.act/flux10.7/daily/DAILYPLT.adj, last accessed July 19, 2024.
[13] R. Howard. In *Illustrated glossary for solar and solar-terrestrial physics*, ed. by A. Bruzek, C.J. Durrant (D. Reidel Publishing Company, Dordrecht–Hollad/Boston–USA, 1977), v. 2, p. 7–12.

Translated by E.Ilinskaya