BRIGHTNESS OF THE CORONAL GREEN LINE AND PREDICTION FOR ACTIVITY CYCLES 23 AND 24

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Abstract. Cyclic variations of the mean semi-annual intensities I_λ of the coronal green line λ530.3 nm are compared with the mean semi-annual variations of the Wolf numbers W during the period of 1943–1999 (activity cycles 18–23). The values of I_λ in the equatorial zone proved to correlate much better with the Wolf numbers in a following cycle than in a given one (the correlation coefficient r is 0.86 and 0.755, respectively). Such increase of the correlation coefficient with a shift by one cycle differs in different phases of the cycle, being the largest at the ascending branch. The regularities revealed make it possible to predict the behaviour of W in the following cycle on the basis of intensities of the coronal green line in the preceding cycle. We predict the maximum semi-annual W in cycle 23 to be 110–122 and the epoch of minimum between cycles 23 and 24 to take place at 2006–2007. A slow increase of I_λ in the current cycle 23 permits us to forecast a low-Wolf-number cycle 24 with the maximum $W \sim 50$ at 2010–2011. A scheme is proposed on the permanent transformation of the coronal magnetic fields of different scales explaining the found phenomenon.

1. Introduction

Prediction of solar activity for a few years ahead and, in particular, for a following cycle has long been a vital problem of solar physics. It is connected, on the one hand, with the practical needs of solar and other sciences and, on the other hand, with the general unsatisfactory situation in long-term forecasting of solar activity. Before each cycle maximum, a number of papers appear giving predictions of the sunspot (Wolf) numbers at the coming maximum in the range from 50–60 to 200 (see, e.g., the reviews of predictions for cycle 23 by Obridko, 1995; Lantos and Richard, 1999; Hathaway, Wilson, and Reichmann, 1999).

Not aspiring to a complete analysis of the question and referring the reader to the extensive reviews by Vitinskii (1965), Hathaway, Wilson, and Reichmann (1999), Lantos and Richard (1998), we shall outline here the prediction methods available and try to fit our method in the general scheme of forecasts. Most authors predict the Wolf numbers by analyzing various correlations or spectral characteristics (e.g., Fourier analysis) found in the Wolf number series available. Examples are the methods proposed by McNish and Lincoln (1949), Calvo, Ceccato, and Piacentini (1995), Conway *et al.* (1998), and Bondar', Rotanova, and Obridko

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(1996); various techniques used to improve the accuracy or enlarge the lead time of prediction (Chistyakov, 1983; Kuklin 1993, 1996; Dmitrieva, Kuzanyan, and Obridko, 2000); and the methods describing the internal structure of the cycle (Stewart and Panofsky, 1938; Hathaway, Wilson, and Reichmann, 1994).

Some methods forecast specific points of the cycle only, relying on some indices known from the preceding cycles. Sometimes, those are the same Wolf numbers exhibiting, for example, the well-known rule of Gnevyshev and Ohl (1948) or its modification by Kopecký (1950). The date or the latitude of the first sunspots appearing in a new cycle (Wilson, Hathaway, and Reichmann, 1998a, b), the dispersion in Wolf numbers at different phases of the cycle (Obridko, 1988), the period –amplitude relationship (Waldmeier, 1935; Chistyakov, 1983; Schove, 1983), etc., have also been used within the precursor methods.

Among the methods utilizing the precursor techniques, we should mention those predicting Wolf numbers on the basis of other solar and geophysical indices. The method of Ohl (1966) developed later by Ohl and Ohl (1979) is, probably, the best known of this category of predictions. This technique predicts a following cycle on the basis of geomagnetic activity observed at the ascending branch of a given cycle. The Ohl method was afterwards used in various modifications by Thompson (1990, 1993), Feynman (1982), Obridko (1995), Lantos and Richard (1998), Hathaway, Wilson, and Reichmann (1999). In a number of cases, this method gives considerably more reliable results than any of the direct extrapolation techniques.

Of special note and interest are the methods by Hathaway, Wilson, and Reichmann (1999), who used modifications of the precursor technique together with the extrapolation method, and those by Makarov and Makarova (1996), Makarov and Tlatov (2000), and Nagovistyn (1988), who exploited data on the polar magnetic field or polar faculae (the lead time was 5–6 years in this case).

The method we propose below is in some aspects close to that of Makarov and his colleagues. We have noticed that the cyclic curve of the green-line corona brightness is similar to the Wolf-number curve shifted by $\sim$ 10 years backwards (i.e., the curve of the green-line corona brightness in a given cycle is similar to the Wolf-number curve in the following cycle). It is this striking similarity that we base our prediction on. Physically, it may be interpreted as the fact that the brightest coronal features manifest a peculiar structure of the large-scale magnetic field in the solar equatorial zone which, after several years, pre-determines the structure and energetics of the magnetic field at high latitudes of the Sun. Then, at the second stage of this process, the high-latitude field, with the additional shift of about 5–6 years, controls the energetics of local fields in the equatorial zone and manifests itself in the intensity of the following Wolf number cycle. Surely, this is quite a preliminary interpretation, which needs further reasoning and verification.

2. Observations and Data Reduction

2.1. Short description of observations

B. Lyot started with the daily monitoring of the Fe XIV 530.3 nm coronal emission line intensities (the so-called coronal green line – CGL) at the high-altitude Pic du Midi (PdM) Observatory close to the beginning of the second world war. The success of Lyot's work with coronagraph ($D = 20$ cm, $f = 400$ cm) has stimulated the construction of other coronagraphs on the same pattern and led to the establishment of other observatories high in the mountains, where the intensity of the light scattered by the dust particles of the Earth's atmosphere is already substantially suppressed, not exceeding 10^{-4} of the solar disk brightness. At the same time, Waldmeier began systematic observations of the coronal emission lines at Arosa in Switzerland. The full set of his green-line Fe XIV 530.3 nm and red-line Fe X 637.4 nm measurements in the period 1939–1949 was published (Waldmeier, 1951) in the form of 'coronal contours'. Later, shortly after the war, a world-wide network of coronal stations was set up. The participating observatories are listed in Table I.

The time intervals in the last column of Table I indicate the periods when the measured data were published in numerical form in the *Quarterly Bulletin on Solar Activity* (*QBSA*). Fortunately, the PdM numerical data from already 1943 were at our disposal. The Sacramento Peak Observatory (SPO), after changing its method of measurements, reestablished its observations in 1973. Its extremely fruitful and valuable data is now published in the form of intensity contours and in the form of synoptic charts in the *Solar-Geophysical Data* (*SGD*) bulletin (see 'explanation of data reports' in *SGD* 515 (Supplement), 1987). Through limited periods of time some other observatories, for example, Crimea (Ukraine), Abisco (Sweden), Kodaikanal (India), and Arcetri (Italy) have tried and sometimes succeeded in making coronal measurements but they never published their data. At present there are only four observatories (SPO, Norikura, Kislovodsk, and Lomnický Štít (LS)) where patrol measurements of the CGL are performed regularly (Kislovodsk and Norikura with some gaps in the last few years); their data is regularly published in the QBSA or *SGD*, or they are available on request prior to publication.

The CGL intensities are usually measured in steps of five degrees around the Sun's disk (three degrees at SPO), starting from the north pole, continuing through the east, south and west limbs, and going back to the north. Mostly the intensities are expressed in so-called absolute coronal units (a.c.u.), i.e., in millionths of the energy radiated from the centre of the Sun's disk in the 0.1 nm strip of the spectral continuum situated close to the CGL. Thus, to obtain the 'coronal contour', characterizing the large-scale distribution of the CGL brightness around the whole solar disk, spectral measurements have to be made at 72 points. Some years ago, it took more than half an hour to record the photographic spectra at those points and it took almost the whole day to reduce and derive the final intensities by applying

TABLE I
List of the coronal observatories

Observatory	Country	Longitude	Latitude	Altitude	Published data
Pic du Midi	France	$-0°8.7'$	$+42°56.2'$	2862 m	1947–1974
Arosa	Switzerland	$+9°40.1'$	$+46°47.0'$	2050 m	1947–1975
Climax	USA	$-106°12.0'$	$+39°23.0'$	3410 m	1947–1957
Wendelstein	Germany	$+12°0.8'$	$+47°42.5'$	1837 m	1947–1979
Kanzelhöhe	Austria	$+13°54.4'$	$+46°40.7'$	1526 m	1948–1964
Norikura	Japan	$+137°33.3'$	$+36°6.8'$	2876 m	1951–till now
Sacramento Peak	USA	$-105°49.2'$	$+32°47.2'$	2811 m	1953–1966
					1973–till now (*SGD*)
Kislovodsk	Russia	$+42°31.8'$	$+43°44.0'$	2130 m	1957–till now
Alma Ata	Kazakh Rep.	$+76°57.4'$	$+43°11.3'$	3001 m	1957–1962
					1973–(1991?)
Lomnický Štít	Slovak Rep.	$+20°13.2'$	$+49°11.8'$	2632 m	1966–till now
Ulan Bator	Mongolia	$+107°03.0'$	$+47°50.0'$	1600 m	1971–1973

the methods of classical photometry. That is why there were continual efforts to develop and to use faster procedures of obtaining the final data.

Unfortunately, the huge amount of original data could not be subjected to statistical study immediately, because of the diverse methods of obtaining and reducting the raw data obtained at different observatories (e.g., visual, radial-slit photographic, circular slit photographic and photoelectric methods of observation have been applied, different heights above the Sun's limb were undertaken to record the intensities and even the units to express the values of the CGL intensities were not identical – both the a.c.u. and arbitrary units have been used, etc.). That is why it was first necessary to perform the tedious work connected with the transformation of all the accessible data to the unified photometric system.

It has been found (Sýkora, 1971) that several systematic errors (differences) exist among the data of different coronal observatories. It was emphasized that, at least, the differences among the photometric scales of the observatories, casual 'jumps' in the stability of the photometric scale of a given observatory (for example, due to occasional changes of the observational technique and method of observation or due to modifying the reduction of the data, etc.), systematic errors in linearity of the position angle scales, errors in position of the zero points of those scales and objectively different thresholds of measurements at various observatories should be analysed, taken into account and eliminated when all the accessible data is compiled and treated together.

2.2. Reduction of the Data

Such an analysis of the heterogeneity of the data was carried out and described by Sýkora (1971, 1983, 1992a). Since the longest, most homogeneous and extensive set of the CGL measurements at the beginning of the seventies was that of Pic du Midi, we have decided to transform all the other data to the photometric scale of this observatory. In spite of the termination the CGL patrol measurements at the PdM observatory in 1974, we still maintain its previous photometric scale in the presently compiled data through the whole 1943–1997 period (during the last more than two decades this is achieved by an extensive correlation analysis of the long-lasting contemporary observations of the PdM, Norikura, Kislovodsk, and LS coronagraphs). This implies that our data on the CGL intensity refer to the altitude of 60″ above the photosphere, as it was accepted for the CGL measurements at the PdM observatory (Trellis, 1957).

All the published *QBSA* and *SGD* data, together with the unpublished PdM data (courtesy of J. Rösch), were reduced to a common photometric scale using the following procedure. Firstly, the average coronal intensities in semi-annual periods were calculated for each 5° of position angle, separately for each coronal observatory (as mentioned, the CGL measurements are performed with step of five degrees around the Sun's limb). Then, all the intensities recorded at each coronal station during a given half-year were transformed to the PdM scale using a correlation relationship between the PdM and pertinent observatories. At the same time, all the systematic errors as identified by Sýkora (1971) were taken into account. To create the final database, we have successively used measurements of the PdM, Kislovodsk, LS, SPO, Climax, Norikura, Wendelstein, Arosa and Alma Ata coronal observatories. This was done according to the written sequence. It means that we have used all the accessible PdM data; on days when there was no observation at PdM the possible data of Kislovodsk were used to fill in the gaps; on days when there were no observations at the first two observatories we used the data available from LS, etc. This procedure resulted in obtaining a homogeneized CGL database reduced to the unified PdM photometric scale, when in each year about 300 days (sometimes even more) were covered by measurements. Finally, for the uncovered DOY (days of year) the CGL intensities were linearly interpolated using the data measured in the day preceding and in the day following the missing day(s).

Summarizing, the final original database represents a matrix of 72 values of the CGL intensity (expressed in a.c.u.) for each day in the period 1943–1993. Thus, the space resolution of the data is one day (about 13°) in the solar longitude and 5° in the solar latitude.

For the period 1994–1999 only the semi-annually averaged data is at our disposal. This, however, is completely sufficient to fulfill the aims of the present work.

Along with that, by the earlier exploitation of our database, the presence of the rigid and differential components in the coronal rotation (Sýkora, 1980) and the clear regularities in the long-term longitudinal and latitudinal distributions of the CGL brightness (Sýkora, 1994; Sýkora, Badalyan, and Storini, 2001) were revealed, together with the identification of a particular importance of the CGL activity within the middle latitude zones for the long-term cosmic ray modulation (Storini *et al.*, 1997) and the level of geoactivity (Sýkora, 1992b).

3. Intensity of the Coronal Green Line 530.3 nm in an Activity Cycle and Reasons for the Prediction Method Proposed

3.1. Comparison of Cyclic Variations of the Green-Line Intensity and Wolf Numbers

A detailed analysis of cyclic variations of the coronal green-line (CGL) intensity I_λ was performed by Sýkora (1980, 1994). It was shown that the 11-year activity cycles were clearly identified in the CGL intensity, coinciding in phase with the Wolf number W cycles. However, essential differences were noticed in the cycle amplitudes of both curves. This fact is especially pronounced when comparing the activity cycles 19 and 20: the maximum of the Wolf number curve is very high in cycle 19 and relatively low in cycle 20, whereas the maxima of I_λ curve do not show such an expressive difference. Sýkora (1980, 1994) has also pointed out that the range of the CGL cycle variations was considerably less than that of the Wolf numbers.

The behaviour of CGL intensity was studied in more detail after the set of data was extended up to 1993. The analysis of distributions of CGL intensity within narrow latitudinal belts and separately in the northern and southern hemispheres shows that the cyclic variations of I_λ in the equatorial, mid-latitude, and polar zones differ significantly (e.g., Sýkora, 1992a; Storini and Sýkora, 1995). The highest correlation with the Wolf numbers was found for the mid-latitude zones of both solar hemispheres. In these zones the Gnevyshev–Ohl–Kopecký rule is valid for the CGL intensity (Storini and Sýkora, 1997; Sýkora and Storini, 1997).

Below, the cyclic curves of I_λ based on the extended series (1943–1999) of CGL brightness were compared with the corresponding Wolf number curve. Everywhere in this paper, we use the mean non-smoothed semi-annual values of the corresponding parameters.

Figure 1 (the upper panel) shows variations of the CGL intensity in the equatorial zone during the past five 11-year cycles of solar activity. The dashed line represents I_λ values in the latitudinal zone from $+20°$ to $-20°$, i.e., without separation between the two hemispheres. The Wolf number curve is shown with a solid line. One can notice some peculiarities in the behaviour of I_λ – a rather low cycle 19 as compared to cycle 20, and less extensive variations in I_λ from cycle to cycle as compared to the Wolf numbers.

Even a superficial inspection of both curves in the upper panel of Figure 1 suggests that cyclic variations in the Wolf numbers follow the green-line variations

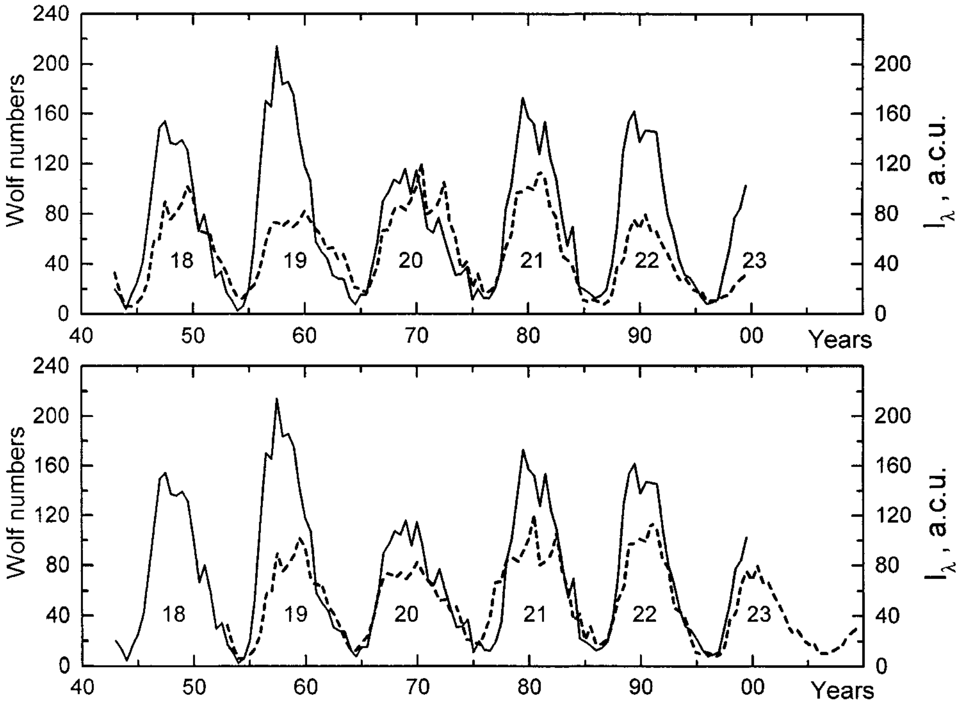

Figure 1. Cyclic variations of the mean semi-annual Wolf numbers (*solid lines*) and coronal green-line intensities I_λ (*dashed lines*) for the period of 1943–1999 (activity cycles 18–23). On the lower panel, the values of I_λ are shifted forward by 10 years. Figures on the graph denote the number of sunspot cycle.

with a delay of one cycle. To verify this impression, we shifted the I_λ values forward by 10 years (the mean length of cycles 18–22) when plotting the lower panel of Figure 1. It is evident that the shifted CGL curve does agree better with the Wolf number curve. This conclusion can be corroborated numerically by calculating the correlation coefficients. The highest correlation coefficients are obtained when I_λ is shifted by 9.5 years (the difference in correlation coefficients at 9.5- and 10-year shifts is relatively insignificant). It should be noted that the comparison can only be carried out with an accuracy down to half a year, taking into account our semi-annual averaging.

The left panel in Figure 2 represents the regression dependence between the Wolf numbers and the 'non-shifted' CGL intensities for the entire period of 1943 –1999 (the points correspond to the upper panel in Figure 1); and the right panel shows the same dependence for I_λ shifted forward by 9.5 years (the points corresponds to the lower panel in Figure 1). A comparison of the right and left panels makes it evident that the correlation is noticeably higher on the right panel than on the left one, the correlation coefficients being $r = 0.860 \pm 0.027$ and $r = 0.755 \pm 0.040$, respectively. In contrast to that, the effect under discussion is not

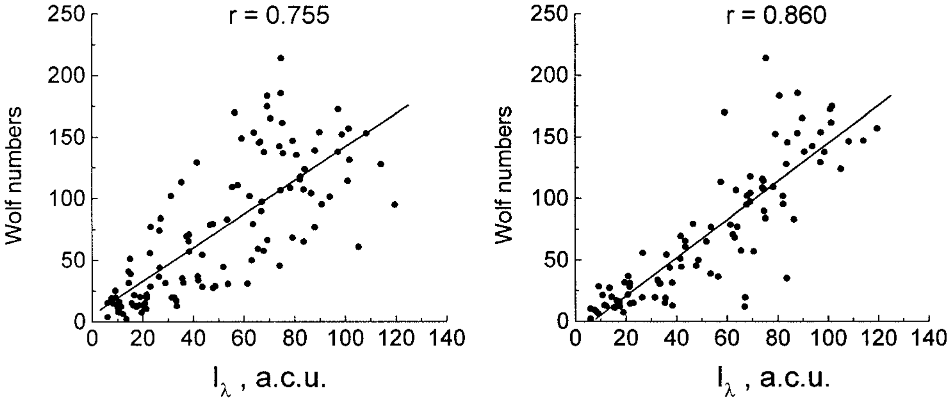

Figure 2. Regression dependence between the Wolf numbers and CGL intensities in the equatorial zone ± 20° for the entire period of 1943–1999. Values of I_λ on the left panel are not shifted, and the values on the right panel are shifted forward by 9.5 years. The corresponding correlation coefficients are indicated on both panels at the top.

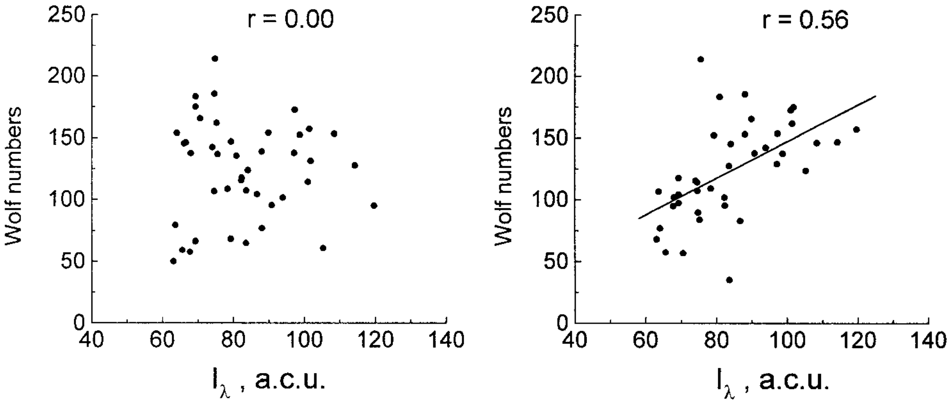

Figure 3. The same as in Figure 2 for the bright corona during the maxima of solar activity (evolutionary regime A, see text).

observed in the mid-latitude zones (from ± 25° to ± 50°): I_λ shifted forward by 9.5 years correlate with the Wolf numbers much worse than 'non-shifted' I_λ. The correlation coefficients are now 0.656 ± 0.060 and 0.860 ± 0.026, respectively.

We have analyzed correlation relations in the pairs of consecutive cycles. The correlation coefficients appeared to be always higher if I_λ was shifted forward by about a cycle. This effect is best pronounced in the pair of cycles 19-20, where $r = 0.592 \pm 0.100$ in the case of unshifted I_λ curve and $r = 0.867 \pm 0.046$ when the curve is shifted.

Thus, the analysis performed shows that the CGL brightness correlates with the Wolf numbers much better when shifted forward by 9.5–10 years, i.e., for a cycle approximately.

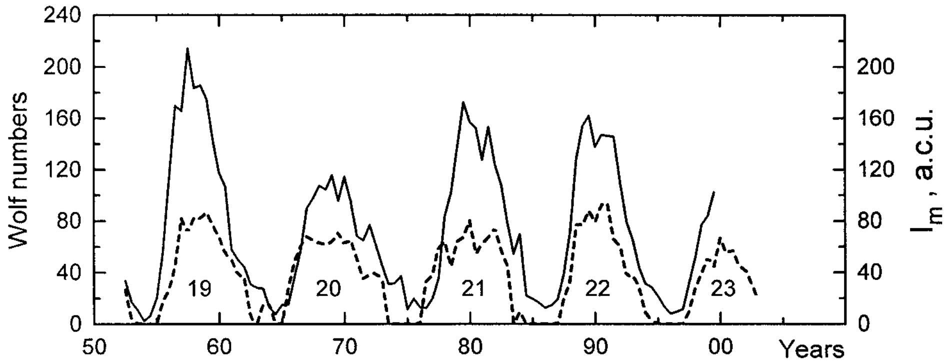

Figure 4. Cyclic variations of the Wolf numbers (*solid line*) and I_m (the most probable CGL intensity in a given half-year, *dashed line*), the latter curve being shifted forward by 9.5 years. Figures on the graph denote the number of sunspot cycle.

3.2. Other characteristics of CGL intensity and $I_\lambda - W$ relation in different phases of a cycle

To plot Figure 3, we selected the points relevant to the bright corona during the maxima of solar activity cycles (the so-called regime A in the behaviour of the CGL brightness). The evolutionary regimes of the CGL brightness were defined by Badalyan and Kuklin (1993, 2000) when investigating the CGL intensity distributions by means of a principal component analysis. The A-regime evolves in equatorial coronal regions close to the cycle maximum and lasts approximately till the middle of the descending phase of the cycle. Badalyan and Kuklin (1993, 2000) supposed that this regime was related to coronal condensations above the large active regions or/and complexes of activity. During these periods, the measured I_λ values are mainly determined by the bright active regions in the corona. As seen in the left panel of Figure 3, I_λ in a given cycle does not correlate at all with the Wolf numbers in the same cycle. When I_λ are shifted forward by a cycle (the right panel in Figure 3), the correlation becomes significant and reaches $r = 0.56 \pm 0.11$.

Another interesting characteristic is the I_m value – the most frequent CGL intensity in a given half-year interval. This value is represented by the abscissa of the maximum in the intensity distribution histogram, see Badalyan and Kuklin (1993, 2000). Figure 4 shows the Wolf numbers (solid line) and I_m values in the equatorial zone (dashed line) shifted forward by 9.5 years. (Note that I_m cannot be determined at the minimum of the cycle, because the most probable CGL intensity is close to zero.) The corresponding correlation dependencies are illustrated in Figure 5. The correlation coefficients are $r = 0.600 \pm 0.074$ and $r = 0.800 \pm 0.044$ for the non-shifted and shifted I_m, respectively. A comparison between I_m and Wolf numbers for the A-regime shows that correlation is almost absent in the same cycle, but is quite significant ($r = 0.66 \pm 0.09$) when a shift by 9.5 years is used (cf., Figure 3 for I_λ).

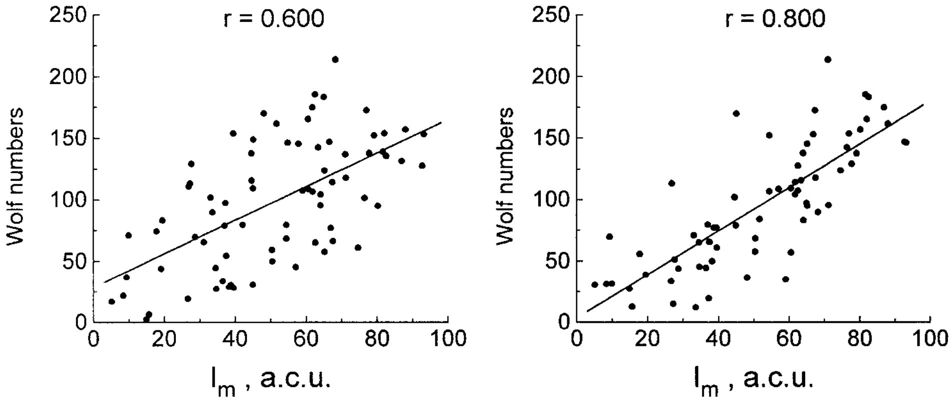

Figure 5. The same as in Figure 2 for I_m in the period of 1943–1999.

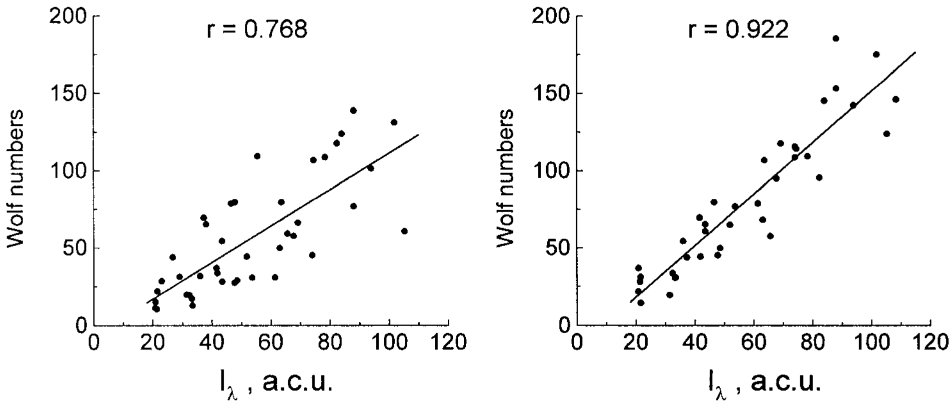

Figure 6. The same as in Figure 2 for the descending branch of the activity cycle from the polarity reversal up to the cycle minimum.

The comparison between I_λ and Wolf numbers is most impressive at the descending branch of the activity cycle, after the polarity reversal takes place (Figure 6). At this time, the correlation with the Wolf numbers for CGL intensities shifted by 9.5 years as compared to the unshifted I_λ increases most pronounceably, the correlation coefficient changing from $r = 0.768 \pm 0.064$ to $r = 0.922 \pm 0.024$. Note that the values of $I_\lambda < 20$ a.c.u., i.e., right at the cycle minima, are excluded from consideration, because their inclusion would 'fictitiously' increase the correlation coefficients.

Consequently, we can conclude that I_λ in every cycle contains encoded information about the following Wolf number cycle. It appears that the epoch of I_λ maximum (regime A) 'stores' information on the height of maximum of the following cycle and the phase of decreasing activity 'foresees' the shape of the descending branch of the following cycle. This means that such a relation between the given and the following cycles may exist permanently. The correlation between

TABLE II
Prediction of the height of cycle 23

Regression equation	Correlation coefficient	W
$-10.160 + 1.546 I_\lambda$	0.86	114
$-0.922 + 1.482 I_\lambda$	0.56	118
$-8.159 + 1.954 I_m$	0.66	122
$-7.140 + 1.461 I_\lambda$	0.96	110

I_λ in a given cycle and W in the following cycle somewhat changes in different phases of the cycle. However, it is always higher than the correlation between these quantities within the same cycle.

3.3. Prediction for Cycles 23 and 24

The effect described above makes it possible to forecast the cycle of solar activity with a lead time of $\sim$ 10 years.

The height of maximum of cycle 23 can be predicted by using different regression dependencies: (a) derived from the general dependence in Figure 2, (b) found for the periods of maximum activity (regime A, Figure 3), (c) found from I_m for the periods of maximum activity, (d) obtained for the period of 1986–1999 (cycle 22 and the ascending phase of cycle 23).

The corresponding regression equations, correlation coefficients and predicted values of W are listed in Table II. With the maximum I_λ in cycle 22 equal to $\approx$ 80 a.c.u. and I_m equal to $\approx$ 66 a.c.u., all four equations give the height of cycle 23 in W ranging from 110 to 122. Note that Table II contains the mean non-smoothed semi-annual values.

It follows from Table II that the Gnevyshev–Ohl–Kopecký's rule (Gnevyshev and Ohl, 1948; Kopecký, 1950), according to which an odd cycle is always higher than the preceeding even cycle, is likely to fail in cycle 23.

The same regression equations allow us to forecast the behaviour of activity at the descending branch of cycle 23. In Figure 7, the part of the cyclic Wolf number curve (cycles 22–23) is presented together with the CGL intensities shifted forward by 10 years. The predicted Wolf numbers, calculated on the base of first equation, are shown with open circles in Figure 7. The minimum between cycles 23 and 24 can be predicted for approximately 2006–2007.

A long lead time ensured by the method under discussion permits us to forecast the height of cycle 24 right now. As follows from Figure 1, the CGL intensity increases slowly in cycle 23. At present, actually close to the maximum of cycle 23, I_λ is still rather low. It means that a relatively low cycle 24 with maximal

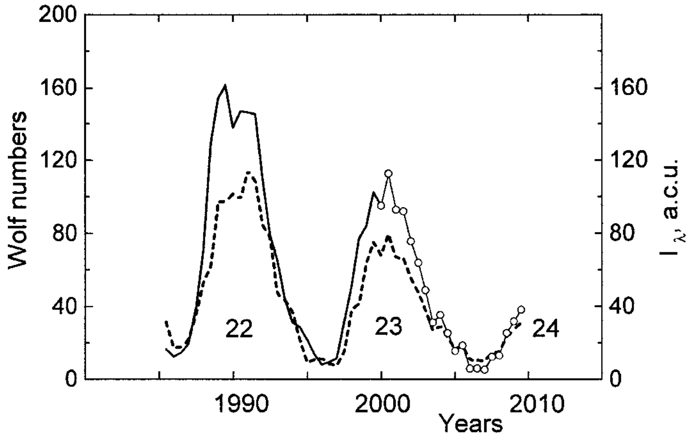

Figure 7. The part of the cyclic Wolf number curve (cycles 22–23, *solid line*) and CGL intensities I_λ (*dashed line*) shifted forward by 10 years. *Open circles* indicate our forecast of the Wolf numbers for solar cycles 23-24. Figures on the graph denote the number of sunspot cycle.

$W \sim 50$ should be expected. The maximum of cycle 24 is foreseen in 2010–2011 (see Figure 7).

4. Discussion

We have shown that characteristics of the CGL brightness within the solar equatorial zone are closely related to the Wolf numbers of the following cycle. At the same time, the cyclic curves of the Wolf numbers and CGL brightness shifted by ~ 10 years coincide well enough in some details. This effect is especially pronounced at the descending branch of the solar cycle. Besides, one can note that CGL brightness near the cycle maximum (regime A – the bright equatorial corona) does not correlate at all with the Wolf numbers in the same cycle, but displays a significant correlation with W shifted by 10 years.

The above regularities allow us to predict the Wolf number curve in any cycle on the basis of the CGL brightness curve in the preceding cycle. The fact that our method forecasts the entire W curve relates it to the extrapolation techniques; and the fact that the prognostic parameter is not the Wolf number, but some other indicator of solar activity, makes it similar to the precursor techniques. The closest methods to ours are described by Makarov and Makarova (1996), Makarov and Tlatov (2000), and by Hathaway, Wilson, and Reichmann (1999). Makarov used for prediction the characteristics of activity at the solar poles (polar faculae, polar and global magnetic fields), which reached their maximal values some 5–6 years prior to the solar maximum. Hathaway, Wilson, and Reichmann (1999) combined the extrapolation and precursor techniques. These authors used later improvements of the Ohl (1966) method by Feynman (1982) and Thompson (1993) to forecast the height and term of maximum of the following cycle. Then, the whole curve of the cycle was calculated by using the method of a two-parametric cycle-shape function.

In our method, the regression dependence found between the CGL brightness and the Wolf numbers shifted by 10 years is used without any additional hypotheses or assumptions. It should be noted that, like the polar field in the Makarov's method, the curve of the CGL intensity is not only a precursor, but it also forecasts the whole Wolf number curve for a certain time ahead. An important difference from the Makarov's method is that, in our technique, the lead time is extended to cover the entire activity cycle.

A certain conceptual link between our method and that of Ohl should be pointed out. In principle, a cause-consequence relation was found by Ohl (1966) between the characteristics of the large-scale magnetic field close to the cycle minimum and the local fields at the cycle maximum. This relation has a time lag of about 5–6 years, which proves to be quite suitable for prediction. When proposing his method, Ohl utilized the characteristics of geomagnetic disturbances. However, it soon became clear that geomagnetic disturbances in themselves reflect the global (apparently, poloidal) magnetic field of the Sun. In further investigations, many authors compared directly the global field characteristics and the Wolf numbers with a half-cycle shift. The distinction of our method is that it links the coronal characteristics and the Wolf numbers continuously, thus indicating a permanent character of the relation. This means that the process interrelating the global field at the minimum of a given cycle and the Wolf numbers at the maximum of the following cycle is not limited to these two phases only, but continues without interruption over all the cycle.

The papers by Ohl (Ohl, 1966, 1972; Ohl and Ohl, 1979), and by Makarov and his colleagues (Makarov and Makarova, 1996; Makarov and Tlatov, 2000) clarify the mutual relationship of the global solar magnetic field with the local fields of the equatorial zone. Somewhat less clear is another part of the process apparently relating the brightest features in the equatorial corona (probably, the toroidal field) with the global poloidal field. Generally speaking, one could refer here to the well-known paper by Leighton (1969) where the polar field was interrelated with the remnants of the local magnetic field drifting slowly to the poles and forming the polar field of the following cycle minimum. This scenario meets some difficulties. Nevertheless, it does not contradict our findings. Moreover, any dynamo mechanism involves mutual transformation of the poloidal fields into toroidal ones, and vice versa. However, in theoretical investigations, these two processes are usually separated in time: from minimum to maximum, the toroidal field is generated from the poloidal one and then, during the second part of the solar cycle, the reverse process takes place. Our results indicate that these two reciprocal processes are not separated in time though they are, probably, separated in space. Therefore, one may speculate that the drift of equatorial fields to the poles and the reverse equatorward drift, in which the global field is transformed into the local fields of sunspots (Wolf numbers), take place at different depths. This scheme is, in a certain sense, close to that developed by Simon and Legrand (1992).

Our calculations provide the maximum semi-annual value of W in cycle 23 equal to 110−122 and the epoch of maximum in the first half of 2000. Hence, the present cycle is not as high as was expected and predicted several years ago, nor as low as forecasted by some authors. This shows that the Gnevyshev–Ohl–Kopecký rule fails in this cycle. The end of the cycle is expected at 2006−2007. Proceeding from the current CGL brightness (the second half of 1999), we can predict a low cycle 24 with the maximal W not exceeding 50 (similar to cycles 5−6) and the epoch of maximum at 2010−2011. Thus, as inferred by our results, we are on the eve of a deep minimum of solar activity similar to that at the beginning of the 19th century.

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