Long-term variations of the green coronal (530.3 nm) irradiance

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Abstract. There is growing evidence that solar variability influences the heliosphere, biosphere and Earth's climate. The solar variability finds its representation via a large number of phenomena and structures observed in the solar atmosphere. Changes in the green coronal irradiance over solar cycles are very pronounced and their long-term temporal behavior is in a good agreement with the corresponding variations of the solar magnetic flux, the latter being generally agreed to be the agent responsible for all aspects of solar activity. The green coronal irradiance index exhibits a very good correlation not only with other solar indices, e.g., the 2800 MHz radio flux, the X-ray flux and the total solar magnetic flux, but also with cosmic ray flux (in the inversion course). Measurements of the total magnetic flux and some "space-borne" indices have been available since 1978, or around this period. On the other hand, the green corona index has already been available since 1939. In the present work, a long-term pattern of the green coronal irradiance, as expressed in terms of the coronal index of solar activity (CI) and based on a homogeneous coronal data set, was compared with the corresponding behaviour of the number of sunspots, the 2800 MHz radio flux, the total magnetic flux and cosmic rays, and this comparison yielded a remarkable good correlation between these indices in the period between 1947–2004. Employing the correlation between the CI and sunspot numbers provides us with a unique tool to extrapolate the CI back to 1848, or even to the earlier years. The extended CI thus obtained is then compared with other similarly reconstructed solar indices. Cycle-to-cycle variations (17–23 cycles) of the CI are also discussed.

Index Terms. 530.3 nm corona, irradiance, long-term variations.

1. Introduction

There are several emission lines observed in the solar corona, e.g., the 530.3 nm (the green line, Fe XIV), the 637.4 nm (the red corona, Fe X), and the 569.4 and 544.5 nm (the yellow lines, Ca XV). Each of them varies in its intensity over a solar cycle, reflecting the physical conditions across the corona and its dependence on the local magnetic field configurations in the photosphere. The best indicator of the solar variability in the emission corona is the green line intensity, e.g., Waldmeier (1957), Leroy and Trellis (1974), Altrock (1988), Makarov, Tlatov and Callebaut (2003) and Rušin et al. (2004).

The solar corona is the outermost – very hot and diluted – layer of the solar atmosphere; its temperature is about 2 million degrees and electron density of 10^8 cm^{-3}. The green line intensity is visible during a complete 11-year solar cycle activity and around the entire solar limb. Measurements of the green coronal intensity represent one of the longest-running direct indices of solar activity, being surpassed only by the sunspot number (available since 1610), sunspot area (since 1874) and calcium plage index (since 1905; Lean, 2000, and references therein). Therefore, the green corona intensity can easily be compared with similar solar indices inferred from both ground-based and space-borne experiments within the past few decades. Hence, employing a well-pronounced correlation between the CI and the 2800 MHz radio flux one could extend several indices back to 1939, while using the relation between the sunspot number and the CI a similar extension of the CI (for the Sun as a star) can be extended as far as to 1848, or even earlier.

2. Coronal index of solar activity

Although first studies of the emission spectral line of the 530.3nm (see Fig. 1) can be dated back to 1939, its first systematic observations and analyses began only after the World War II.

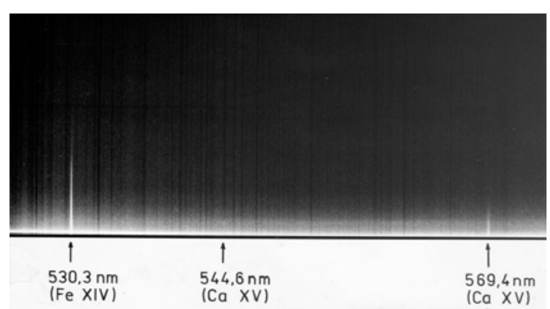

Fig. 1. A typical pattern of coronal emission spectral lines, together with "parent" ions indicated below.

It was soon realized, however, that the observed intensities of the green corona were different from different coronal stations (Rybanský et al., 2005). The main reasons for such discrepancies were different strategies/methodologies of acquiring the data, the height of observing above the solar limb, etc. There were a number of attempts to unify these observations, yet all these attempts proved to be unsuccessful. In this paper, we shall employ the data transformation due to Lomnický Štít photometric scale.

To facilitate comparisons of ground-based green line measurements with observations in extreme ultra-violet and soft X-ray wavelengths made from space, (Rybanský, 1975) proposed a new index of solar activity based on Lomnický Štít 530.3 nm measurements that he called the "coronal index of solar activity" (CI). The CI expresses the irradiance of the green corona for the Sun as a star and can easily be compared with similar full-disk solar indices. CI values are expressed in power units [W sr^{-1}] and can straightforwardly be transferred to similar units obtained from space-borne measurements as shown below:

$$10^{16}\ \mathrm{W\ sr^{-1}} \equiv 4.5 \times 10^{-7}\ \mathrm{W\ m^{-2}}\ \text{(at 1 AU)} \equiv 1.2 \times 10^{8}\ \mathrm{photons\ cm^{-2}\ s^{-1}}. \qquad (1)$$

Monthly averages of the CI for the period from 1939 to 2004 vary from 2 x 10^{16} W sr^{-1} (around cycle minima) to 20 × 10^{16} W sr^{-1} (around cycle maxima). Daily CI maximum values have never exceeded 30 × 10^{16} W sr^{-1}. The green line intensity in calibrated observations is expressed in absolute coronal units (ACU). One ACU represents the intensity of the continuous spectrum of the center of the solar disk in the width of 1 Å, at the same wavelength as the observed coronal spectral line (1 ACU = 3.89 W m^{-2} sr^{-1} at 530.3 nm).

Based on the "consensus", in 1947, between several observers of the corona, coronal intensities are derived at least once a day at heights of 40 – 60 arcsec above the solar surface with a lag of 5 degrees in the positional angle. An example of such an observation is shown in Fig. 2.

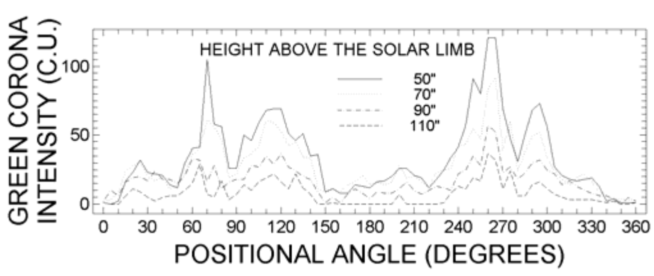

Fig. 2. Plots of the green line intensities, expressed in absolute coronal units, as measured at different heights above the solar disk at the Lomnický Štít coronal station on June 5, 2002.

The initial observation is made above the solar north pole, and 71 subsequent data points are made at the same height proceeding in the counterclockwise direction (north, east, south, west) (d'Azambuja, 1947). The CI for a given day is based on limb observations of the green line for that day and intervals of six days on either side of that day. The distribution of the intensity above the solar surface is obtained by using the observations at the E-limb (W-limb) from the six days preceding (following) the given day to specify the coronal intensities above the eastern (western) half of the disk. By integrating over the solar disk, we obtain the irradiance in front of the visible part of the Sun (E_H) to which we add the irradiance above the solar limb (0.5 E_L) (see Fig. 2 in Rybanský, 1975) to obtain the coronal index

$$CI = E_H + 0.5\ E_L, \qquad (2)$$

which is the total irradiance of the green corona into one sterradian (sr) towards the Earth (see Rybanský, 1975, for more details).

Today, the CI is widely used for a study of solar variability. A comparison of the CI prior to the (Rybanský et al., 2005) analysis, as illustrated by Fig. 3, indicated that the homogeneous coronal data set from which the CI is computed needs to be reexamined and modified for years before 1966, as well as for several short periods in 1966 – 2002. Both the revised and old CI's are depicted in Fig. 4, together with their differences.

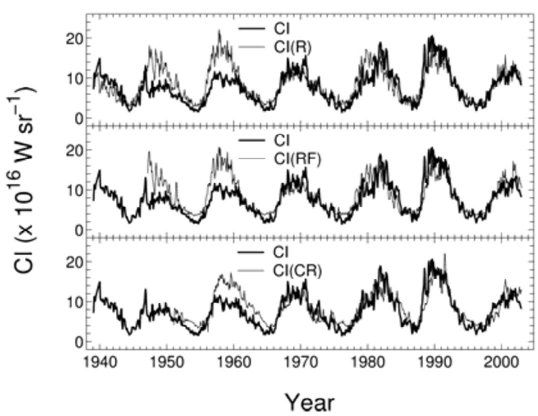

Fig. 3. Monthly averages of the CI from 1939 to 2002 (heavy lines) compared with the proxy CI indices (thin lines), taken from (Rybanský et al., 2005).

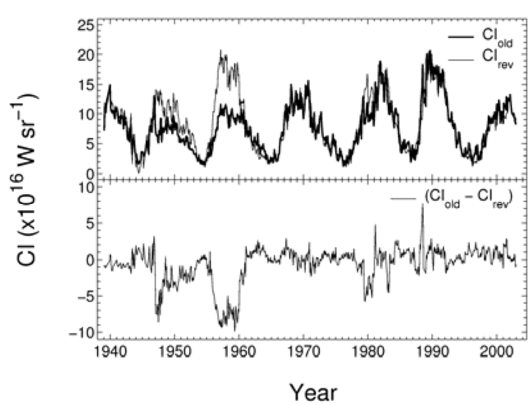

Fig. 4. A plot, for 1939–2002, of the old and revised CI monthly means (top) and their difference (bottom).

3. The green corona and similar solar indices

It is a firmly established fact that the intensity of the green corona is, in general, well correlated with the distribution of local solar surface magnetic flux (Wang et al, 1997; Zhang et al., 1999; Rušin and Rybanský, 2002). It is also a well-known fact that local magnetic fields are responsible for all the major manifestations of solar activity. This implies that there must be a high correlation between the behavior of the CI and other full disk solar variability indices such as the 2800 MHz radio flux (Fig. 5), sunspot number (Fig. 6) and cosmic rays (Fig. 7), as it is indeed the case.

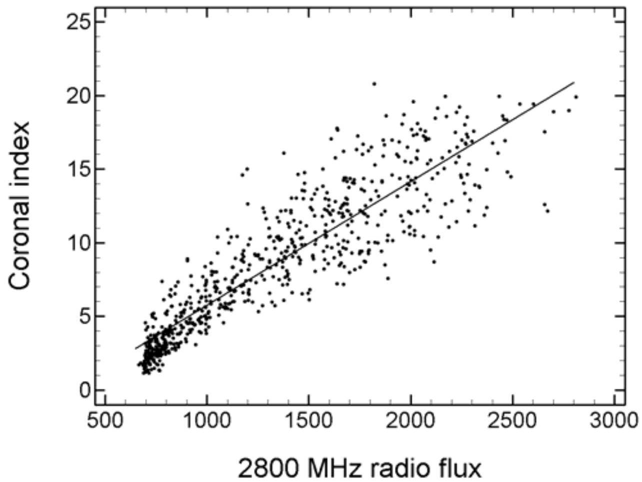

Fig. 5. Correlation between the CI and 2800 MHz radio flux (monthly averages). The correlation coefficient is 0.900.

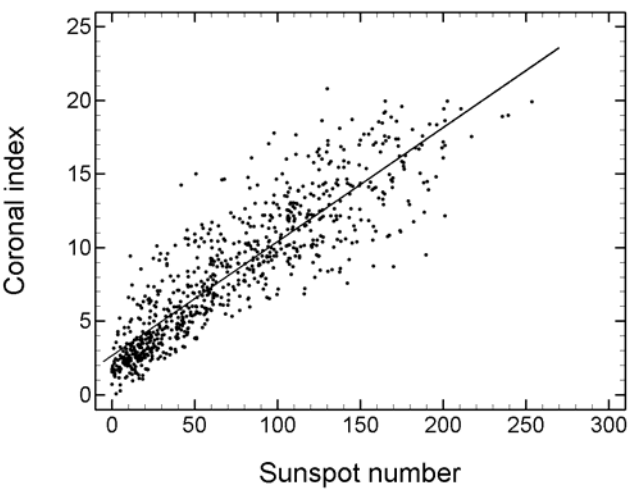

Fig. 6. Correlation between the CI and sunspot number (monthly averages). The correlation coefficient is 0.883.

A similarly high coefficient of correlation was, in 1976–2002, found between the green line intensities and magnetic flux (cc=0.869, Rušin and Rybanský, 2002) as well as between the CI and the X-ray flux (cc=0.864) as obtained from space-borne equipments (Rybanský, Minarovjech and Rušin, 2003). To check an intricate relation between the CI and solar total magnetic fields we have compared the CI with the absolute magnetic flux (expressed in Gauss) as obtained at the Kitt Peak solar observatory in 1997–2004; this comparison is shown in Fig. 8.

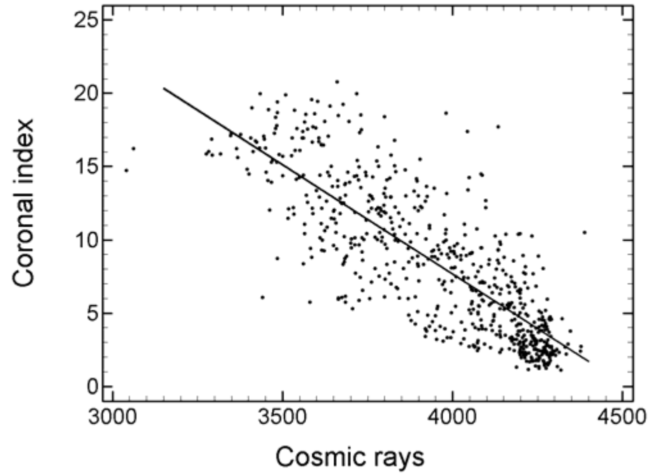

Fig. 7. Correlation between the CI and cosmic rays (monthly averages). The correlation coefficient equals 0.812.

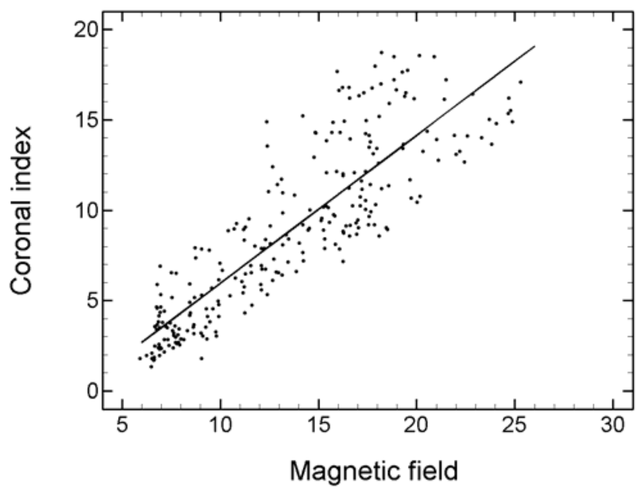

Fig. 8. Correlation between the CI and the Kitt Peak magnetic flux data (27-day averages). The correlation coefficient equals 0.864.

All in all, the CI, which ranks amongst the oldest "energetical" indices, can well be used for studies of solar activity from as early as 1939. In addition, with its help we can extrapolate all "modern" indices (Total Solar Irradiance, Magnetic Flux, etc.) back to 1939. On the other hand, a well-established correlation between the CI and sunspot number can be used to extrapolate the former back to 1848 (see Fig. 9).

The CI obtained this way can be compared with a reconstructed magnetic flux and/or the total flux discussed by Krivova and Solanki (2003 and references therein), with the empirical reconstruction of magnetic flux by Loockwood et al. (1999) and the concentration of the ^{10}Be isotope in ice cores by Beer et al. (1990). From the above-described statistical analyses we have arrived at the following relations:

CI = 0.00841 RF – 2.655,

CI = – 0.149 CR + 67.3,

CI = 0.0755 SN + 2.638,

and

CI = 8.81 MF – 2.229,

which valid on a statistical basis, between the CI and 2800 MHz radio flux (RF), cosmic rays (CR), sunspot number (SN) and magnetic flux (MF).

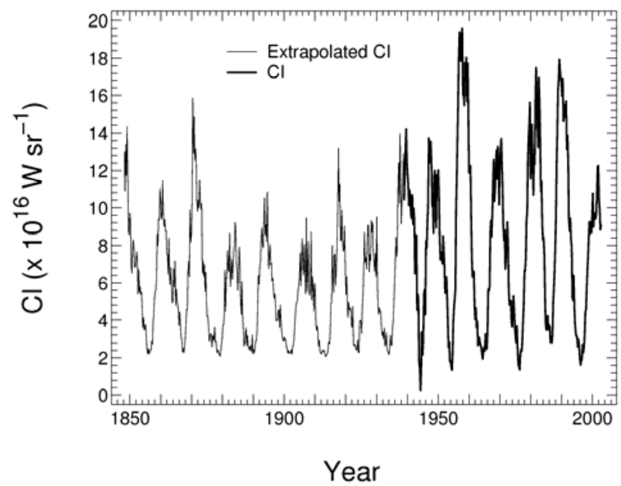

Fig. 9. Monthly averages of the CI (1848–2002). Heavy line – CI_{rev} (1939–2002), thin line – the CI extrapolated from the sunspot number (1848–1938).

4. Cycle to cycle variability of the CI

The intensity of the green corona has been measured since 1939, which is a sufficiently long period to find out its changes not only within a solar cycle, but also between individual cycles, as depicted in Fig. 10.

Daily measurements clearly demonstrate that the intensity of the green corona is always enhanced above active regions in the photosphere, which move from middle heliographic latitudes at the beginning of a cycle towards the equator. An illustrative example of a green coronal intensities time-latitude distribution of the local maxima is shown in Fig. 11 (see Minarovjech et al., 1998; Rušin et al., 2000).

The ratio between the intensity of the green corona above the polar regions and that measured above active regions varies within a cycle from the value of about 1:4 around minima to 1:20 around maxima. If we look at Fig. 10, we see that this variation is fairly good and follow the behaviour of the CI, which yields the ratio 1:5–9. It is worth mentioning that these variations are not induced by the changing average temperature of the corona, but stem from the variations of the electron density and the number of associated active regions.

It is worth mentioning that in our earlier work (Rušin et al., 2004 and references therein) we found out that the maxima of the last five cycles are characterized by a gradual increase of the CI, while our latest analysis with the revised data set (Rybanský et al., 2005) did not confirm this trend. This feature is observed only for the cycles 18 and 19 and 20 to 22. It is also interesting to note that the values of the CI in cycle 23 are the lowest ones for the whole period under study.

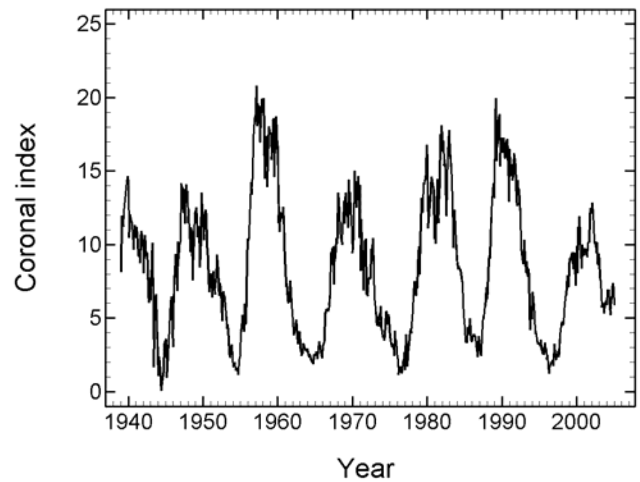

Fig. 10. Monthly averages for the CI in the period 1939–2004.

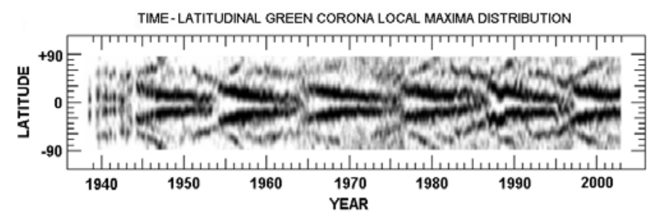

Fig. 11. Time-latitudinal distribution of the local maxima intensities of the green corona as derived from the homogeneous coronal data set.

A frequently discussed phenomenon is the so-called “double-maxima” phenomenon (also known as the “Gnevyshev gap”), discovered in 1963 by (Gnevyshev, 1963). This phenomenon also finds its reflection in other manifestations of solar activity and cosmic rays as well (Storini et al., 2003) and we have discussed it in detail in (Rybanský, Minarovjech and Rušin, 2003). We suggested that the distribution of the maxima of the intensities of the green corona is more or less of random nature, and different for the northern and southern hemispheres. From Fig. 10 we cannot say with certainty when the maxima of the green corona’s intensities are correlated with the maxima of sunspot number, i.e., occur approximately 1.5 to 2 years later than the latter. The most remarkable observation in this regime was cycle 21, when the CI maximum was observed in 1982, while the maximum of sunspot number was in 1979; in this particular cycle the maxima of the CI also coincided with those of cosmic ray, soft X-ray flux (Veroning et al., 2004), and of the Ca II K 1.0 A intensities (Lean, 1987). Something similar has been observed in the preceding cycle 23. There are several scenarios for explanation of this behaviour, e.g., dynamic energy balance in the corona (Wheatland and Litvinenko, 2001) and/or connection with a magnetic field reversal in odd- and even-numbered cycles. Mavromichalaki et al. (2002) came to the conclusion that the occurrence of maximum green coronal line intensities is connected with the distribution of photospheric magnetic fields.

5. Summary

The work focused on the behavior of the CI in the period from 1939 to 2004 and its comparison with distributions of other long-term indicators of solar activity such as the 2800 MHz radio flux, sunspot number, cosmic rays and total magnetic flux. We have found a good correlation between these indices. This enabled us to extrapolate all the modern indices up to the beginning of the corona's observations, and the CI up to the beginning of sunspots' observations. We have also found that the maxima of the CI differ from cycle to cycle, with no clear-cut pattern behind. It is, however, obvious that the CI is not only a good quantitative indicator of solar activity in the corona, but also a reliable "energetical" index which serves as a substitute and background for many indices based on space-borne observations. It is also an index which has applications based in solving the problems connected to influence of the heliosphere on the climate of the Earth — the problems which are of crucial importance in programmes like 'Living with a Star' and 'Space Weather'. After all, solar activity has impact on numerous scientific and practical areas, e.g., space operations, electric power transmissions, cosmic ray flux, climate impact, etc. So, the study of the solar irradiance in many long-term indices is very important. Finally, we mention that the revised values of the homogeneous set of data of the intensities of the green corona and those of the CI itself are available for free on http://www.ta3.sk/corona.

Acknowledgments. This work was supported by the Science and Technology Assistance Agency (Slovakia) under the contract No. APVT-51-012704. One of the authors (V. R.) would like to thank INSA for its financial support to participate in ILWS and IIAP in Bangalore. The NSO/Kitt Peak magnetic data used here are produced cooperatively by NSF/NOAO, NASA/GSFC and NOAA/SEL.

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