

Rotation of the Solar Corona from Observations of Radio and X-Ray Solar Emission for Solar Activity Cycles 22–24

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Abstract—The values of the radio and X-ray solar flux over the last three cycles of solar activity were studied for the presence of quasi-periodic oscillations via the construction of a combined spectral periodogram. The revealed quasi-periods are mainly caused by the modulation of prolonged radio and X-ray fluxes by the proper rotation of the Sun. Particular attention was paid to the study of the time variation of the quasi-periods over the solar cycles via the construction of a sample estimate of the normalized spectral density of the data in a moving time window of up to 2 years. The dynamic diagrams of the variations in the quasi-periods constructed in this manner indicate that the differential rotation of the solar corona manifests itself at individual stages of the development and existence of the last three cycles of solar activity.

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1. INTRODUCTION

Systematic radio astronomical and extra-atmospheric measurements of solar radiation on the GOES satellites made it possible to introduce two new solar activity (SA) indices. One of them is the adjusted daily radio flux from the total disk of the Sun at a frequency of 2800 MHz (wavelength 10.7 cm). It is known as the Penticton flux and is measured in solar flux units (SFU), one unit of which is $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. The other index is the soft X-ray (SXR) flux from the total solar disk measured in the wavelength range 1–8 Å, the values of which (W m^{-2}) are logarithmized. Such an operation allows the elimination of the exponential trend of the initial data (Rittenour et al., 2000) and the influence of the individual values that exceed the others in magnitude (i.e., rare, intense bursts) on the result of subsequent data processing to reveal hidden periodicities, since such a transformation does not change the position of local extreme values in a data series.

Three components are distinguished in the solar radio emission during the SA cycle: a constant (quiet) component, which is due to thermal radiation of the corona and chromosphere; a variable component from coronal condensations (compactions over large sunspot groups), and brief bursts that last from seconds to hours and are associated with chromospheric flares (Fokker, 1980). In turn, SXR comes from bright (hot) loops of magnetic active regions filled with hot plasma, which is a source of quasi-thermal X-ray radiation that forms the slowly varying background component of the solar SXR (Hara et al., 1992; Tobiska, 1994).

SXR is also generated by brief (minutes or hours long) solar flares that occur in these magnetic structures and result in a sharp increase in the SXR flux that exceeds the background radiation by several orders of magnitude (Aschanden, 1994).

Therefore, both of these indices, which reflect the intensity of the formation of active magnetic regions in the solar atmosphere and their evolution, can be used to study the regularities of the physical properties of the solar chromosphere and corona.

At present, the differential character of the rotation of the solar photosphere is beyond doubt. Back in the middle of the last century, a formula for the rotation of the horizontal layers of the photosphere depending on the heliolatitude was derived from the sunspot zones (Howard, 1980; Allen, 1973). As for the solar corona, the views on the character of its rotation are very contradictory, since the results of the study of the properties of its rotation primarily depend on the energy range of the solar observation.

Ground-based optical observations of the intensity of the green coronal line (Fe XIV 5303 Å), the source of which is located at altitudes of ~ 105000 km above the level of the solar photosphere, were performed on the coronagraph of the Sacramento Peak Observatory over the course of SA cycle 21 (from 1973 to 1985). Based on these data, it was concluded that the corona rotates more rigidly than objects in the photosphere or chromosphere (Sime et al., 1989). Based on similar but more prolonged regular observations (Fe XIV 5303 Å) of the global network of high-latitude observatories from 1939 to 2001 (SA cycles 17–21), it was found that

the synodic period of the corona rotation during the SA cycle increases from 27 days at the equator to 29 days at latitudes $\pm 40^\circ$; starting from higher latitudes above $\pm 40^\circ$, the differential rotation gradually fades and the corona rotates as a rigid body with a period of approximately 29.5 days at the poles (Badalyan and Sýkora, 2005). Later, the character of the differential rotation of the corona with respect to the phase of the SA cycle was established from the same data (Badalyan et al., 2006). Specifically, it was found that there are only small differences in rotation similar to that of a rigid body during the cycle decline. During the cycle rise, these differences become more significant immediately before its maximum and sometimes even at the maximum itself. A similar result was obtained based on data from the SXT telescope of the Yohkoh satellite in the SXR range (Weber et al., 1997) for the decline of cycle 22 (1994–1997): during the decay stage of the cycle. The solar corona rotates like a rigid or almost like a rigid body with a synodic period of 28.1 days.

Numerous radio observations of solar radiation are also indicative of a differential character of the rotation of the solar corona. Based on the data of the 10.7 cm (2.8 GHz) solar radio flux known as the Penticton flux during SA cycle 22 (1985–1995), it was found via data-processing autocorrelation that the sidereal period of rotation of the corona over the course of the solar cycle varies from 24.07 to 26.44 days regardless of the number of sunspots (Vats et al., 1998). Later, it was found with the same data processing method and the same data but on a longer time interval of SA cycles 18 to 23 (1947–2009) that the period of the sidereal rotation of the corona ranges from 19.0 to 29.5 sidereal days; its average value over this interval was 24.3 sidereal days (Chandra and Vats, 2011). Almost coincident radio observations of the corona with the Nobeyama Radioheliograph at a frequency of 17 GHz (1.76 cm) in the period from 1999 to 2005 and the SXR observations with the SXT telescope of the Yohkoh satellite from 1992 to 2001 revealed that the solar corona rotates differentially, and its equatorial rotation speed is comparable to the rotation velocity of the photosphere and chromosphere (Chandra et al., 2010; Vats and Chandra, 2011a, 2011b). Moreover, analysis of the dependence of the solar corona rotation on the heliographic latitude and time based on the processing of radio map images of the total solar disk obtained at a wavelength of 1.76 cm (17 GHz) in the same period of SA cycle 23 (1992–2001) showed that the solar corona has alternating bands of faster and slower rotation that shift from high latitudes toward the equator over the course of the solar cycle (Gelfreikh et al., 2002).

In addition to the latitude-dependent differential rotation of the corona, it was also established that its nonuniform rotation depends on the altitude above the level of the solar photosphere. Based on daily measurements of solar radio emission carried out for 26 months from June 1997 to July 1999 (SA cycle 23)

simultaneously in 11 radio frequency bands of the 275–2800 MHz range (the radio emission in this frequency range occurs in the solar corona at altitudes of $\sim(6-15) \times 10^4$ km above the photosphere), it was found that the sidereal rotation period at the frequency of 2800 MHz, which corresponds to the level of the lower corona 6×10^4 km, is ~ 24.1 days and, depending on the decrease in the observation frequency, the period decreases to ~ 23.7 days at the frequency of 405 MHz, which corresponds to an altitude of $\sim 13 \times 10^4$ km (Vats et al., 2001).

The difference between the analysis of the solar corona rotation in this study and the examples above is the processing of the weighted average series of solar X-ray radiation, which were constructed with the developed original technique based on patrol measurements of solar radiation from the GOES satellites for SA cycles 22–24, as well as the original technique to study the features of the temporal structure of the resulting series.

2. EXPERIMENTAL DATA AND THEIR TREATMENT METHOD

To study the temporal structure of solar radiation in the radio and X-ray ranges for SA cycles 22–24, the daily data of the 10.7-cm radio flux measured in SFU (Fig. 1a) (<http://www.wdcb.ru/stp/data/solar.act/flux10.7/daily/>) and the daily data on the SXR flux in the wavelength range 1–8 Å in units of W m^{-2} (Fig. 1b) of 11 GOES satellites (<ftp://ftp.swpc.noaa.gov/pub/lists/xray/>) from the total solar disk were used. A single series of daily solar SXR data over the last three 11-year solar cycles was synthesized based on the developed method to combine multiple measurement series of the same type made at different times into a single weighted average series based on the GOES data.

The algorithm to construct the weighted average series was as follows: for each time point (date) of the total time interval of all measurements, the measurements obtained at that time point from each satellite were processed among themselves according to the principle of the processing of measurement series of unequal accuracy with given weights (Agekyan, 1972); the weights are determined for each measurement of a specific satellite through the computed value of the sample variance of the data from this satellite. Thus, for each given time point (date) of the total time interval of all initial measurement series, one value of the weighted average series of measurements and the root-mean-square error of this value are calculated. The values of this series were logarithmized (Dmitriev and Miletskii, 2002). As mentioned above, the logarithmization makes it possible to eliminate the exponential trend of the initial data (Rittenour et al., 2000) and the influence of rare strong bursts (in our case, rare strong solar flares) on the result of subsequent signal

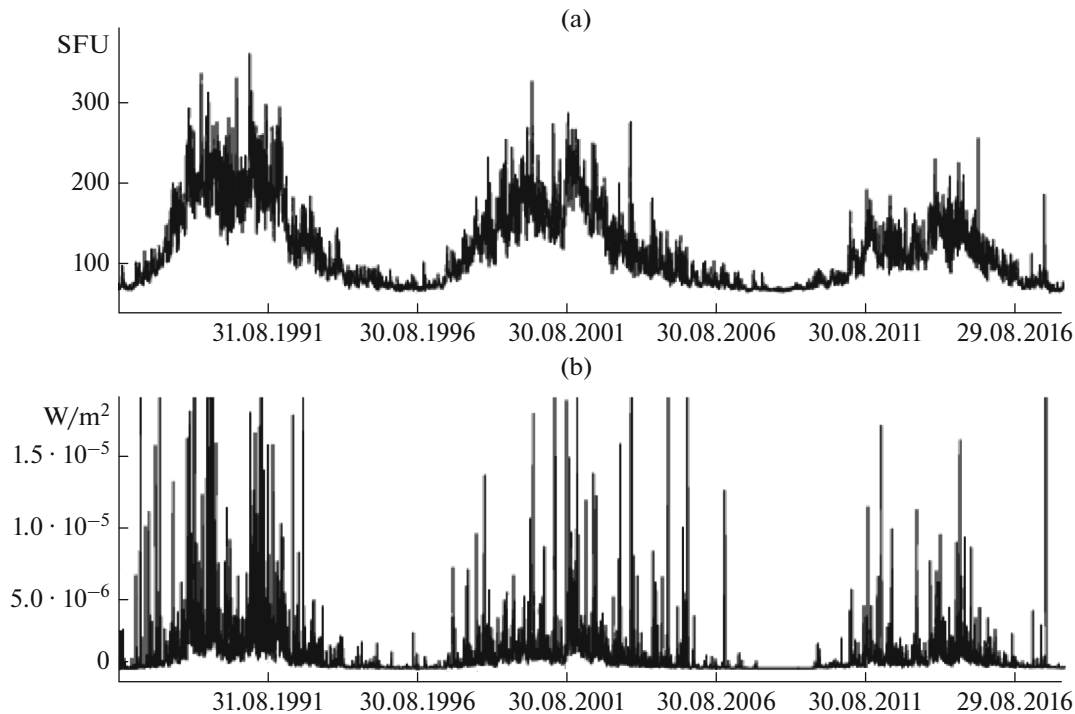


Fig. 1. (a) Solar activity daily radio index in SFU; (b) weighted average daily SXR solar flux calculated from the GOES measurements in the wavelength range $1-8 \text{ \AA}$ in units of $W m^{-2}$ from the total solar disk over SA cycles 22–24.

processing (revealing hidden periodicities), since it does not change the position of local extreme values in the data set.

The temporal structure of the data series was studied in detail with a modified spectral analysis method: the construction of a combined spectral periodogram (CSP), the essence of which, in short, is as follows. The sample spectral density (SNSD) (Jenkins and Watts, 1969) for the initial time series is calculated with respect to the trial period rather than the frequency. This is determined by the very formulation of the problem of the identification of the hidden periodicity in the initial data (Serebrennikov and Pervosvansky, 1965). In addition, the original time series are subjected to preliminary, high-frequency filtering (Alavi and Jenkins, 1965) with a predetermined filter cut-off frequency at half of the signal power, which corresponds to the separation period $T_{\text{cut-off}}$ in the time domain. The source data are filtered in order to eliminate the trend and more powerful low-frequency components. Further, for each high-frequency component filtered with its own specific value of the $T_{\text{cut-off}}$ parameter, the SNSD from the period is calculated again, and all of these estimates calculated for different values of the $T_{\text{cut-off}}$ parameter are superimposed on each other in the same field of the graph forming the CSP. This method is described in more detail by Dranevich et al. (2009), Raspopov et al. (2013), Dergachev et al. (2016), and Tyasto et al. (2020).

3. RESULTS AND DISCUSSION

Figures 2a, 3a, and 4a show the results of the processing of the daily average radio flux from the total solar disk over the last three SA cycles. Figures 2c, 3c, and 4c show the results for the logarithmic values of the daily weighted average values of the SXR flux. Table 1 gives the overall result of the revealed quasi-periods for all of the data. The table shows the periods with corresponding peaks on the periodograms that satisfy the selection criterion of a random burst at a level of significance $>2\sigma$, as if the CSP values were the values of a random variable distributed normally with mathematical expectation and standard equal to the sample estimates of these parameters obtained from the values of the calculated CSPs. The horizontal lines in Figs. 2a, 2c, 3a, 3c, 4a, and 4c mark the significance levels corresponding to the values of σ , 2σ , and 3σ .

The presented figures show the CSP (with the values of the separation period of the high-frequency filter $T_{\text{cut-off}} = 7, 17, 29, 37, 47, 61, 83, 97$ days) constructed according to the above method for the radio and SXR data of each individual SA cycle: 22—Figs. 2a, 2c; 23—Figs. 3a, 3c, and 24—Figs. 4a, 4c. These periodograms clearly show both the presence of individual peaks and groups; some of them are represented in the form of doublets and triplets. The CSP structures for different data from different cycles are quite nonuniform, but one can distinguish among them peaks with corresponding values of the periods that can be inter-

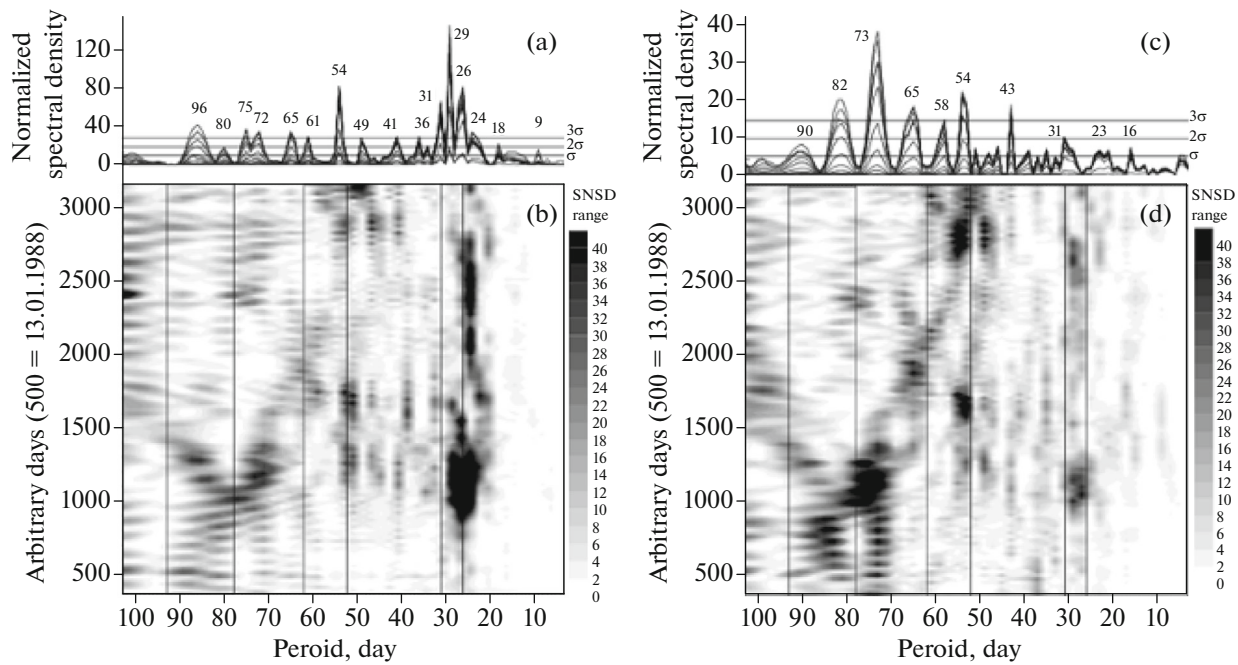


Fig. 2. (a) CSP and (b) SNSD calculated for the values of the SA daily radio index; (c) CSP and (d) SNSD calculated for the solar SXR values (1–8 Å) in the interval of the trial periods from 3 to 103 days for cycle 22. SNSD is plotted in a moving time window of 731 days. The ordinate axis of the SNSD diagram shows the relative days counted from the start of the 22nd cycle, September 1, 1986.

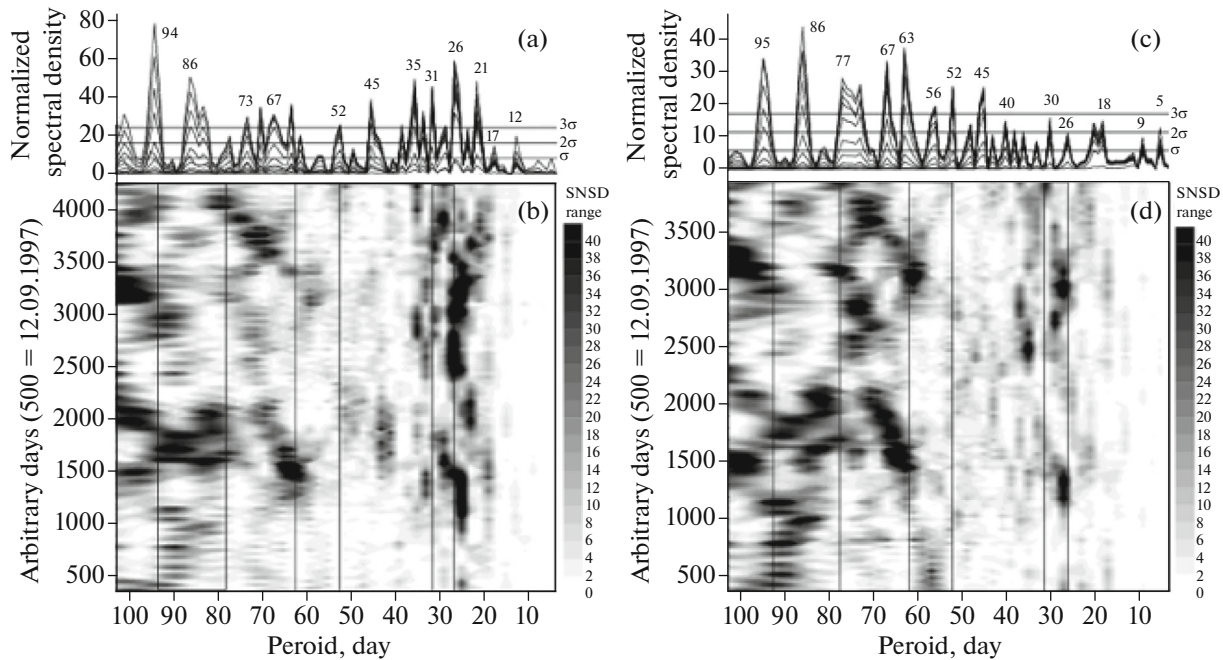


Fig. 3. The same as in Fig. 2 but for SA cycle 23. Days are counted from the start of the 23rd cycle, May 1, 1996.

interpreted as a result of the rotation of the chromosphere and the solar corona with radiation sources located at altitudes from 5000 to 11 000 km in the chromosphere and from 40 000 to 60 000 km in the corona above the

solar photosphere (Ternullo, 1986; Donahue and Keil, 1995; Vats et al., 1998, 2001). In this case, the absence of strong SXR peaks in the range of the solar rotation period (20–30 days) in comparison with the radio flux

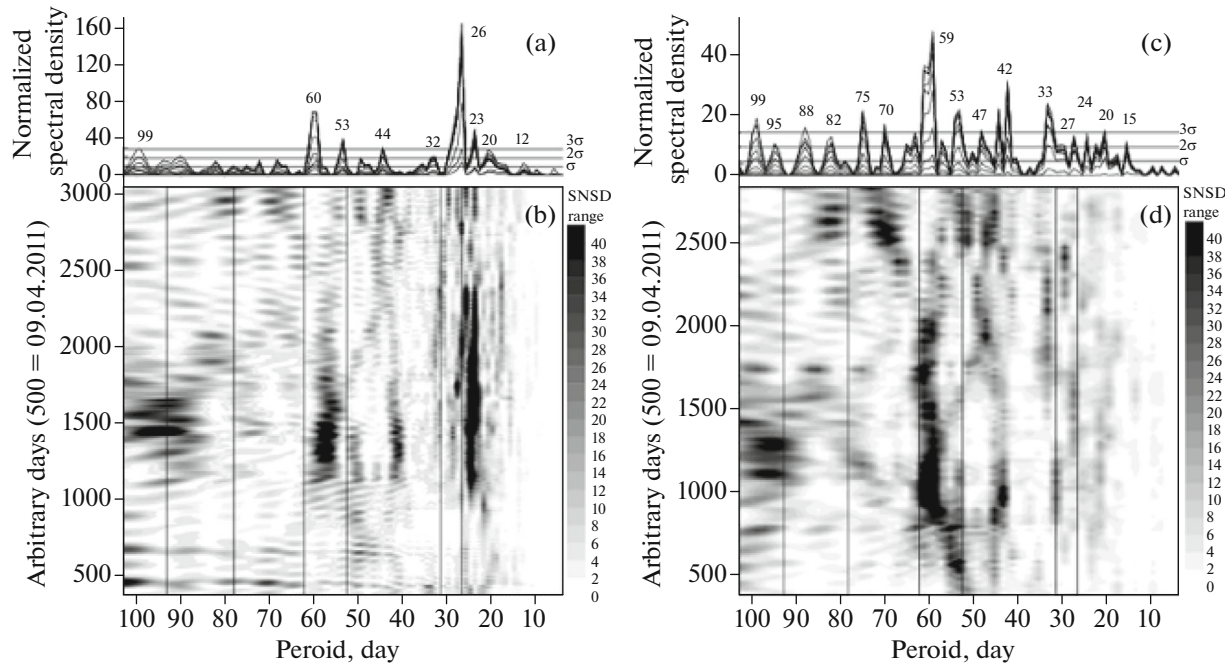


Fig. 4. The same as in Fig. 2 but for SA cycle 24. Days are counted from the start of the 24th cycle: (b) January 1, 2009, for the radio index and (d) November 26, 2009, for SXR.

most likely indicates that SXR weakly reflects the spatial inhomogeneity of solar activity. In turn, it can be noted that the values of the quasi-periods of some peaks coincide with the average lifetime of solar active formations (Allen, 1973), such as the usual group of sunspots (the average lifetime is approximately 6 days); chromospheric faculae (average lifetime is approximately 15 days); large groups of sunspots that determine variations in solar activity (approximately 45 days); and large faculae, which also, in turn, determine variations in solar activity (approximately 80 days).

Since the solar photosphere harbors active formations that last more than one solar revolution, the periodograms should have peaks that appear on the CSP due to the modulation of the radiation flux of these active formations by solar rotation. That is, the peaks should appear in intervals corresponding not only to single, but also to double, triple, or more solar revolutions, but they should not exceed the maximum duration of the radiation sources. In our case, these are single, double and, at the most, triple solar revolutions.

In order to verify this statement and to study the dynamics of the behavior of period groups, as well as individual CSP peaks, over the last three SA cycles, dynamic diagrams of time variations in the identified periodicities were constructed via the calculation of the SNSD for the radio and SXR data in a moving time window of 731 days (two years); these diagrams are demonstrated in Figs. 2b, 2d, 3b, 3d, 4b, and 4d. The abscissa axis shows the values of the trial periods in the range from 3 to 103 days, and the ordinate axis

shows the relative days counted from the start of each cycle: from September 1, 1986 for the 22nd cycle (Figs. 2b, 2d); May 1, 1996 for the 23rd cycle (Figs. 3b, 3d); and for the 24th cycle, from January 1, 2009, for radio data (Fig. 4b) and from November 26, 2009, for X-ray radiation (Fig. 4d). The three bands plotted on the fields of the dynamic diagrams denote the intervals of allowable values of the variation in the synodic period of the Sun's rotation from latitude 40° to the solar equator (0°) calculated on average from the data on the sidereal rotation of the solar coronal plasma given in (Howard, 1980; Simon and Noyes, 1972; Chandra et al., 2010; Chandra and Vats, 2011). The band from 26.1 to

Table 1. Values of the revealed quasi-periods (day) for SA cycles 22–24

SA cycle 22		SA cycle 23		SA cycle 24	
radio	SXR	radio	SXR	radio	SXR
18		12	5, 18		15
24, 26		21, 26	26	20, 23, 26	20, 24, 27
29, 31, 36	31	31, 35	30	32	33
41, 49	43	45	40, 45	44	42, 47
54	54, 58	52	52, 56	53	53, 59
61, 65	65	67	63, 67	60	
72, 75	73	73	77		70, 75
86	82	86	86		82, 88
		94	95	99	95, 99

31.2 days corresponds to a single solar rotation, the band from 52.1 to 62.3 days corresponds to a double rotation, and the band from 78.2 to 93.5 days corresponds to a triple rotation.

If the corona rotates differentially (faster at the equator than at the poles) and not as a rigid body, the rotation periods of the corona radiation sources in the ideal case should decrease with their latitudinal shift toward the equator over the course of the solar cycle by analogy with Maunder's butterfly diagram (Howard, 1980), and their corresponding revealed values should shift from left to right within the marked interval bands of dynamic diagrams. This displacement effect is partially visible in the diagrams below.

The shift occurs in the middle of the cycle in the range of values of a single solar revolution for the radio flux data in Fig. 2b (cycle 22) and in the last quarter for Fig. 3b (cycle 23). No such displacement is visible in Fig. 4b (cycle 24), and the corona rotates as a rigid body. Conversely, for the SXR data in Fig. 4d (cycle 24), we can see the displacement happening twice, at the end of the first third of the cycle and at the beginning of the last quarter, while it is difficult to talk about any displacement of this kind for cycles 22 (Fig. 2d) and 23 (Fig. 3d). In the interval of periods corresponding to the double solar revolution, the displacement of periods toward smaller values also partially manifests itself, while nothing clear can be said for the interval of periods of the triple revolution, since the lifetime of active formations emitting in the radio and X-ray range most likely does not exceed three or four solar revolutions.

Thus, based on the above, it is not possible to draw an unambiguous conclusion regarding the character of the solar corona rotation; we can only note that the corona can exhibit the properties of both differential and "rigid" rotation at different stages of solar cycles.

4. CONCLUSIONS

Based on measurements of the daily mean radio fluxes (10.7 cm) and soft X-ray (1–8 Å) fluxes from the total solar disk over SA cycles 22–24 with a modified method of spectral analysis (the method of constructing a combined spectral periodogram), quasi-periodic components with periods from a few days to three months were revealed in the data series. They reflect the synodic rotation of the Sun over the last three SA cycles.

Particular attention was paid to the study of the time variation of the revealed quasi-periods over solar cycles via the construction of a sample normalized spectral density of the data in a moving time window of up to 2 years. Based on dynamic diagrams of variations in the quasi-periods constructed in this way, it can be concluded that the differential rotation of the solar corona is not constant and manifests itself at sep-

arate stages of the development and existence of solar activity cycles.

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