Solar coronal rotation according to soft X-ray solar radiation during the 22nd, 23rd, and 24th solar cycles

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Abstract. Using the developed method of combining numerous scattered time series of the same type of measurements into a single weighted average series, according to the data of the GOES series satellites, a single series of daily data was synthesized during the 22nd, 23rd and 24th solar cycles (1986 – 2019 years). The flare and background components were distinguished from this data series, which were investigated by means the method of constructing a composite spectral periodogram for the presence of quasiperiodic oscillations at various solar cycles. Some of these found quasiperiods may be explained by both synodic and sidereal rotation of the Sun, while others coincide with the average lifetime of the solar atmosphere active formations such as the sunspot groups and the facular plages. Special attention was paid to the study of the change over time the revealed quasiperiodic values over the course of solar cycles by calculating the sample normalized spectral density of the analyzed data in a sliding time window with a value of up to two years. Based on the revealed quasiperiodic value changes presented on the dynamic diagrams, it can be concluded that the differential rotation of the solar corona is unstable and manifests itself only at certain stages of the development and existence of solar activity cycles.

1. Introduction
Due to the solar partial eclipse on October 22, 1987, it was found that four active regions of the solar photosphere contributed 98% to the soft X-ray (SXR) emission from the entire solar disk [1]. Later SXR images of the Sun, obtained by the Yohkoh satellite, confirmed that SXR comes from bright (hot) loops of magnetic active regions, which bottoms go under the photosphere, and the tops are located in the corona [2]. On the one hand, the hot plasma, which is filled with magnetic loops, is a source of quasithermal X-ray radiation [3], which forms a slowly changing background component of the SXR of the Sun, and on the other hand, solar flares occur in these structures, which are characterized by a sharp increase in the SXR flux by several orders of magnitude exceeding the background radiation, and differing from the latter by the transience in time (minutes, hours) [4]. Therefore, SXR can be used as an index of solar activity (SA) [5]: the background component reflects the intensity of formation of active magnetic regions within the solar chromosphere and corona, and the flare component reflects their evolution; and the SXR flux variations can be used to study the properties of the solar chromospheric and coronal rotation, since SXR is generated mostly in the solar atmosphere from the level of the chromosphere to the upper coronal layers.

Currently, the differential nature of the solar photospheric rotation 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 deduced from the sunspot zones [6, 7]. As for the solar corona,
there are several opinions: on the one hand, it is considered that it rotations near rigidly i.e. its rotation does not depend on heliolatitude [8], on the other hand, the coronal rotation at the beginning of the growth of the solar cycle is differential, and at the descending phase of the solar cycle solar corona rotates as a rigid body [9] or these coronal rotation is differential like photospheric [10 – 12].

The data of the GOES satellites (Geosynchronous Operational Environmental Satellites), which have been carrying out patrol measurements of the SXR of the Sun from the 1980s to the present (2020s) in the wavelength ranges of 1 – 8 Å and 0.5 – 4 Å [3], make it possible to study the temporal structure of the SXR flux on such a long period of time. Thanks to this, the opportunity arose to study the oscillations of the temporal structure of the SXR flux during the 22nd, 23rd and 24th solar cycles and to judge from them about the possible differential rotation of the solar corona.

2. Experimental data and analysis technique

To study the spectral-temporal structure of solar radiation in the X-ray wavelength range during 22nd – 24th solar cycles (1986 – 2019 yrs), SXR flux data in the wavelength range 1 – 8 Å (W m²) of eleven GOES satellites from the full solar disk were used (ftp://ftp.swpc.noaa.gov/pub/lists/xray/). On the basis of the developed method of combining numerous time series of the same type, scattered in time, into a single weighted average series, based on the data of eleven satellites, hourly and daily series of solar SXR data were synthesized from 22nd up to 24th solar cycles.

The algorithm for constructing an average weighted series was as follows. At each time (hour or day) of the total time interval of all measurements, those measurements from each satellite that have been obtained at the moment were processed among themselves according to the principle of processing unequal series of measurements with given weights [13]. The weights were determined for each series of measurements of a particular satellite as the values of the sample dispersion of the data series of this satellite. Thus, for each given time point (hour or day) of the total time interval of all the initial measurement series, one value of the average weighted series of measurements and the root-mean-square error of this measurement were calculated. The average daily values of the background solar X-ray (BXR) component were then determined for the SXR flux by selecting the minimum hourly value of this flux in the days under consideration. The flare solar X-ray (FXR) component was obtained by subtraction the values of the background component from the average daily SXR values.

Further, by decimal logarithmizing the values of these SXR components, the solar activity SXR index values were determined [5], the temporal structure of which was subsequently investigated. The logarithmic operation allows us to get rid of the exponential trend of the initial data [14] and the influence of rare strong emissions (in our case, from strong rare solar flares) on the result of subsequent signal processing (revealing hidden periodicities), since it does not change the position in the series local extreme values data.

To study in detail the time structure of the time series mentioned above, a modified method of spectral analysis was applied the essence of which is as follows. A sample normalized spectral density (SNSD) [15] for the initial time series was calculated, not with respect to frequency, but with respect to a tested period, which was stipulated by the formulation of the problem to reveal hidden periodicities in the initial data [16]. It was based on the assumption that the initial time series consists of two components: poly-harmonic, with a limited number of harmonics having different amplitudes and periods, and noise. The latter includes a random signal and any other deterministic signal, but not the harmonics of the first poly-harmonic components. The search for the values of periods of poly-harmonic components in the initial signal was carried out using the so-called test period, whose values were sorted out from a range of possible values specified by the physical conditions of the studied phenomenon.

In addition, the initial time series were preliminarily processed by a high frequency filter [17] with the initially specified cut-off frequency of the filter at the half-power of the signal, which corresponds in the time domain to the separation period T_{cut-off}. The filtration of the initial data was applied to eliminate the trend and more powerful low frequency components. A series of values of parameter T_{cut-off} is selected arbitrarily, usually from the physical conditions of the considered problem:
characteristic peculiarities of the time structure of the processed data and a hypothetical assumption about the possibility of the existence of different groups of periodical components in the data. Then SNSD as a function of the period was again calculated for each filtered high frequency component with a specific value of parameter $T_{\text{cut-off}}$. Eventually, all these estimates calculated for different values of parameter $T_{\text{cut-off}}$ were superimposed in one graphic field forming a composite spectral periodogram (CSP). The method is described in more detail in [18 – 21].

3. Discussion

The results of treatment the average daily values of the solar activity X-ray index (logarithmic values of the daily weighted average SXR values) from the full disk of the Sun during the 22nd, 23rd and 24th solar cycles are presented in Figure 1 – Figure 3 (for the FXR component (a) and (b), and for the BXR (c) and (d)), and the general result of the revealed quasiperiodic values for all data is shown in the table 1. Figure 1 – Figure 3 shows the CSP with the values of the separation period of the high-pass filter: $T_{\text{cut-off}} = 7, 11, 19, 31, 47, 71, 97$ and $113$ days, for each solar cycle: 22nd – Figure 1 (a), 23rd – Figure 2 (a) and 24th – Figure 3 (a).

Table 1. The revealed quasiperiodic values (day).

| Solar Cycle | FXR | BXR |
|-------------|-----|-----|
| 22nd        | 9   | 5   |
| 14          | 14  | 14  |
| 24          | 24  | 29  |
| 32          | 36  | 37  |
| 43          | 45  | 45  |
| 53, 58      | 52, 56 | 53 |
| 65          | 62, 67 | 63, 67 |
| 73          | 76  | 73  |
| 81          | 86  | 86  |
| 95          | 94  | 99  |

Figure 1. (a) – CSP and (b) – SNSD the flare and (c) – CSP and (d) – SNSD the background components of the solar soft X-rays of the 22nd solar cycle. The SNSD is calculated in a sliding time window of two years, and on the ordinate axis the SNSD diagrams (b) and (d) plot the days counted from the 22nd solar cycle start date 01.09.1986.
These periodograms clearly show both the presence of individual peaks and their groups, and some of them are presented in the form of doublets and triplets. The CSP structures for different data of different cycles are rather inhomogeneous, but some characteristic peaks can be distinguished among them. For example, the values of a number of CSP peaks coincide with the values of the average lifetimes of solar active formations [7]. CSP values of 5, 7 and 9 days correspond to the average lifetime of a common group of spots (∼ 6 days), the values of 14 and 15 days correspond to the average lifetime of the average facular (∼ 15 days), values from 43 to 47 days correspond to the average lifetime of large sunspot groups that determine changes in solar activity (∼ 45 days), and values from 75 to 88 days correspond to the average lifetime of large facular plages that also determine changes in solar activity (∼ 80 days).

**Figure 2.** (a) – CSP and (b) – SNSD the flare and (c) – CSP and (d) – SNSD the background components of the solar soft X-rays of the 23rd solar cycle. The SNSD is calculated in a sliding time window of two years, and on the ordinate axis the SNSD diagrams (b) and (d) plot the days counted from the 23rd solar cycle start date 01.05.1996.

Since active formations with a duration of more than one solar revolution exist on the solar photosphere, the periodograms should have peaks, the values of which can be interpreted as a result of the rotation of the chromosphere and the solar corona with emitting sources located in the chromosphere at altitudes from 5000 to 11000 km or in the corona at altitudes from 40000 to 60000 km above the photosphere [22 – 25]. The values of these peaks on periodograms arise due to the modulation of the flux of chromospheric and coronal emitting sources by solar rotation, that is, the values of the peaks fall into the intervals corresponding to single, double, or more multiples of their own solar rotation, but not exceeding the maximum duration of the radiation sources. In our case, these are single, double and triple revolutions of the Sun.

In order to verify this statement and to study the dynamics of the behavior of period groups, as well as individual peaks of the CSP, for the during the 22nd, 23rd and 24th solar cycles, dynamic diagrams of changes in the revealed periodicities were built with time by calculating the SNSD for SXR data in a sliding time window 731 days wide (two years), which are shown in Figure 1 – Figure 3, (b) and (d). In these diagrams, the abscissa shows the values of trial periods in the range from 3 to 103 days, and the ordinate shows the relative days counted from the start date of each cycle: for the 22nd cycle from 01.09.1986 (Figure 1, (b) and (d)), for the 23rd – from 01.05.1996 (Figure 2, (b) and (d)) and for the 24th – from 26.11.2009 (Figure 3, (b) and (d)). Three stripes applied on the fields of dynamic diagrams denote the intervals of admissible values of changes in the synodic period of the solar rotation from...
latitude 40° to the solar equator (0°), calculated on average from the data of the sidereal plasma rotation of the solar corona given in [6, 10 – 12]. The strip from 26.1 to 31.2 days corresponds to a single solar rotation, the strip from 52.1 to 62.3 days corresponds to a double rotation, and the strip from 78.2 to 93.5 days corresponds to a triple rotation.

![Image](image1.png)

**Figure 3.** (a) – CSP and (b) – SNSD the flare and (c) – CSP and (d) – SNSD the background components of the solar soft X-rays of the 24th solar cycle. The SNSD is calculated in a sliding time window of two years, and on the ordinate axis the SNSD diagrams (b) and (d) plot the days counted from the 24th solar cycle start date 26.11.2009.

If the corona rotates differentially (at the equator faster than at the poles), and not as a solid body, then in the ideal case, the magnitude of the rotation periods of the corona radiation sources should decrease with their latitudinal displacement towards the equator during the solar activity cycle (by analogy with the Maunder’s Butterflies diagram [6]), and their corresponding revealed values move from left to right within the marked intervals-bands of dynamic diagrams. This displacement effect is partially visible in the diagrams of Figure 1 – Figure 3. So, for example, for the data of the flare component of the SXR of the 24th solar cycle in Figure 3 (b) in the interval of solar double rotation values the noted shift occurs in the second half of the cycle. For the background component of this cycle (Figure 3 (d)) this shift is also observed and for a single rotation the same tendency is visible too, which indicates shorter times and a stronger intensity of the flare component of radiation compared to the radiation of the background.

For the 22nd cycle SXR data (Figure 1), a similar displacement of the revealed values of quasi-periods is observed in a wider interval of double-rotation values, and in the interval of a single one, this phenomenon is not clearly observed, as well as for the data of the 23rd cycle (Figure 2) it is difficult to talk about any such displacement. As for the interval of the periods of the triple solar revolution, nothing clear can be said since, most likely, the duration of the active formations emitting in the SXR range is no more than three or four solar revolutions. But outside the intervals of rotary modulation in the ranges of existence of large groups of sunspots and large facular (from ≈60 to ≈80 days), which determine changes in solar activity, one can notice a shift in the values of the periods in both decreasing and increasing directions.

So, based on all of the above, it is impossible to make an unambiguous conclusion about the nature of the rotation of the solar corona, we can only note that the corona at various stages of solar cycles can exhibit the properties of both differential and solid rotation.
4. Conclusion

Based on measurements of the average daily soft X-ray flux (1 – 8 Å) from the entire solar disk during 22nd – 24th solar cycles (1986 – 2019 years) by means of a modified spectral analysis method (composite spectral periodogram method) the quasiperiodic components with periods from several days to three months which reflect the characteristic lifetimes of the solar chromospheric and coronal active formations and their evolutions during 22nd – 24th solar cycles were revealed.

Particular attention was paid to the study of the time variation of the values of the revealed quasiperiodic values over the course of solar cycles by calculating a sample normalized spectral density of the analyzed data in a sliding time window up to two years. Based on the revealed quasiperiodic value changes presented on the dynamic diagrams it can be concluded that the differential rotation of the solar corona is unstable and manifests itself at separate stages of the development and existence of solar activity cycles.

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