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Coronal index as a solar activity index applied to space weather

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Abstract

All possible changes of the solar activity can be expressed by the coronal index of solar activity that represents the averaged daily power of the green corona emitted from the Sun's visible hemisphere. The representative character of this index allows us to study long-term, intermediate and short-term variations of the Sun as a star. This index can be expressed well as a function of other solar indices. As green line reflects the distribution of the photospheric magnetic fields in the solar corona, the dependence of this index on the solar magnetic field is confirmed by means of statistical analysis of these two parameters. Daily values of the coronal index, as well as of the magnetic field data obtained from the Wilcox Solar Observatory, has been analysed by Fast Fourier analysis and Wavelet Transform analysis for the time period 1966–1998 covering more than three solar cycles. Periodicities of 11.4, 3.2, 2.3, 1.7, 1, 0.29, 0.07 and 0.04 years have been found in both parameters that means once again that the coronal index is probably related to the underlying photospheric magnetic fields and can be used as a global index of solar activity useful for Space Weather studies.

Keywords: Solar activity index; Space weather; Coronal index; Solar cycles; Wavelet analysis

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1. Introduction

The coronal index of solar activity (CI) belongs to the indices characterizing the coronal activity of the "Sun as a star" and represents the total irradiance of the green corona emitted by the Sun's visible hemisphere. CI is calculated using homogenized Fe XIV 530.3 nm coronal emission line ground-based measurements from the worldwide net of the coronal stations (Rybanský, 1975; Rybanský et al., 1994, 2001; Xanthakis et al., 1990). This index reflects the physical processes that take place in the interior of the Sun. The periodic character of coronal index shows a similar course with the solar cycle as, for instance, the Wolf's sunspot number. Except of the dominant 11-year periodicity, CI also contains many other periodicities (Rušin and Zverko, 1990).

On the other hand it is known that magnetic fields of the Sun govern the dynamics of the solar corona and properties of the solar wind. This is one reason why knowledge of the distribution of magnetic fields on the solar surface during an activity cycle has great importance. However, the time series of satisfactory magnetic field measurements has a short period. For example, data from the Wilcox Solar Observatory cover the period since 1976 only. According to some preliminary conclusions there seems to be, even if contradictory, a connection between the magnetic field of the Sun and the 530.3 nm coronal intensity. For example, Stenflo (1972) showed that the green-line intensity should not be related so much to the polarity pattern of the field but more directly to the field strength. On the other hand, Bumba and Sýkora (1974) concluded that higher green-line

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intensities had been observed above the southern polarity over the studied periods in January 1969–December 1969 and August 1960–September 1961. However, Rybanský and Tjagun (1980) found that higher green-line intensities had been observed above the leading sunspot. Moreover Rušin (1980) proposed that the coronal intensities of the emission line 530.3 nm are in general higher above this hemisphere of the Sun, where stronger magnetic fields are observed. The existence of a homogeneous coronal data set over the period 1939–2000 (Rybanský et al., 2001) and solar surface magnetic field measurements since 1976 provides a good opportunity to compare these data, in general, and to try to find the relation between them from a quantitative point of view. In recent works Mavromichalaki et al. (2002, 2003a) found an empirical relation among coronal index of solar activity, the sunspot number and the grouped solar flares for the time period 1966–1998. In this relation an additional term expressed by the contribution of the solar magnetic field has been attributed in order to find a better accuracy between observed and calculated values of the coronal index time series. In this work long-term, intermediate and short-term variations for the 'Sun as a star' have been found for the time period 1966–1998, using daily values of the coronal index of solar activity. Fast Fourier transform and Wavelet transform analysis have been performed in this time series. Several persistent significant periodicities appear in the spectra, which are related to those found in the solar magnetic field by the same methods of analysis.

2. Data and spectral analysis

High-resolution (daily) data of the coronal index of solar activity are used in the present analysis. They are obtained from the NOAA NGDC website (http://www.ngdc.noaa.gov/stp). The coronal index of solar activity (CI) presents the total energy emitted by the Sun's outermost atmosphere (the E-corona) at the wavelength of 530.3 nm (Fe XIV, the green corona). It is expressed in $10^{16}\,\mathrm{W sr^{-1}}$ or $4.5\times10^{-7}\,\mathrm{W m^{-2}}$ or 1.2×10^{8} photons $\mathrm{cm^{-2}\,s^{-1}}$ at the Earth (Rybanský, 1975; Rybanský et al., 1994). Homogeneous coronal data sets are used for calculating the coronal index of solar activity (Altrock et al., 1999). Several coronal stations such as Sacramento Peak, Arosa, Pic du Midi, Kislovodsk, etc. were used in this database with Lomnicky Peak being the reference station from 1965. The coronal index presents important advantages that make it a representative index of the solar activity (Rybanský et al., 2001). Solar magnetic field data were obtained from the Wilcox Solar Observatory website of the Stanford University (http://quake.stanford.edu/~wso/wso.html).

The purpose of this work is to study coronal index and solar magnetic field power spectral densities in the frequency range from 10^{-4} to 10^{-1} c/days in order to access the suggestion of a close correlation between these parameters. Given our primary interest to study periodicities in these time series, we have chosen the Fast Fourier transform (FFT) and Wavelet Transform (WT) techniques in order to calculate the power spectral densities of the constructed time series. It is known that the commonly used methods, as the Fourier transform (FFT), are not able to disclose possible changes in periodicities over the studied period.

A more modern method, the Wavelet Transformation (WT), achieves something further than FFT. It does not only calculate how much each frequency contributes to the modulation of the signal, but it also gives out the above information for each single moment during the measurements. For example, the result is not an 1-dimensional frequency-amplitude diagram, but a 2-dimensional surface (a contour plot) which displays the time on the horizontal axis, the period on the vertical axis and for each point the appropriate color represents the amplitude of the according period at the according instance. The significance of this method is obvious. It does not only reveal which periods have modulated the signal, but additionally when they did so. Thus, we may compare this information with independent astronomical observations and verify or turn down some scenarios about the origin of cosmic radiation.

The wavelet transform is suitable for an analysis of time series containing non-stationary power at many different frequencies as its functions – wavelets – are localized in both time and frequency (Foufoula-Georgiou and Kumar, 1995; Torrence and Compo, 1998). The Morlet wavelet, consisting of a complex sine wave modulated by a Gaussian, was selected to search for variability at different frequencies over the whole length of the time series. For comparison the wavelet diagrams were obtained also from the IDL software given exactly the same results.

The FFT power spectra of the coronal index time series over the epoch 1966–1998 is presented in Fig. 1. A network of periodicities at 11.4, 7.4, 3, 2.3, 1.7, and ~1 year as well as 192, 100, 27 and 13.5 days is appeared. The corresponding FFT power spectra of the solar magnetic field is presented in Fig. 2, where significant peaks at 11.4, 3.2, 2.5, 1.7 and 1 year, as well as at 100, 70, 27 and 13.5 days are appeared. A summary of the results presenting the most significant peaks of the spectra with their related uncertainties which are calculated as the widths at the half maximum of the corresponding peaks are given in Table 1. Peaks appearing in this Table are significant at least to the 68% level of confidence using procedure by Maravilla et al. (2001). Analysis by the wavelet method on the same time series has shown common periodicities, as it is appeared in Figs. 3 and 4, respectively. The white contour is 95% confidence level (Torrence and Compo, 1998) in the wavelet diagrams include variations with confidence level greater than

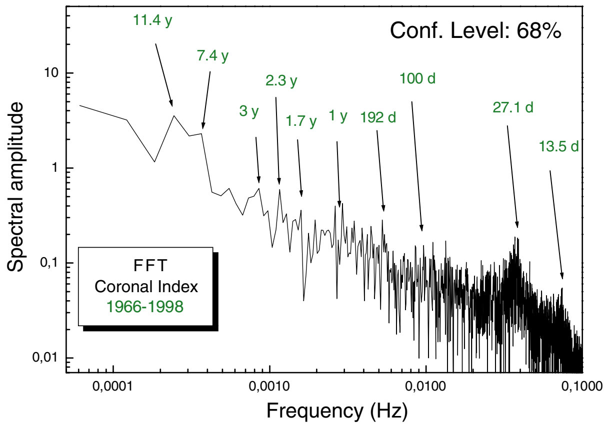

Fig. 1. FFT power spectra of coronal index time series for the epoch 1966–1998.

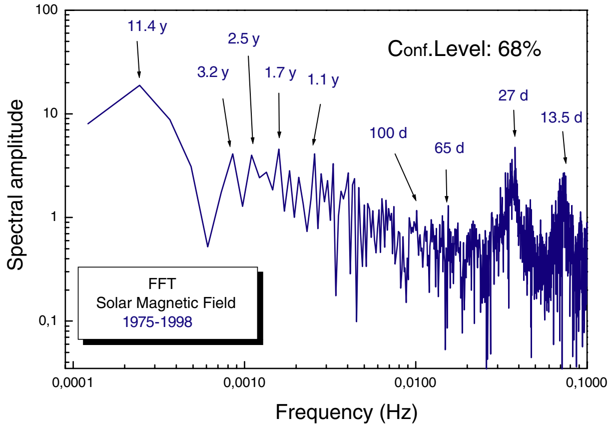

Fig. 2. FFT power spectra of solar magnetic field time series for the epoch 1975–1998.

Table 1
FFT and WT results for coronal index and solar magnetic field time series

Coronal index (in years)		Solar magnetic field (in years)	
FFT, 68%	WT, 99%	FFT, 68%	WT, 99%
11.42 ± 4.09		11.42 ± 4.09	
7.41 ± 1.66	7.01		
	4.93		4.93
3.04 ± 0.29	3.5	3.22 ± 0.99	3.5
2.28 ± 0.16		2.49 ± 0.19	2.46
1.71 ± 0.09	1.75	1.71 ± 0.09	1.42
0.99 ± 0.03	1	1.05 ± 0.03	
0.53 ± 0.009	0.53		0.64
0.29 ± 0.003	0.3	0.27 ± 0.002	0.29
	0.11	0.18 ± 0.001	0.11
0.07 ± 0.0002		0.07 ± 0.0002	
0.04 ± 0.00004		0.04 ± 0.00004	0.04
			0.03

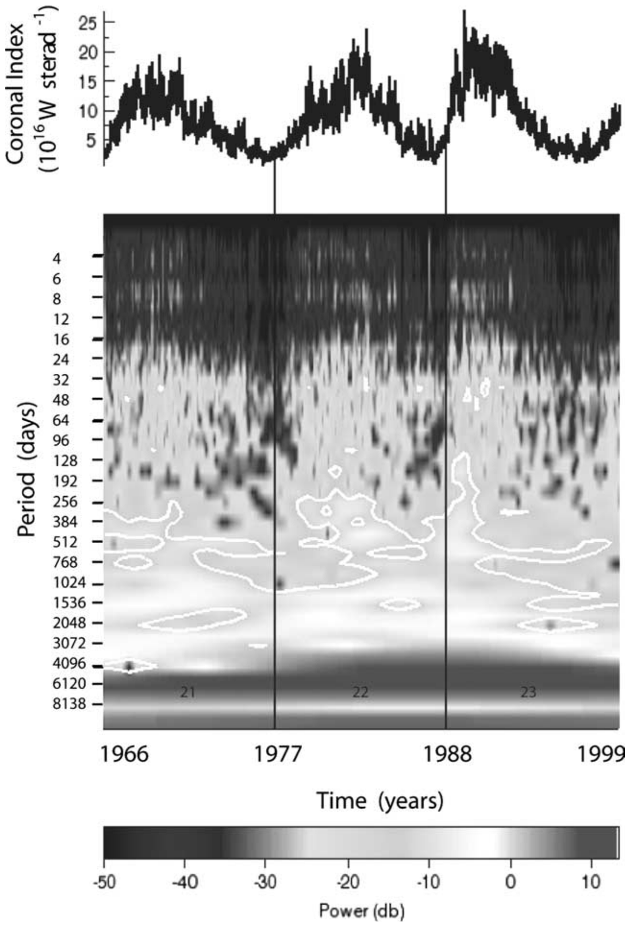

Fig. 3. Wavelet diagrams (99% confidence level) for coronal index time series for the epoch 1966–1998.

95%. The results of Wavelet Transformation analysis are given in Table 1 for a comparison with those of Fast Fourier Transformation. Periods of 11.4, 7.4, 3.2–2.3, 1.7 y, 100 d, 27 and 14 d are common in both time series. The period of 1.7 y is present in both time series. This is a well-known period in cosmic-ray intensity observed at the Earth and might appear as a consequence of phenomena routed in the solar interior and could help in understanding the origin of the solar magnetic cycle (Valdès-Galicia and Mendoza, 1998; Kudela et al., 2002). Two distinct periods varied from 3.2 to 2.5 years are also obvious in both parameters. This is connected to the three-year periodicity found also in the magnetic flux emergence from the Sun and in interplanetary phenomena of solar origin such as shocks and SSCs (Maravilla et al., 2001).

The same analysis was carried out cycle by cycle given interesting results. For each separate cycle, the significant peaks for the coronal index and magnetic field power spectral densities are shown in Tables 2 and 3 for the FFT results and in Tables 4 and 5 for wavelet analysis, respectively. Many coincidences in the spectral peaks were found between these time series when we

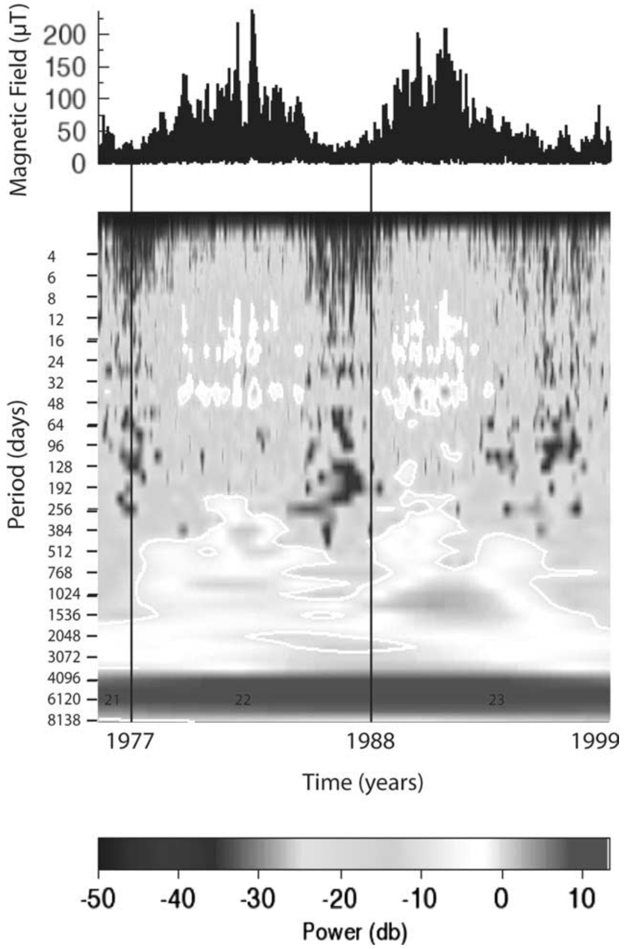

Fig. 4. Wavelet diagrams (99% confidence level) for solar magnetic field time series for the epoch 1975–1998.

Table 2
FFT results for coronal index time series for each solar cycle (conf. level 68%)

Coronal index (in years)		
Cycles		
20	21	22
11.23 ± 3.96	11.23 ± 3.96	11.23 ± 3.96
2.81 ± 0.25	2.80 ± 0.025	2.28 ± 0.16
1.88 ± 0.11	1.61 ± 0.08	
1.02 ± 0.03	0.94 ± 0.03	0.94 ± 0.03
	0.52 ± 0.008	
0.21 ± 0.001		
0.11 ± 0.0004		
0.08 ± 0.0002	0.07 ± 0.0002	0.07 ± 0.0002
0.04 ± 0.00004	0.04 ± 0.00004	0.04 ± 0.00004

worked with either the complete series or with separate cycles. This comes as no surprise since these phenomena are part of the same magnetic cycle (Sýkora, 1992) but it also reveals the solar atmosphere reacting as an entity in the most fundamental periodicities. It is noteworthy that a period of 2.8 years is observed in coronal index and solar magnetic field in the cycles 20 and 21, while a variation around 2.3 years is appeared in the two indices in cycle 22.

The known fluctuations of 1.6–1.9 y and 154–192 days (0.93–0.51 y) are present significantly only in cycle 21 in all indices. This is consistent with results of other authors reported that the contribution of 1.7 year and 154 days are dominant during solar cycle 21 (Mavromichalaki et al., 2003c). It implies the relevance of the identified differences between even and odd solar activity cycles (Mavromichalaki et al., 2003b).

Table 3
FFT results for solar magnetic field time series for each cycle (conf. level 68%)

Solar magnetic field (in years)		
Cycles		
20	21	22
	11.23 ± 3.96	11.23 ± 3.96
	2.80 ± 0.25	2.28 ± 0.16
	1.61 ± 0.08	
	1.01 ± 0.03	1.01 ± 0.03
	0.07 ± 0.0002	0.07 ± 0.0002
	0.04 ± 0.00004	0.04 ± 0.00004

Table 4
Wavelet analysis results for each cycle separately (conf. level 99%)

Coronal index (in years)		
Cycles		
20	21	22
7.01	7.01	7.01
	4.93	
3.5	3.5	
1.75	1.75	
1.00	1.00	1.00
		0.53
	0.3	0.3
0.11	0.11	0.11

Table 5
Wavelet results for solar magnetic field time series (conf. level 99%)

Solar magnetic field (in years)		
Cycles		
20	21	22
	4.94	4.94
	3.6	3.6
	2.46	2.46
	1.42	1.42
	0.64	0.64
		0.29
	0.11	0.11
	0.06	0.06
	0.04	0.04
	0.03	0.03

3. Discussion and conclusions

The spectral analysis of daily values of coronal index and solar magnetic field for the entire time period 1966–1998 and for each separate solar cycle (20, 21 and 22) has permitted us to present a comprehensive description of the behaviour of spectral density distributions in an interval of periodicities ranging from 11 years to 13.5 days. Coronal index is the total irradiance of the green corona in the solar visible hemisphere and possibly reflects the distribution of the photospheric magnetic fields in the solar corona. Therefore the similarities or differences in their temporal behaviour might offer important clues to elucidate the global solar atmosphere dynamics and also help to find better grounds to establish the basic mechanisms of how these dynamics influence the structuring of the heliosphere.

Several time series in solar physics are of statistically non-stationary character. Recently, Rybàk and Dorotovic (2002) have shown that a temporal variability of the coronal index is presented using wavelet transform over the epoch 1939–1998. A significant index variability was found for all periods, particularly for the periods of 150 days and 1 year as well as 28 days. A similar variability has also been found in our analysis on the short term fluctuations smaller than five years.

On the other hand periodicities from 154 to 27 days on solar activity data have already refereed by various authors. The periodicity of about 154 days was first found in gamma-ray and soft X-ray flares data obtained from February 1979 till September 1983 (Rieger et al., 1984). This period seems to be dominant in cycle 21, especially in the time interval 1978–1983 corresponding to the solar activity maximum. Evidence for a periodicity of 154 days has also been found in non-flare indices of solar activity as sunspot number, the Ottawa 10.7 quiet Sun flux etc. (Ichimoto et al., 1985). Bai and Sturrock (1993) reported that besides the 154d periodicity, periodicities of 51, 78, 104 and 129 days are often detected in solar activity and these periods are very close to integral multiples (2, 3, 4, 5, 6) of 25.8 days. These periodicities are not continuously in operation but rather are episodic in nature. The cause of 154 day periodicity remains unknown, but a suggestion that it was related to enhanced flare activity in certain longitude bands has been given. Pap et al. (1990) also reported that 51-days and 150–157 day periods are more pronounced in those solar data which are related to a strong magnetic field. Bai (2003) analyzing solar flare occurrence for cycles 19–23 found mid-range periodicities of 153 days and 51 days with some differences from cycle to cycle, which are very close to integral multiples of 25.8 days.

From our analysis the existence of 11.2 years which is the known named sunspot variation, the annual periodicity related to the orbital motion of the Earth, the 27-days synodic recurrence which is a good indicator of the global sectorial pattern of heliospheric magnetic fields is well reported. The 1.6–1.9 yr variation is present in all examined indices. This was reported in coronal holes and not in sunspots for the period 1939–1996 as well as in interplanetary phenomena such as SSCs and cosmic-ray intensity (Valdès-Galicia and Mendoza, 1998; Maravilla et al., 2001). This result reflects the enhanced importance of these parameters especially of the coronal index of solar activity in describing heliospheric properties.

It is noteworthy that a quasi-triennial periodicity identified in coronal index and solar magnetic field time series for the solar cycles 20 and 21 was shifted to 2.3 years in the cycle 22. This periodicity was also reported in solar magnetic flux emergence, in interplanetary shocks and SSCs during cycles 21 and 22 (Maravilla et al., 2001; Mendoza et al., 1999). This periodicity in these series indicates a strong correlation and a possible influence of the rate of solar magnetic flux emergence to produce these interplanetary phenomena. Recently a relation between the strength of photospheric magnetic fields and limb green line intensities (530.3 nm Fe XIV) has been found which enable us to extend solar surface magnetic fields since 1976 back to 1939 (Rušin and Rybansky, 2002). In this study the similarity in the temporal evolution between coronal index and magnetic field in the fluctuation of 2.8–2.3 years, can be consistent with an empirical relation proposed in a previous work studied the long-term modulation of the coronal index (Mavromichalaki et al., 2002). The derived relation between coronal index (CI), sunspot number (R) and solar flares (F) was improved by the addition of a sinusoidal term $P(t)$ of about 2.8 years. This term was well explained theoretically by the contribution of the solar magnetic field. In this work it is resulted that there are evidences that the term $P(t)$ ought to be expressed by a network of periodicities including the period of 3 years (Table 1). These periodicities can explain the occurrence of maximal green coronal line intensities connecting with the contribution of photospheric magnetic fields (Rybanský et al., 2003). The explanation of this model studying the spectral behaviour of the high-resolution data of coronal index of solar activity will help to predict the maxima of next cycles as the magnetic field intensity has given a better precision around the maxima of solar activity (Altrock, 2003). The Sun is the primary driver of space weather and its cycle of activity gives us some satisfaction to its predictability. Although the most severe solar activity occurs around the cycle maximum, its influence on the Earth continues through solar minimum. Predictions of transient events such as flares and CMEs rely on the appearance of the underlying active region growth and remain probabilistic in nature. High-resolution space-based imagery of magnetic flux emerging from the photosphere is likely to increase warning times.

From the above it is concluded that daily values of the coronal index of the solar activity allow us to study wide ranged variations for the Sun as a star as well as its rotational rate. Obtained results have shown similar results as were obtained for other features of solar activity by different authors, such as sunspot number, flare index, cosmic ray intensity etc (Rušin and Zverko, 1990; Rybàk et al., 1994; Mavromichalaki et al., 2003b). However the long-term coronal index can be a better indicator of the physics of the corona than radio flux and sunspot indices that reveal more about conditions in the lower atmosphere. This index of solar activity might prove to be a better measure of solar-terrestrial effects than sunspot number, as it is the "home" of coronal holes and coronal mass ejections, both of them being important for space weather studies. For example, Altrock (2003) gave a prediction of the exact date of the maximum of the 11-year solar activity cycle using ground-based coronal data. Mavromichalaki et al. (2002, 2003a) proposed an empirical model of the coronal index using sunspot number, solar flares and magnetic field useful to the next solar cycles prediction. All these works prove that the coronal index can be used as a important tool for the space weather prediction.

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