

TEMPORAL VARIABILITY OF THE CORONAL GREEN-LINE INDEX (1947–1998)

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Abstract. Temporal variability of the coronal index – the ‘Sun as a star’ coronal green-line irradiance – is presented using wavelet transform over the epoch of almost 5 solar cycles. A significant index variability was found for all periods, particularly for the periods of 150 days and 1 year as well as 28 days. Connection of the variability with the phase of solar magnetic activity is outlined. The enhanced power of the 150-day period is dominant before and after the magnetic activity maxima in four out of the five cycles analyzed. To the contrary, no enhanced power was found just during the maxima of all cycles for this period. No clear periodic power behavior was found for the periods at about one year. Substantial rotation period variations of the coronal index up to 5 days take place over relatively short time intervals. A comparison of the results of the Fourier transform and the time-period wavelet transform of the coronal index time series shows that only the application of the wavelet analysis enables one to find the relation between the coronal index variability and the course of the magnetic activity of the Sun.

1. Introduction

The coronal index of solar activity (CI) belongs to the indices characterizing the coronal activity of the ‘Sun as a star’. CI is calculated using homogenized Fe XIV 530.3 nm coronal emission line ground-based measurements from the world-wide net of the coronal stations. CI introduced by Rybanský (1975) represents the total irradiance of the green corona emitted from the Sun’s visible hemisphere. This index enables study of the ‘Sun as a star’, for example by comparing it with similar solar indices in X-ray, EUV or radio wave bands (Rybanský, Rušin, and Minarovjeh, 1998, 2001; Ramesh, 1998).

Several time series in solar physics are in fact of statistically non-stationary character. The periodic character of CI is indisputable since CI shows a similar course with the solar cycle as, for instance, the Wolf’s sunspot number. In addition to the dominant 11-year periodicity, CI also contains other periodicities (Rušin, Rybanský, and Zverko, 1987, 1988; Rušin and Zverko, 1990). These periodicities could vary in general over a long epoch of the studied series as was found by Rušin and Zverko (1990) in the case of the rotation period. However, the commonly used methods, e.g., the Fourier transform (FT), are not able to disclose possible changes in periodicities over the period studied (see, e.g., Bracewell, 1965; or Kay and



Marple, 1981). In search of the temporal variability it is inevitable to apply a time-frequency algorithm like for example the wavelet transform (WT). The aim of this paper is to look for the possible temporal changes of the green corona emission variations of the ‘Sun as a star’ over a broad range of periods (including its rotation period) applying the WT approach.

2. Data

The definition of CI, the data homogenization method, and some CI results for the period between 1939 and 1991 were presented by Rybanský *et al.* (1994a, b), Rybanský, Rušin, and Minarovjeh (2001), and references cited therein¹. Briefly, CI is the estimated irradiance, emitted in the coronal green line from the entire solar corona as observed from the Earth. Some assumptions had to be introduced in order to calculate the daily CI values including estimation of green-line emission in front of the solar disk from the available limb measurements (Rybanský, 1975). Interpolation of the existing measurements was used for days with missing data. Only CI starting from the year 1947 was used for our calculation as there were more than 200 days of missing data per year before the year 1947 (Dorotovič, 1996). This constitutes the 52-year data set of CI daily values (Figure 1).

It should be said here that WT power spectra of CI could be influenced by the long-term CI trend which is clearly visible in Figure 1. The instrumental effects and data homogenization procedure peculiarities which could cause such a long-term trend were discussed earlier by Sýkora (1971, 1983, 1992) and Rybanský (1979). Trying to avoid possible negative consequences of the influences mentioned, this trend was eliminated. At first, temporal behavior of the CI maximal values of all cycles was linearly approximated. Then the CI time series was divided by this trend approximation, which put the CI data of each cycle to the same level, removing the CI scale increase over the whole epoch. Without such a modification, the significance of WT CI power spectra amplitudes would be suppressed in cycles 18 and 19 and the amplitudes in later cycles could be enhanced because the estimation of CI noise was calculated from the whole data series. Therefore WT power spectra were calculated from the modified CI data set.

3. Method of processing

The wavelet transform is suitable for an analysis of a time series containing non-stationary power at many different frequencies as its functions – wavelets – are localized in both time and frequency (e.g., Daubechies, 1990; Kumar and Foufoula-Georgiou, 1997; Torrence and Compo, 1998). The Morlet wavelet, consisting of a

¹CI data are available at: ftp.ngdc.noaa.gov/STP/SOLAR_DATA/CORONA/INDEX.

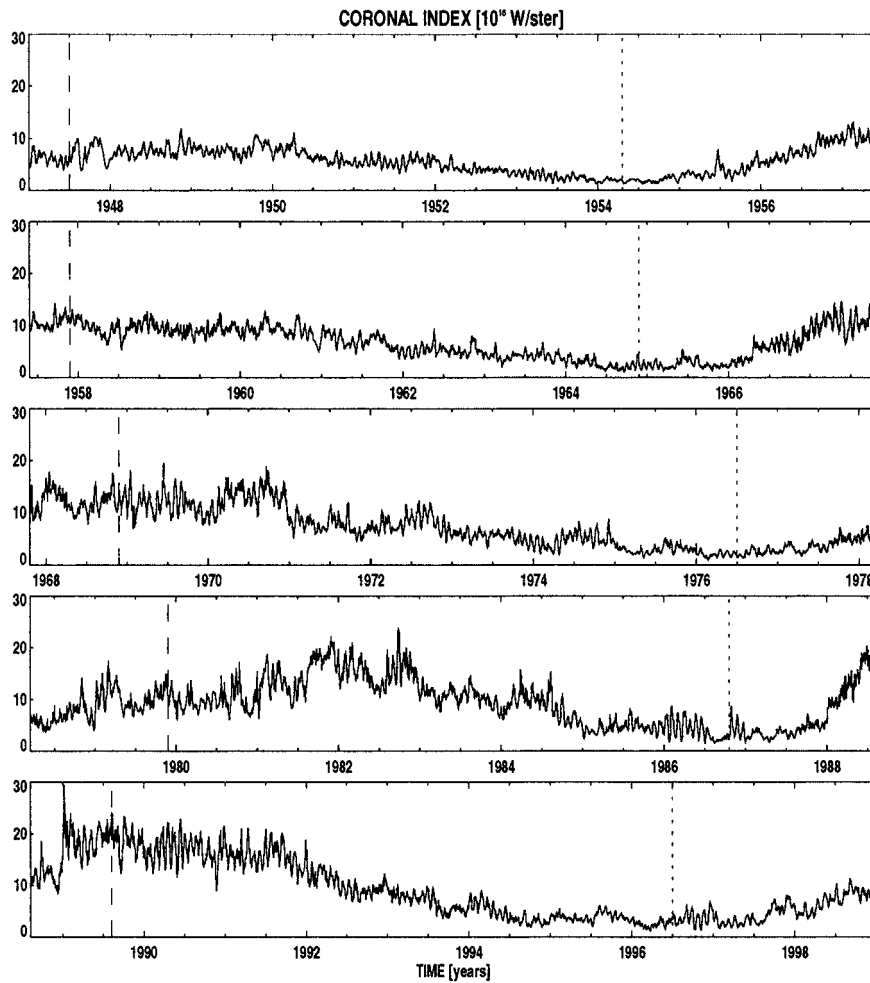


Figure 1. Behavior of the CI daily values for the solar cycles 18–22 and for the onset of the cycle 23. Dashed and dotted vertical lines mark the solar activity cycle maxima and minima according to the Wolf's sunspot index, respectively.

complex sine wave modulated by a Gaussian, was selected to search for CI variability at different frequencies over the whole length of the time series. The WT computational algorithm of Torrence and Compo (1998) was applied to the CI time series. The wavelet power spectrum was calculated to visualize the time-frequency behavior of the data series power using two convenient sets of scales in order to obtain the two period ranges 32–1024 days and 18–38 days. For both ranges the scale resolution was fixed to 48 scales per octave giving a scale resolution changing from 0.71 (0.23) to 87.8 (0.98) days for the 32–1024 (18–38) day period ranges. Due to the applied WT algorithm the wavelet power spectra are suppressed within a cone of incidence (Torrence and Compo, 1998). The cones are indicated in our

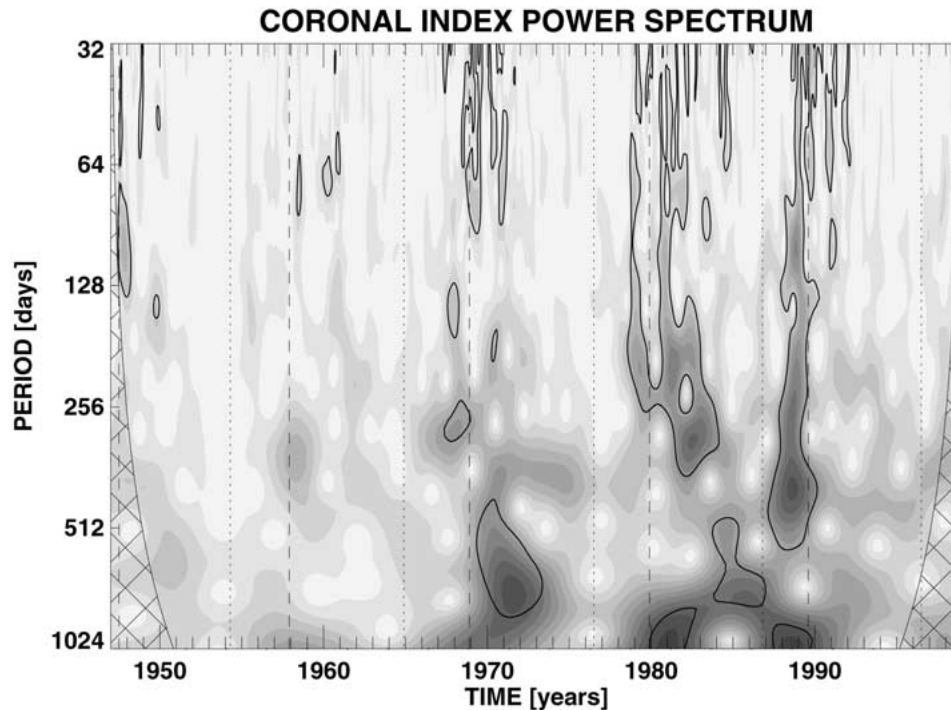


Figure 2. The wavelet power spectrum of CI for the epoch 1947–1998 and the period range 32–1024 days. The temporal spacing of the series is 1 day, the scale resolution is 48 scales per octave. Grey-scale coding from white to black represents the square root of power in a linear scale. The *thick solid curve* shows the 95% confidence level of the local power spectrum above the global WT power spectrum of CI. The cone of incidence is marked by the *cross-hatched regions*. Meaning of the *dashed* and *dotted vertical lines* is the same as in Figure 1.

plots by cross-hatched regions. The significance level of the derived wavelet power spectrum was derived using the null hypothesis according to Torrence and Compo (1998) assuming that the time series has a mean power spectrum. If a wavelet power spectrum is well above the background mean power spectrum, it can be assumed to be real with a certain confidence level. The 95% confidence level, used in this study, implies that 5% of the wavelet power should be above this level for each scale. The global wavelet spectrum was used as an estimate of the background mean power spectrum against which the significance of the local wavelet power spectrum features can be tested (Percival, 1995; Kestin *et al.*, 1998).

4. Results

The 2-dimensional CI power spectrum for the broad period range of 32–1024 days for the whole epoch studied is shown in Figure 2. The narrow period range of 18–38 days power spectrum is shown for the individual cycles of solar activity in

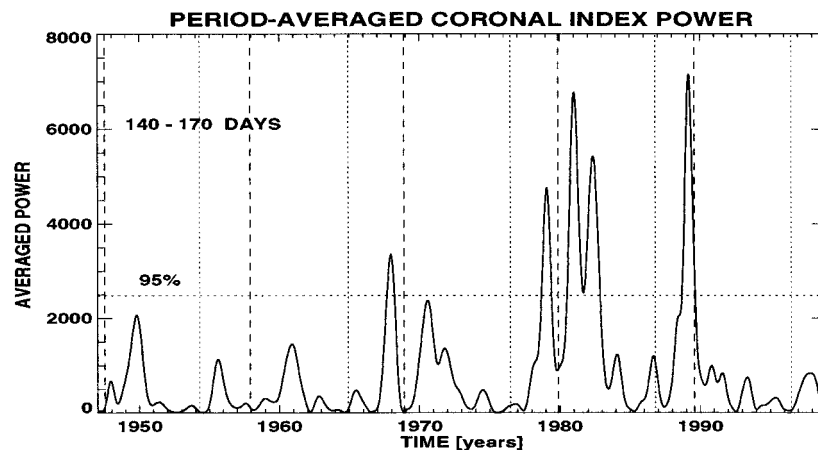


Figure 3. Behavior of the period-averaged WT power of the intermediate periods (140–170 days). The *dotted horizontal line* shows the 95% confidence level of this period-averaged power spectrum. Solar activity cycle maxima and minima are marked with the *dashed* and *dotted vertical lines* as in Figure 1.

Figure 4. The amplitudes of the WT power spectra show a significant variability of power for all periods in both period ranges. There are regions of amplitudes defined well above the 95% confidence level which are relatively stable over certain temporal epochs. On the other hand, there are other parts of the time-period domain which do not show amplitudes above the estimated level of noise.

However, this does not mean that in fact the solar green corona emission did not evolve or the green corona could not rotate during those temporal epochs. The wavelet transform is in fact very sensitive to the distribution of the active regions (with their enhanced green line emission) around the Sun. It may happen that, e.g., three active regions are distributed almost symmetrically, each at a distance of about 120° in longitude from the neighboring ones. In such a case no significant amplitude will appear in the CI wavelet power spectrum around the rotation period of the Sun. The same effect can take place for longer periods in the case of the cumulative enhancement of the green emission on the onsets of the solar cycles.

It is important to verify the applicability of the WT with the selected wavelet and its parameters to the CI data series. This is possible only in those temporal intervals, where (non-)existence of the CI periodicity is unambiguous. The characteristic sinusoidal CI changes seen at the beginning of the year 1986 and then again at its end are clearly separated by an interval of almost constant CI values (Figure 1). These three different regimes are also visible in the WT power spectrum (Figure 4) as two distinct regions of the enhanced amplitudes of the WT power spectrum separated by the region without power above the noise level. Moreover, the WT power spectrum indicates some shortening of the period during the first event. This verification shows that the WT with the selected parameters provides sufficient temporal and frequency resolution of the CI wavelet analysis in the narrow period

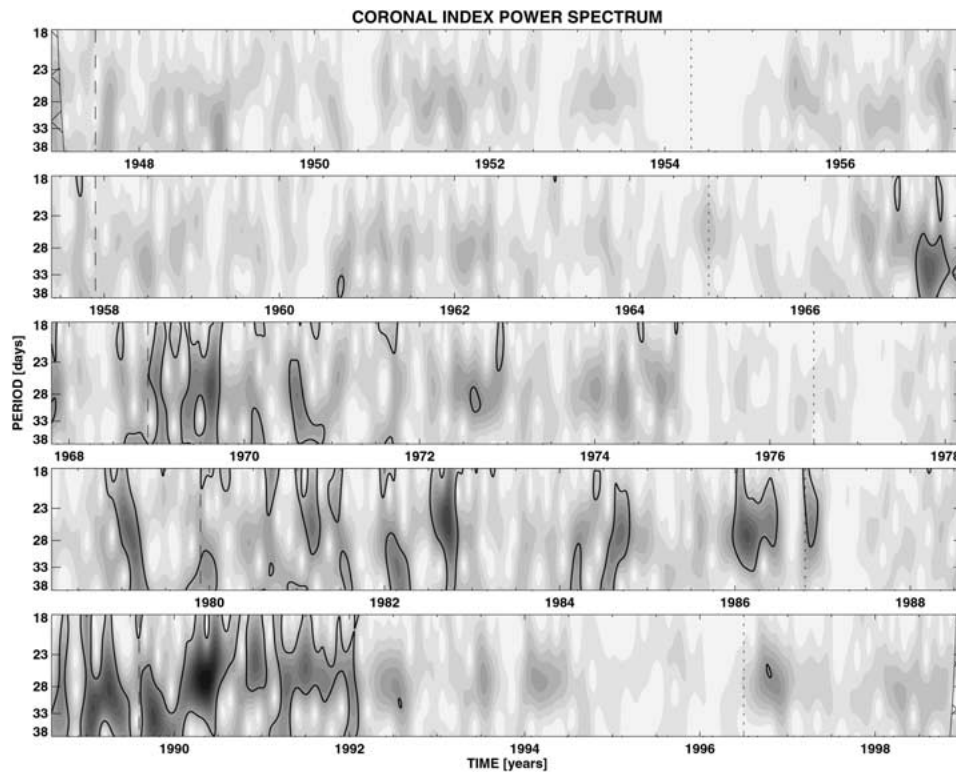


Figure 4. The wavelet power spectrum of CI for the solar cycles 18–22 and for the onset of cycle 23 and the period range 18–38 days. The WT parameters, the grey-scale coding, the confidence level and the cone of incidence are the same as in Figure 2. Meaning of the *dashed* and *dotted* vertical lines is the same as in Figure 1.

range. In addition to the clearly isolated WT power peaks at longer periods (e.g., the year 1947 – period 100 days, 1968 – 300 days) with unambiguous CI data counterparts, some temporal intervals of the enhanced power in the extended period ranges were detected (e.g., year 1989 – period range 32 – 500 days). These features coincide with the abrupt changes of CI, represented by the WT as features covering broad period intervals. Nevertheless, such features cannot influence power spectrum behavior at adjacent epochs of CI.

Intermediate periods around 150 days were already found in several solar magnetic flux and flare indices (e.g., Lean and Brueckner, 1989; Ballester, Olivier, and Baudin, 1999; Antalová, 1999; Bai and Sturrock, 1993; Rybák, Antalová, and Storini, 2000, and reference therein). Analyzing the CI WT power spectrum (Figure 2) in the range of these periods around 150 days it was found that the CI exhibited these periodicities especially in the years 1967–1968, 1978–1979, 1980–1981, 1981–1982, 1988–1989 (Figure 3). Other clearly distinguishable power peaks are present also in the years 1949, 1955, 1960–1961, and 1970–1971 although they are below the selected 95% confidence level. If all these isolated

enhanced power impulses are taken into consideration they seem to create pairs in cycles 19, 20, and 21 where the first intervals of the power impulses are situated shortly before the maxima of the solar cycles and the second intervals of the pairs just after those maxima. On the other hand in the cycle 22 there was no enhanced power on the descending branch of this cycle. Nevertheless the absence of such power enhancements during the time of the solar magnetic activity maxima is evident for all solar cycles studied. This phenomenon recalls the so-called Gnevyshev gap (Gnevyshev, 1977; Feminella and Storini, 1997), not in the CI behavior, but in the amplitude of CI intermediate periods. Additionally, some power impulses are not single but they are of the multicomponent character.

The situation is different for periods at about one year. The enhanced amplitude pulses in the years 1958 (at a period of 340 days), 1968 (295 days) are close to the time of activity maxima, but for cycle 21 the amplitude pulse is shifted to the year 1982 and a period of 320 days. In cycle 22 the most significant power peak in this period range is located in the year 1988 and the period 420 days but it is masked by the already mentioned enhanced power feature over the broad period range 32–500 days. Summarizing this behavior there is no clear periodic pattern for the periods at about one year.

The CI WT power spectrum in the range of the solar rotation period (Figure 4) displays with sufficient precision time intervals when CI exhibits changes due to solar rotation. The synodic rotation period of the green corona of the ‘Sun as a star’ can be determined in these time intervals including its changes in the range of several days. The most characteristic variability recorded (years 1989–1990) clearly shows change of the rotation period of the corona from a period of 33 days just after the maximum of the cycle to a value less than 28 days during less than half a year. Such changes are evident in several other cases in all cycles. These changes of the rotation period of the emission corona enhancement accompanying different active regions are consistent with the green corona rotation periods at different heliographic latitudes and at different phases of the solar cycle (Rybák, 1996, 2000, 2001). On the other hand, there exist temporal intervals near the minima of the cycles where no amplitudes above the noise level are present (e.g., year 1954).

5. Discussion

The FT decomposes the data series into different sines and cosines, which cannot be localized in time (Bracewell, 1965). Therefore, the FT is not suitable for studying the data series which show significant changes in their variability. FT power spectra of the whole CI data series, shown in Figure 5 for the period ranges of 32–1024 days and 18–38 days, were calculated just for the purpose of comparison with the WT time-frequency power spectra (Figures 2 and 4). The high FT frequency resolution (10^{-4} day^{-1}) does not guarantee revealing of the nature of CI variability. FT power spectra allow to distinguish individual periods, e.g., 400, 500, 700, and

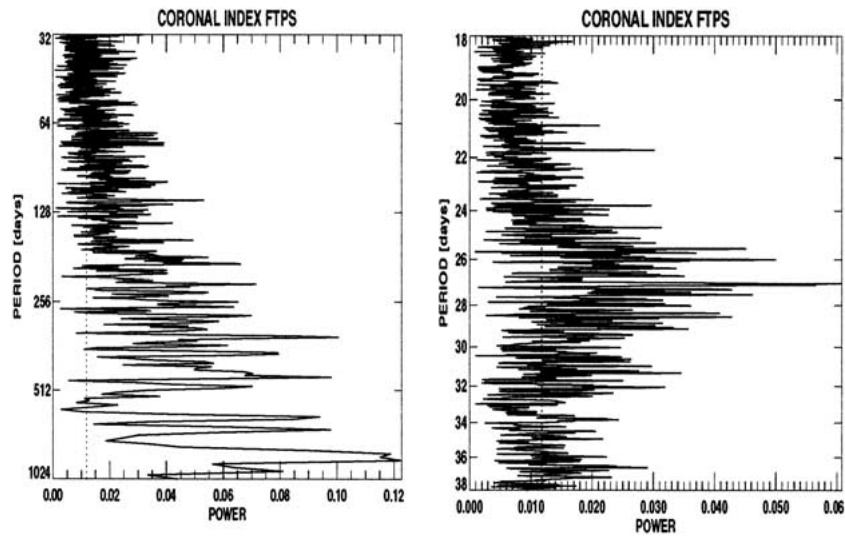


Figure 5. The FT power spectra of CI over the epoch 1947–1998 for the period range 32–1024 days (*left panel*) and the period range 18–38 days (*right panel*) in the plot orientation of Figure 2. The *vertical dotted lines* show the estimations of the noise level in the FT power spectrum of CI (Groth, 1975).

800 days or 25.6, 26.0, and 27.3 days (Figure 5), but with an intrinsic assumption of the CI data stationarity. This was found to be unrealistic since the intrinsic temporal variation of power is not provided.

Periodicities of the CI were studied earlier by Rušin, Rybanský, and Zverko (1987, 1988) and Rušin and Zverko (1990). Our results confirm their findings on the changing rotation period as well as the existence of the double rotation periods for different time intervals of the green corona emission of ‘the Sun as a star’. Their basic and subsidiary rotation peaks fit very well with those given in Figure 5 (*left panel*). On the other hand, only our time-period power spectrum (Figure 2) can declare the highly variable nature of the CI data series contrary to results of Rušin and Zverko (1990) or our reference plot in the *right panel* of Figure 5.

Existence of the intermediate periods around 150 days was already studied in the case of the CI time series (Rušin and Zverko, 1993). They found the periodicities very close to 150 days only for the time intervals between years 1964–1972 and 1986–1991 without any more detailed temporal allocation. Our CI intermediate periodicities were localized in each cycle with much higher resolution and the most significant power is not exactly at the same period in each cycle. When the intermediate periods are enhanced then the power near the rotation period is increased as well. The inverse relation is not always fulfilled. For an unknown reason these CI periodicities have the lowest amplitude in cycle 19 when the magnetic flux emergence displays the maximal variability power (Olivier, Ballester, and Baudin, 1998).

An approximate scaling law between the green line emitting plasma density and the average magnetic field strength at the coronal loop footpoints in the photosphere was derived by Wang *et al.* (1997). They compared the LASCO C1 coronagraph green-line images with current-free extrapolation of the photospheric magnetic field. Investigation of the temporal variability of both the CI and the overall photospheric magnetic flux will be the topic of our future work with the aim to search for their relation in the case of the ‘Sun as a star’ data.

A possible link of the solar CI variability to late-type stars would also be of particular interest. Kürster and Dennerl (1994) reported on the first results on the spatial correlations between coronal X-ray emission and photospheric magnetic flux distributions on late-type stars. Altrock *et al.* (1996) confirmed the relation of the green line and the soft X-ray (SXR) emission in the case of spatially resolved observations of the Sun. Therefore the presented CI variability could be used as an illustration of late-type star corona emission behavior also in SXR. Nevertheless, an explanatory relation presented by Rybanský, Rušin, and Minarovjech (1998) between the SXR full-disk impulsive flux and CI (see their Figure 3) shows that the CI variability around the rotation period could differ from that of the SXR due to the selection of long-lasting CI responses on SRX flares.

6. Conclusions

Coronal index is a strongly non-stationary data series describing the green-line emission of the ‘Sun as a star’ showing variability of power for all periods. Its power in the period ranges of 150 days, 1 year, as well as 28 days varies significantly. A relation with the solar magnetic activity cycle was found for period ranges of 150 days. Dominant is the double peak power behavior in the 150 day period range, found in four out of the five cycles analyzed, where power is located in the intervals of the enhanced local magnetic activity but only before and after the actual solar maxima. There is no enhanced power at this period range directly at intervals of the highest Wolf’s number in all studied cycles. No clear periodic behavior was found in the period range at about one year. The emission corona rotation period changes of ‘the Sun as a star’ occur on relatively short periods and these changes sporadically reach values up to 5 days around its canonic value.

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²Program is available at URL: <http://paos.colorado.edu/research/wavelets/>

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