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Coronal manifestations of solar variability

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Abstract

This contribution is mostly about phenomenology of what we see in space–time evolution of coronal green line brightness (CGLB), including its cyclic variations. Our own database (1943–2001) of the coronal Fe XIV 530.3 nm emission line intensities is used to display different aspects of the large-scale CGLB regularities and cyclic behaviour. Hemispheric asymmetry and relation of the longitudinal CGLB distribution to the rotational characteristics of the solar corona are particularly underlined.

Keywords: Solar emission green-line corona; Solar 11-year cycle; N-S asymmetry; Active longitudes; Coronal rotation

1. Introduction and data

Solar corona represents a highly rarefied completely ionized plasma. That is why, temporal and spatial organizations and structures of the solar corona are extremely sensitive to topology and strength of the solar magnetic field. On the other hand and undoubtedly, all the active processes and regularities present in the solar corona modulate physical state of heliosphere and contribute to creation of space weather. Thus, any findings about distribution of coronal radiation and about its large-scale variability may contribute to a better understanding of both the linked topics.

Intensity of the brightest emission line Fe XIV 530.3 nm of the optical solar corona is, indeed, a very informative index of solar activity. Nowadays, quite a long set of systematic patrol measurements of the CGLB is available, covering almost six solar activity cycles (1943–2001). A specific advantage of the CGLB index results from its almost simultaneous registration at all solar latitudes. This allows the solar activity to be studied all over the Sun by uniform data unlike, for example, to the Wolf numbers characterizing activity at lower latitudes only and the polar faculae appearing at high latitudes.

The coronal green line (CGL) originates in the inner corona at a temperature of ~2 MK, most favourable for the Fe XIV ion to be generated. Since the CGL intensity is proportional to the square of electron density, regions of the strongest CGL emission are mostly identical with dense loops and loop clusters in the inner corona. Such structures are related to and controlled by the coronal magnetic fields. The period covered by the CGLB measurements substantially exceeds the period of reliable large-scale synoptic photospheric magnetic field data (accessible from about 1976). Therefore, a proper analysis of the CGLB space–time distribution may indicate also some aspects of the coronal magnetic field evolution well backwards.

Let us give a basic characterization of our CGLB database (for a detailed historical background of coronal observations see, e.g., Storini and Sýkora, 1997). The patrol coronagraphic measurements, regularly (daily) carried out by a small world-wide network of high-altitude observatories, were synthesized to create photometrically homogeneous database of the Fe XIV 530.3 nm coronal emission line intensities (data for

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about 15% of individual days not covered by observations were interpolated). The measurements of different observatories were reduced to a common photometric scale and to the height of 60″ above the photosphere. The spatial resolution of the final data is one day in the solar longitude (∼13°) and 5° in the solar latitude. Originally, the measurements are available from both the east and west solar limbs. From these a central meridian (CM) data were derived as an average of intensities measured 7 days before and 7 days later, i.e. as an average of values when the proper meridian passed the E and W limbs, correspondingly. At the same time, the original position angles were transformed to the solar latitudes. Subsequently, namely the CM data were used to construct all the figures and maps in this contribution. As a result, our CGLB database covers the 1943–2001 period and its temporal analysis was performed at individual solar latitudes, over arbitrary latitudinal zones, separately in the N and S solar hemispheres, and/or a daily index of the coronal activity of the Sun as a star was possible to derive. Suitable temporal averages and smoothings were taken to reduce noise.

To our opinion, the present CGLB database represents now the second longest set of data (after the sunspots) among synoptic indices of solar activity. Naturally, measurements of the CGLB obtained at individual coronal observatories were frequently spatially and temporarily analysed in the past from many points of view. Even if here is no space to summarize previous findings of all the authors still, the classical investigations of Trellis (1957), Waldmeier (1951, 1971) and Gnevyshev (1967, 1977) should be, at least, enumerated. Our older papers describing a number of aspects in large-scale and long-term distributions of coronal activity derived from analysis of the photometrically homogenized database could be also mentioned (Sýkora, 1971, 1980; Letfus and Sýkora, 1982). In the present paper, most of our previous results are up-to-dated and developed.

2. The CGLB large-scale and long-term variabilities

Temporal variations of the CGLB plotted separately for five latitudinal zones (two polar zones, two middle-latitude zones and one equatorial zone) almost equally wide in latitude disclose quite negligible contribution of extensive polar zones to the total CGL radiation coming from all the remaining zones (Fig. 1, left panel). This is mostly because of practical absence of the stronger local magnetic fields in the solar polar regions and, therefore, the absence of dense and hot coronal loops and loop clusters necessary for the coronal green line to be generated. Consequently, the solar cycle is poorly manifested in the polar zones, as well. Differences between the maximum and minimum CGLB values found within the individual five latitudinal zones, understandably, exhibit a degree of the CGLB variability within any of the zones. The highest level of the CGLB variability (proportional to the shaded area in the right panel of Fig. 1) is characteristic for the middle-latitude zones of both solar hemispheres. In addition, the course of the solar cycle curves is substantially different and considerably shifted if drawn for different latitudinal zones (Fig. 2). For example, the maxima of the cycles occur in the equatorial zone (±15°) for about 2–4 years later in comparison with those in the middle-latitude zones (20°–50°). Except of that, the maxima of the middle-latitude zones coincide much better with the solar cycle maxima

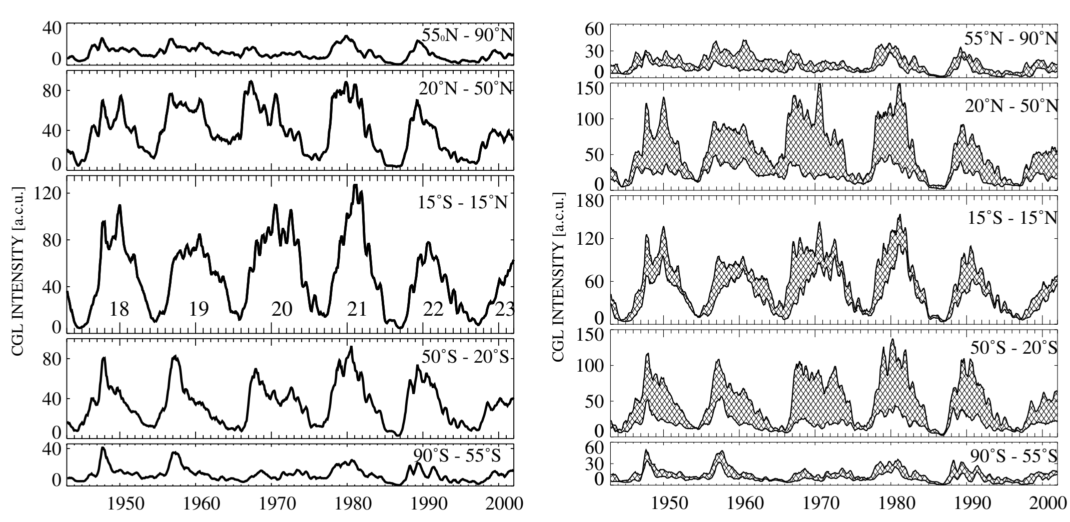

Fig. 1. Time variations of the half-yearly averaged CGL intensity plotted for five latitudinal zones and differences between the courses of the maximum and minimum intensity values found in the same zones are plotted in the left and right panels, respectively. Numbers of the solar cycles are indicated in the middle of the left panel, while the absolute coronal units (a.c.u.) are explained when describing Fig. 5 in the text.

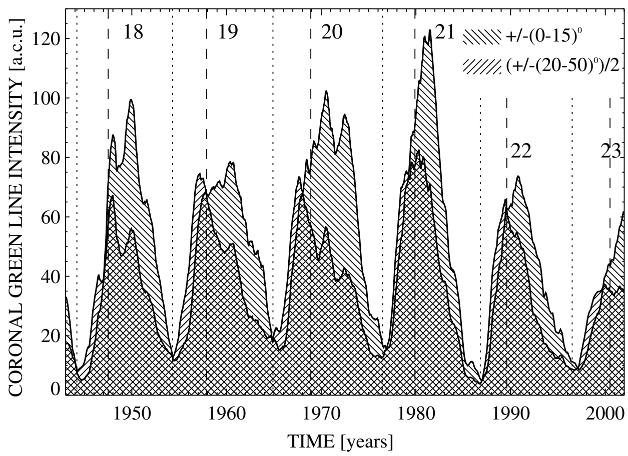

Fig. 2. Appearance of the solar cycle curves derived from the data of equatorial and middle-latitude zones is considerably different primarily as for time and height of their maxima. The vertical dashed and dotted lines represent maxima and minima of the sunspot solar cycles, respectively.

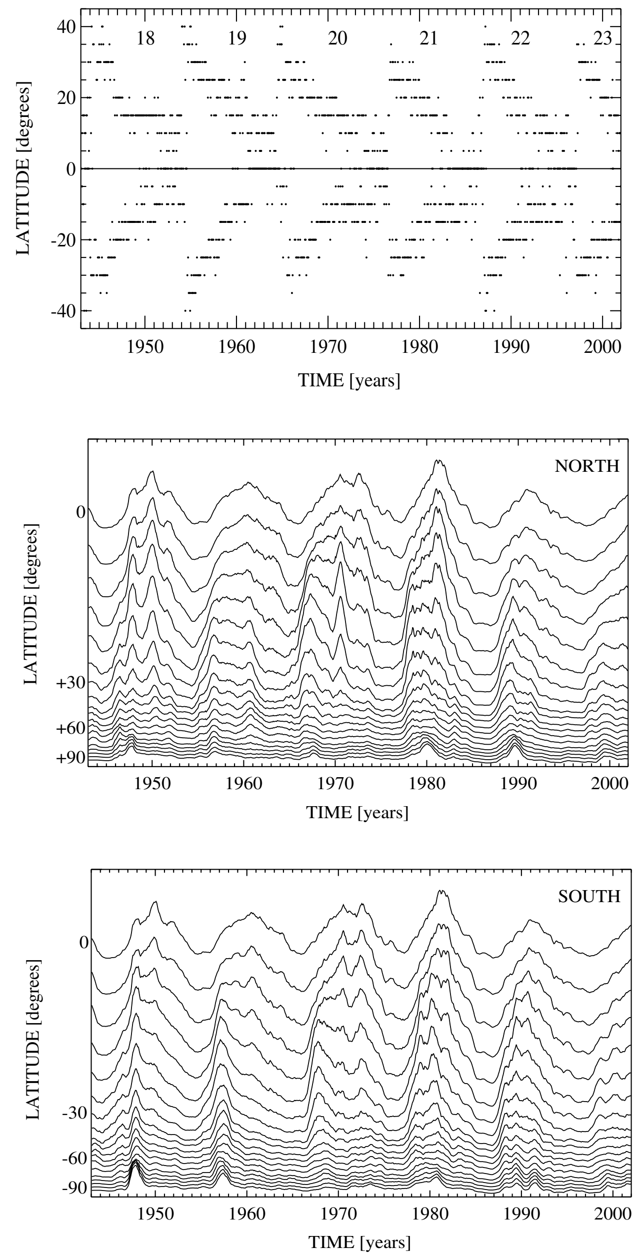

Fig. 3. The course of the CGLB intensity drawn separately for each 5° of solar latitude of the northern and southern hemispheres (two bottom panels). The zero levels of the different curves are not indicated. The latitudinal positions of the CGLB maxima found within the CGLB averages as calculated for each Carrington rotation at different latitudes are plotted in the top panel, displaying a gradual shift of coronal activity towards the equator throughout the solar cycles (the Spörer's law).

determined by sunspot number (see the vertical dashed lines in Fig. 2) than the cycle maxima in the equatorial zone do. The latter appears for 1.5–3.0 years after the sunspot cycle maxima.

As already mentioned, one of the most exceptional advantages of the CGLB measurements is their spatial resolution. The temporal CGLB variations may be drawn for the discrete latitudes (with the step of 5°). The lowest curves in two bottom panels (cf. solar hemispheres) of Fig. 3 demonstrate repeatedly very low coronal brightness in the polar regions and only slightly visible 11-year cycles in these zones. It seems that the phenomenon of double solar cycle maximum in the CGL intensity introduced by Gnevyshev and based primarily on the 19th cycle data (and the consequential "Gnevyshev gap" invented by other authors) can hardly be considered "an essential feature of each 11-year solar cycle" (Gnevyshev, 1977). However, the fact that the gap in the cycle curve does appear in 3 or 4 of the last six solar cycles might be worthy of investigation. Recently, Wang and Sheeley (2003) doubted physical reality of the "Gnevyshev gap" (cf. double maximum in the solar cycle curve). They conclude that stochastic processes provide a viable explanation for the "Gnevyshev gap" and for the existence of quasi-periodicities in the range of about 1–3 years. In the top panel of Fig. 3, a gradual shift of the CGLB maximum values (cf. coronal activity) from the higher latitudes to the equator (Spörer's law) is shown. Notice that no of the CGLB maximum values appear above ±40° during the solar cycles.

It is now well understood that the northern and southern solar hemispheres proceed somewhat independently. In the temporal variations of different solar activity indices a "discordance" in the phase and magnitude may last from months to several years. Unfortunately, even such basic theories and concepts of solar activity as the dynamo theory, theory of solar differential rotation and helioseismology are still not able to incorporate the indisputable observational fact of the N–S asymmetry of solar activity. In Fig. 4, we present the CGLB N–S asymmetry as calculated by a simple well-known relation $A = (N - S)/(N + S)$. It is evident that the N–S asymmetry of one sign may currently persist for as long time as several years. A clear prevalence

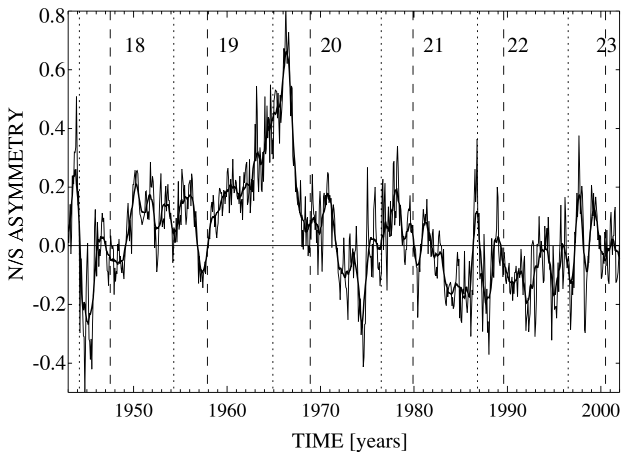

Fig. 4. The N–S asymmetry of the CGLB as calculated by a simple well-known relation $A = (N - S)/(N + S)$. The vertical dashed and dotted lines represent maxima and minima of the sunspot solar cycles, respectively.

of the northern hemisphere and a noticeable prevalence of the southern hemisphere are observed in the first and the second half of our graph, respectively, creating somewhat as a 45–50-years wave in the N–S asymmetry.

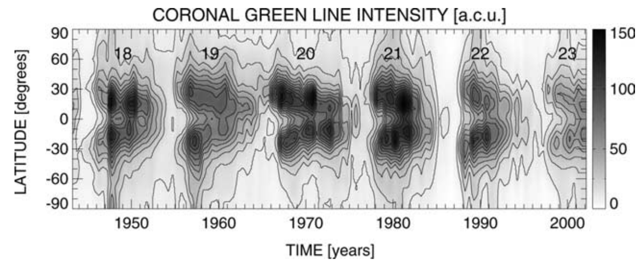

Fig. 5. Time–latitude distribution of the semi-annual CGLB averages displayed for the last five and a half solar cycles.

The highest positive N–S asymmetry was observed in the 1960s.

Contours of semi-annual CGLB averages are used to display its time–latitude distribution during the last five and a half solar cycles (Fig. 5). The isophotes are drawn with step of 10 absolute coronal units – a.c.u. (the units are millionths of the brightness of the solar disk centre at the given wavelength – in this case close to 530.3 nm). A completely non-uniform distribution of the CGL intensity over the sun's surface during solar cycles is evident. One can notice that the maxima of coronal brightness come from the large local regions situated

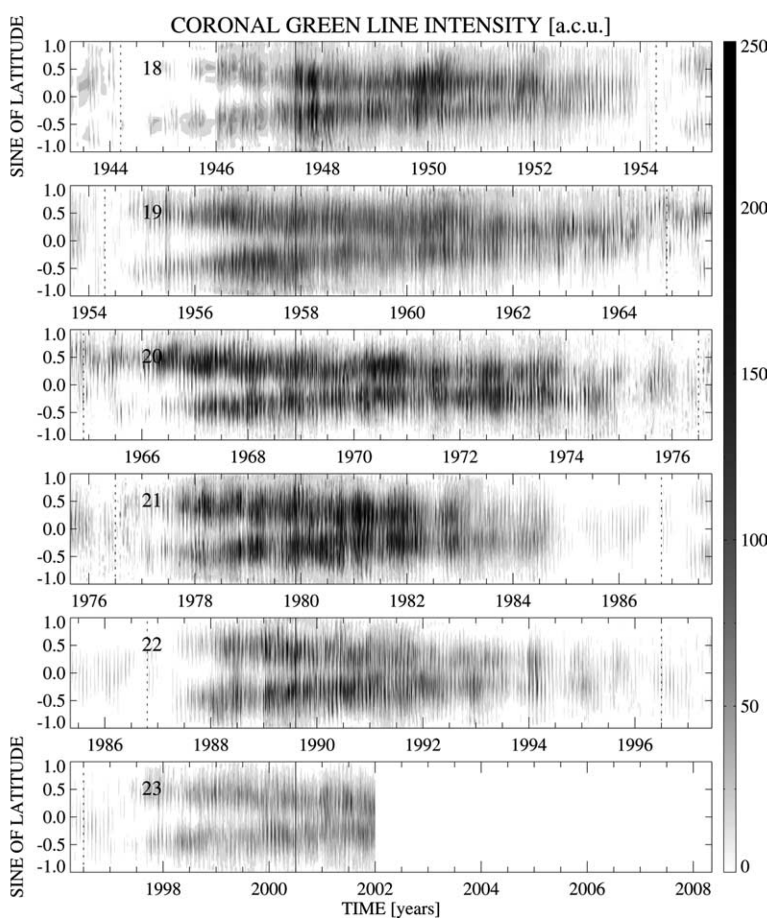

Fig. 6. Synoptic plot of the CGL intensity displayed separately for solar cycles 18–23. The vertical solid and dotted lines represent maxima and minima of the corresponding sunspot solar cycles, respectively.

in the middle heliographic latitudes. Those regions are, most probably, connected with the birth, development and decay of the so-called complexes of solar activity producing a series of active regions in discrete range of solar longitudes. Being the lifetime of active complexes about 1.5–2.0 years, their close relation with existence of the quasi-biennial oscillations may be suggested. Clearly visible are extensions of coronal activity to the poles around the time of solar cycle maxima. This may be due to known high inclination of the heliomagnetic equator with consideration to the heliographic equator and, thus, due to the common presence of coronal streamers close to the solar poles at the solar cycle maxima (e.g., Sýkora et al., 2003).

Fig. 6 shows a synoptic plot of the CGL intensity displayed separately for solar cycles 18–23. The cycles are aligned by the moments of the sunspot cycle maxima (see the vertical solid line in each cycle). The vertical dashed lines indicating the minima of sunspot cycles differ for as much as 2.5 years in different cycles. Smoothing by 3-day running mean was applied to the original data. The coronal activity associated with all the cycles is clearly visible, descending from approximately 35° of latitude to the equator. Sometimes (e.g., at the end of 19th cycle and beginning of the 20th cycle) macroscopic differences between the hemispheric activity are well expressed. Under the soft smoothing used in this figure, a fine regular pattern is clearly visible along the time (longitudinal) axis. This is coming from a discrete CGLB distribution within each individual Carrington rotation (on average, 13 tiny strips may be counted during each year in this graph). Such a pattern, in fact, undoubtedly demonstrates a permanent presence of ‘‘active longitudes’’ (ALs) in the inner corona.

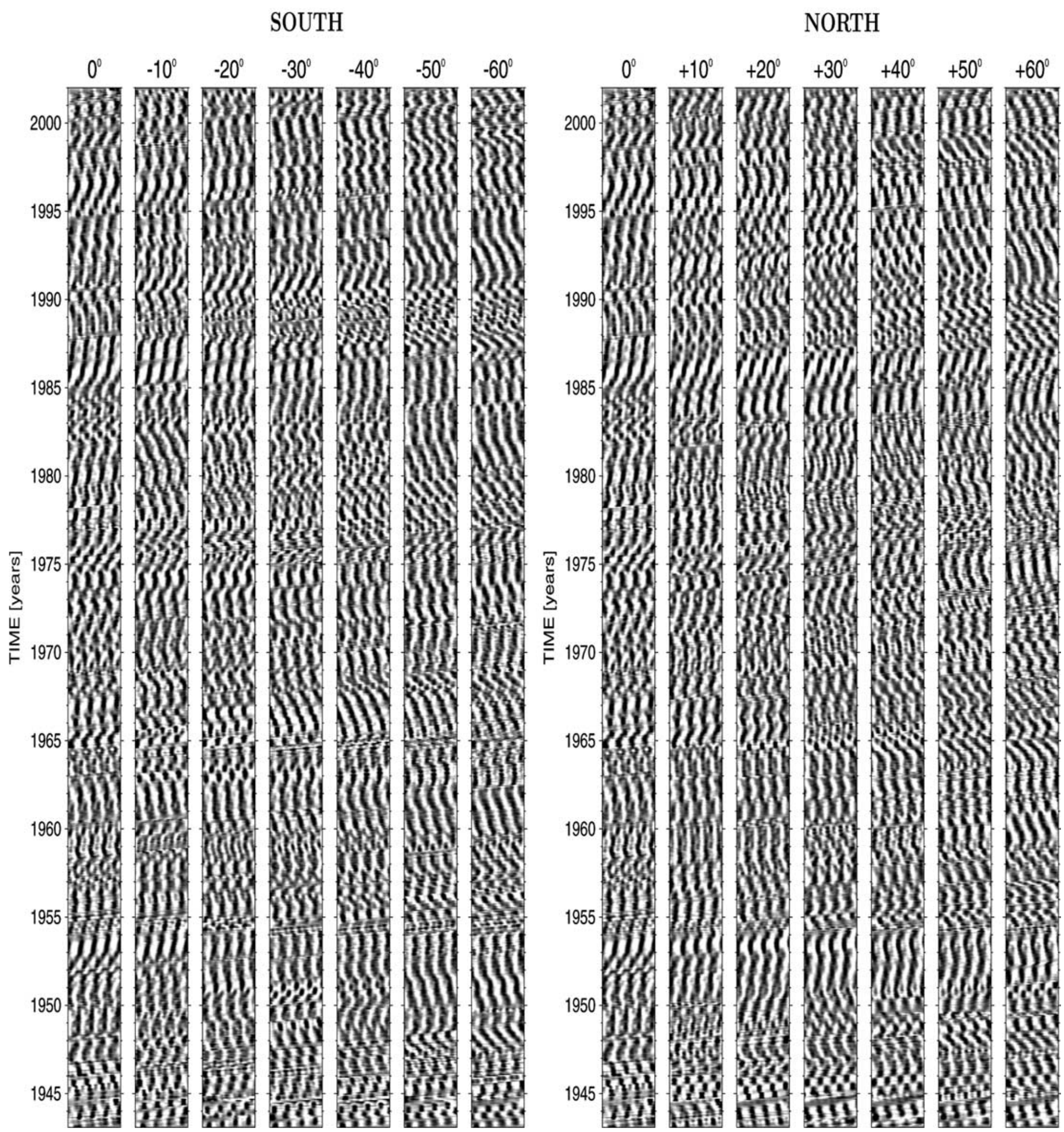

Fig. 7. The longitudinal CGLB distribution is plotted for discrete latitudes of the northern and southern hemispheres. The daily CGLB data are horizontally organized by four times repeated Carrington rotations. Time in the panels proceeds from the right to the left and upwards.

It should be mentioned, however, that a more detailed analysis performed, e.g., by Badalyan et al. (2005) often reveals incoherent appearance of the coronal ALs on both solar hemispheres. Readily, one can observe simultaneously 27- and 13-day periods of the antipodal ALs (usually, at the ascending phase of solar cycles). These are later replaced with the terms when both or only one of the 27- and 13-day ALs are present on the solar surface (mostly at the beginning of the descending cycle phase). Often they are not concurrent on both the solar hemispheres. Then, 2–3 years before solar minima a clear "intermittence" of the ALs takes place when the 27-day ALs are activated alternatively (with prorogation of 13 days) on the northern and southern solar hemispheres. To the end of the 11-year cycles the 27-day AL is present only, usually crossing solar equator.

A more impressive longitudinal CGLB distribution is presented in Fig. 7 for each 10° within ±60° of solar latitude. In fact, much more extensive set of these data are at our disposal, covering each 5° of latitude within the whole range of ±90°. In the horizontal direction, the daily data are organized by Carrington rotations and these are four times repeated to visualize better discrete and regular structuralism in the longitudinal CGLB distribution. A variable cycle-dependent component was removed from the data by applying a proper filtering.

The main recurrence characteristics are well manifested in Fig. 7. First of all, an expressive component of recurrent activity exists during the whole investigated period (1943–2001) independently of latitude and phase in the solar cycle. Secondly, the period of recurrence, indicated by inclinations of dark vertical streams, is quite variable and directly related to variability in the rotation and differential rotation of the CGLB tracers. Persistence (cf. lifetime) of features with a particular inclination lasts from a number of Carrington rotations to several years. Subsequently, a conversion to another regime of rotation takes place, etc.

The data and pattern of the longitudinal CGLB distribution as seen in Fig. 7 have been successfully used to study rotation of the inner solar corona quantitatively (Badalyan and Sýkora, 2005). It was found that the mean (i.e, averaged throughout the whole database) period of rotation increases from 27 days at the solar equator to slightly more than 29 days at the latitudes of ±40°, displaying much slower differentiation than majority of the solar photospheric phenomena do. At the latitudes from ±40° up to the polar regions, the rotation displays practically rigid character (i.e., independent of the latitude). A more detailed analysis revealed that rotation of the solar corona may be introduced by a superposition of two modes of rotation, the faster one rotating with the period of 27 days and displaying slight increase towards the higher latitudes and the slow mode rotating with the period of about 30.5 days. Badalyan and Sýkora (2005) have shown also that the observed total dependence of coronal rotation on the solar latitude may be well explained by a combination of the two above modes.

3. Conclusions

The study in this paper has been concerned with the large-scale space–time distribution of the coronal green-line brightness on time scales greater than a solar rotation up to a few solar cycles. We have found the CGLB data very appropriate for this kind of investigation mostly because its synoptic character (the CGLB daily data covering more than five solar cycles was at our disposal). Almost simultaneous registration of the CGLB index at all solar latitudes allowed to reveal substantial differences in behaviour, regularities and the CGLB evolution within the equatorial, middle-latitude and polar sun's zones. Namely, the middle-latitude zones at both solar hemispheres exhibit the largest CGLB variability (cf. activity), thus being perhaps the most relevant in active processes within the space weather. Inspection of the longitudinal CGLB distribution gives good indications of organization the CGLB activity (and, probably, of the total solar activity) within a framework of "active longitudes" lasting from a few solar rotations up to several years. We wish to accentuate once more an indisputable convenience of the CGLB data for investigation of such crucial problems of the sun's body and the cyclic nature of active processes on it as they are the solar rotation and differential rotation and the north/south asymmetry. Unfortunately, here we could touch only these questions. More details may be found in our topical studies quoted above.

Acknowledgement

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