Intensity variations of the solar corona over 4.5 solar activity cycles

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Abstract. The large-scale and long-term intensity variations of the green emission line corona FeXIV 530.3 nm over the 4.5 solar activity cycles are presented. Difficulties of putting the data of different observatories to the common photometric scale are discussed. Analysis of variability and periodicity of the coronal brightness in the separated belts of the heliographic latitudes seems to be very useful when studying responses of the solar activity in the heliosphere and geoactivity.

Key words: corona of the Sun

1. Introduction

In the last two decades it has become quite evident that the solar corona does not represent the periphery of the sun. The discovery of coronal holes and coronal mass ejections has made this layer of the solar atmosphere the centre of interest of solar physicist as well as of specialists in solar wind, cosmic rays and solar-terrestrial relationship studies. The large-scale and long-term distribution of coronal strucrures, as well as their short-term dynamics, on the one hand, directly reflect the development and organization of the magnetic and velocity fields in the lower layers of the solar atmosphere but, on the other, they fully determine the physical state of the heliosphere and interplanetary magnetic field.

Basically, there are three ways of observing the solar corona: (a) during the short intervals of total solar eclipses, (b) by coronagraphs located at the high-altitude observatories and, (c) by means of the cosmic technique, where Skylab, Solar Maximum Mission and Yohkoh are the most prominent examples. Any of the types of observation named has its own advantages and shortages, but each is in some way unique.

In this paper we mainly take advantage of the fact that the patrol coronagraph measurements of solar corona intensity in the FeXIV 530.3 nm emission

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spectral line have been performed systematically for a long time. This allows us to present the pattern of coronal radiation over the last 4.5 solar cycles. We believe that these data may be useful as inputs in some studies of the heliosphere and solar-terrestrial relations.

2. Observations

The coronagraph, designed and constructed by B. Lyot (1930, 1931), makes it possible to observe the solar corona outside the relatively seldom total solar eclipses. With regard to the low intensity of the emission corona as compared to the brightness of the solar disk, it was necessary to ensure, above all, two things: firstly, to establish coronal observatories high in the mountains, where the intensity of the light scattered by the dust particles in the Earth's atmosphere, is already sufficiently low (not exceeding 10^{-4} of the brightness of the solar disk) and, secondly, to design the coronagraph so that the scattered light in the instrument itself is restricted to minimum. The second condition is still more a matter of the craftsmanship than of science.

Regular observations with the Lyot coronagraph began at Pic du Midi (2866 m a.s.l.) in 1943. Currently, the intensity of the solar corona is being measured in the three most intensive emission lines in the optical part of spectrum - FeXIV 530.3 nm (green line), FeX 637.4 nm (red line) and CaXV 569.4 nm (yellow line). The instrument, method of observation and the results obtained between 1943 and 1955 are described in detail by Trellis (1957).

In this connection some significant advantages of the green line observations should be mentioned. First of all, the green corona can be measured during each observation. This is not, for example, the case of the yellow line corona which radiates only when very hot and active regions are present near the sun's limb. At the same time, the green corona line also reflects activity very well, because its intensity is proportional to the density as well as to the temperature of the medium in which this line originates. Both the parameters mentioned are considerably higher in active regions and in the periods of maxima of the solar cycles than in the quiescent solar regions and during minima of the 11-year activity cycles. The red line behaves quite differently. The intensity of this line changes little with the solar cycle, and is "insensitive" to solar activity. Its intensity increases with density but decreases with temperature. However, the coronal density and temperature are not physically independent quantities, they vary in roughly the same way - the higher the density, the higher the temperature. That is why the increase of both these parameters in the solar active regions can more or less nullify their common influence on the intesity of the red line. Besides, solar activity is better expressed by the green line corona than by the white-light corona observed in the continuum. The white-light corona can also be measured by coronagraphs regularly, for example, at Mauna Loa, Hawaii. We have found (Sýkora,1980) that the solar cycle maximum/minimum ratio of the green corona brightness goes to about 10 on the average, while the same ratio in case of the white-light corona was found to be only 2.0-2.5 (Hansen et al., 1969).

More than 20 years after observations were begun at Pic du Midi, a small world-wide network of the coronal stations was established. The following observatories gradually joined it: Arosa (1947-1975), Climax (1947-1957), Wendelstein (1947-1979), Kanzelhöhe (1948-1964), Norikura (1951-present), Sacramento Peak (1953-1966), Kislovodsk (1957-present), Alma Ata (1957-1962, 1973-present), Lomnický Štít (1966-present), Ulan Bator (1971-1973). The Pic du Midi Observatory terminated its observations in 1974. The time intervals in the parentheses indicate when the measured data were published in numerical form in the Quarterly Bulletin on Solar Activity. The Sacramento Peak Observatory re-instaled its observations in 1973. Its very fruitful data are now published in graphical form and in the form of synoptic charts in the Solar-Geophysical Data bulletin (Altrock, 1990).

The coronal emission line intensities are measured at intervals of five degrees around the sun's disk, beginning at the north pole through to the east, south and west limbs. The intensities are (usually) expressed in absolute coronal units, i.e. in millionths of the energy radiated from the centre of the sun's disk in 0.1 nm strip of the spectrum near the corona emission line. Thus, to obtain a large-scale picture characterizing the intensity of the corona around the solar disk as a whole, spectral measurements have to be made at 72 points. It takes about half an hour to record the photographic spectra at these points, and it takes almost a whole day to derive the final intensities by applying modified method of classical photometry.

Unfortunately, the methods of observation and measurement of coronal intensities were not identical at the various coronal observatories throughout the history of the green corona measurements. For example, visual, radial-slit photographic, circular-slit photographic and photoelectric methods of observation have been used. Furthermore, the heights above the sun's limb, at which observations were made, were not the same either. They varied between 40 and 60 secons of arc at different observatories. Even the units used to express the value of intensity of the green emission corona were not the same; they were absolute and arbitrary.

For most of the studies of the large-scale and long-term behaviour of the solar corona it is quite insufficient to use the data of only one coronal observatory. Owing mainly to weather conditions, the data of one observatory are usually less numerous (they cover, on the average, only 40 to 150 days per year). The gaps in observations are so large that about 10 observations per month can in no way be considered representative and, for example, no comprehensive synoptic charts can be effectively constructed from them. That is why, in most studies, it is appropriate to use as much data as possible from all the observatories. At this moment, however, the very serious problem connected with the homogeneity of measurements at different observatories arises.

3. The problems of the summary use of the solar corona measurements

It seems that at present only the Sacramento Peak Observatory has sufficiently numerous observations of the corona that an individual approach to the analysis of its own data is justified. From the point of view of other observatories the prompt exchange of data and their subsequent summary analysis was and is still attractive. For the whole scientific community such data are available in the Quarterly Bulletin on Solar Activity published by Eidgenösische Sternwarte Zürich (till 1976) and by the Tokyo Astronomical Observatory (as of 1977).

However, it is a known fact that there exist several systematic errors (differences) between the data of different coronal observatories due to instrumental differences and due to different methods used to reduce the raw measurements. It has been found that, at least, the differences and instability of photometric scales, systematic errors in the linearity of the position angle scales, position of the zero points of those scales and different tresholds of measurements at different observatories should be eliminated when the data are being compiled and treated together (Sýkora, 1971).

In 1967 a consultation was held at Pic du Midi on the normalization of coronal measurements. The aim was to analyse and estimate the above-mentioned errors and to approve some recommendations for coronal stations and the users of coronal data (Trans. IAU XIIIB, 1968). Unfortunately, at the second consultation of this type (held in Leningrad, 1991) it was necessary to state that the recommendations had still not been realised. Moreover, further discrepancies occured (see the next text and Figure 1), their origin being mainly in the changes of technical details of observation at different observatories.

One of the approaches to the summary use of coronal data was that all the original data from QBSA were reduced to the photometric scale of Pic du Midi since the longest, most homogeneous and extensive set of measurements was available from this observatory. The "Atlas of the green corona synoptic charts" was published (Letfus and Sýkora, 1982) and many interesting results related to variability, periodicity and rotation of the green emission corona were obtained from those data (Sýkora, 1980).

We have estimated that for the purpose of this paper it is sufficient to exploit the data of three most productive observatories only - Pic du Midi, Kislovodsk and Norikura - in the interest of diminishing the necessary reductions resulting from the summary use of the data. The following procedure was applied to provide as homogeneous set of data as possible, characterizing the green corona brightness in the period 1943-1991 and showing its large-scale distribution over the solar surface.

The average coronal intensities I for the semi-annual periods were calculated separately for each position angle from the original data of mentioned three observatories. The coronal measurements are regulaely performed in step of

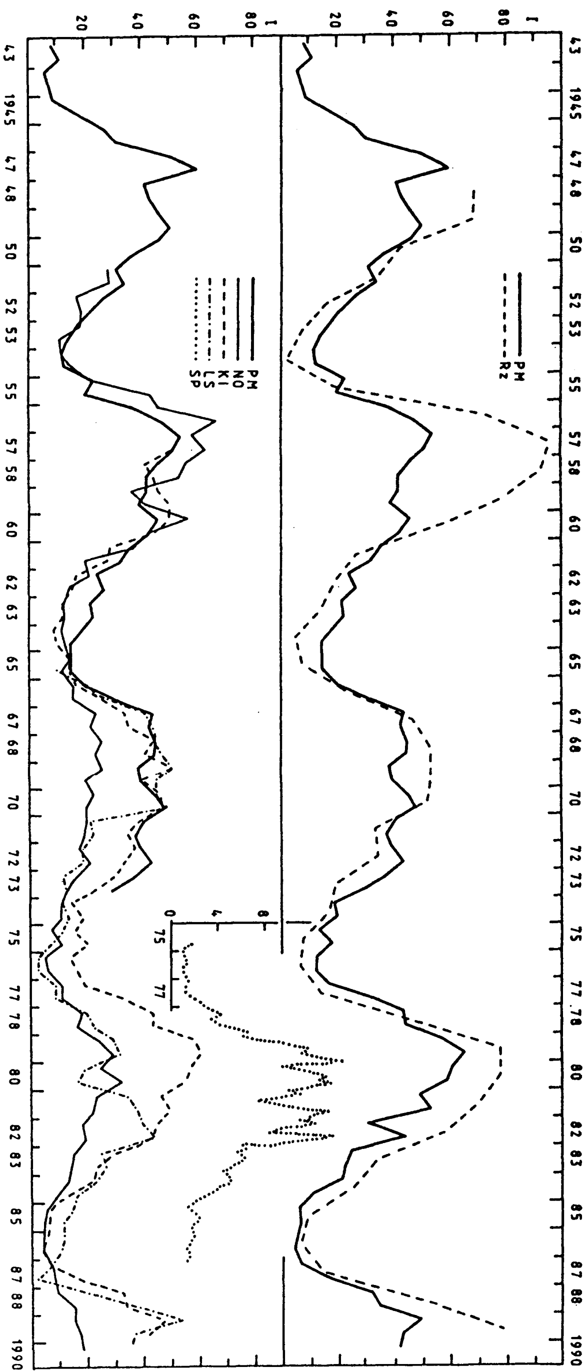

Figure 1. Time variation of the semi-annual averaged green corona intensity as observed at various coronal observatories.

five degrees around the sun's disk, i.e. 72 values were obtained in each half-year. Subsequently, these values were then used to calculate the averaged semi-annual values for the whole limb, characterizing the coronal activity of the sun as a star. To obtain data for a given latitudinal interval the values both from east and west limbs were taken into account.

The original Pic du Midi measurements (PM) were used only to cover the period 1943-1973 in the interest of maximum homogeneity of the resulting data. Unfortunately, PM finished its green corona patrol observations in 1974. Therefore, to get the extended and up-to-dated series of data on the same photometric scale it was necessary to utilize the measurements of other coronal observatories. After analysing the data and after applying the corrections relating to the summary use of the existing corona measurements (as described in Sýkora, 1971), it was found best to use the data of the Kislovodsk Observatory (KI) and Norikura Observatory (NO) to complement the data set. The PM and KI data were correlated for the period 1957-1973 and PM and NO data for the period 1965-1973 when measurements were being made simultaneously at three the observatories and, as we believe, no changes in their photometric scales took place over the shown periods. Linear relations have been found for transforming the later data (1974-1991) of Kislovodsk and Norikura to the previous scale of Pic du Midi to maintain (as far as possible) unuformity of the photometric scale throughout the whole data set (1943-1991).

We re-iterate that for the simple purpose of this study - i.e. to present a representative large-scale and long-term set of data on green corona radiation - it was quite sufficient to restrict ourselves to the measurements of the PM, KI and NO (after 1965) observatories. Inter alia, this was also substantiated by the fact that, for example, the linearity of the photometric scales of some other observatories were questionable throughout some periods of the whole time interval (1965, 1970-71, 1981-82) - one of them discussed by Sýkora (1983). On the other hand such discrepancies in the photometric scales can be removed , and homogeneous data can be derived if indeed necessary, i.e. when it is convenient to compile all the existing coronal measurements (for example, to plot coronal synoptic charts and to perform similar tasks, when data for each day, or even more than one observation per day are necessary). By other words, to exploit the summary data of all the observatories is very suitable when details of their reduction are well known to the person who compile them.

4. The semi-annual coronal intensities as derived from measurements of the FeXIV 530.3 nm spectral line

All the objectives of this study are condensed in Figures 1 and 2 and in Table 1.

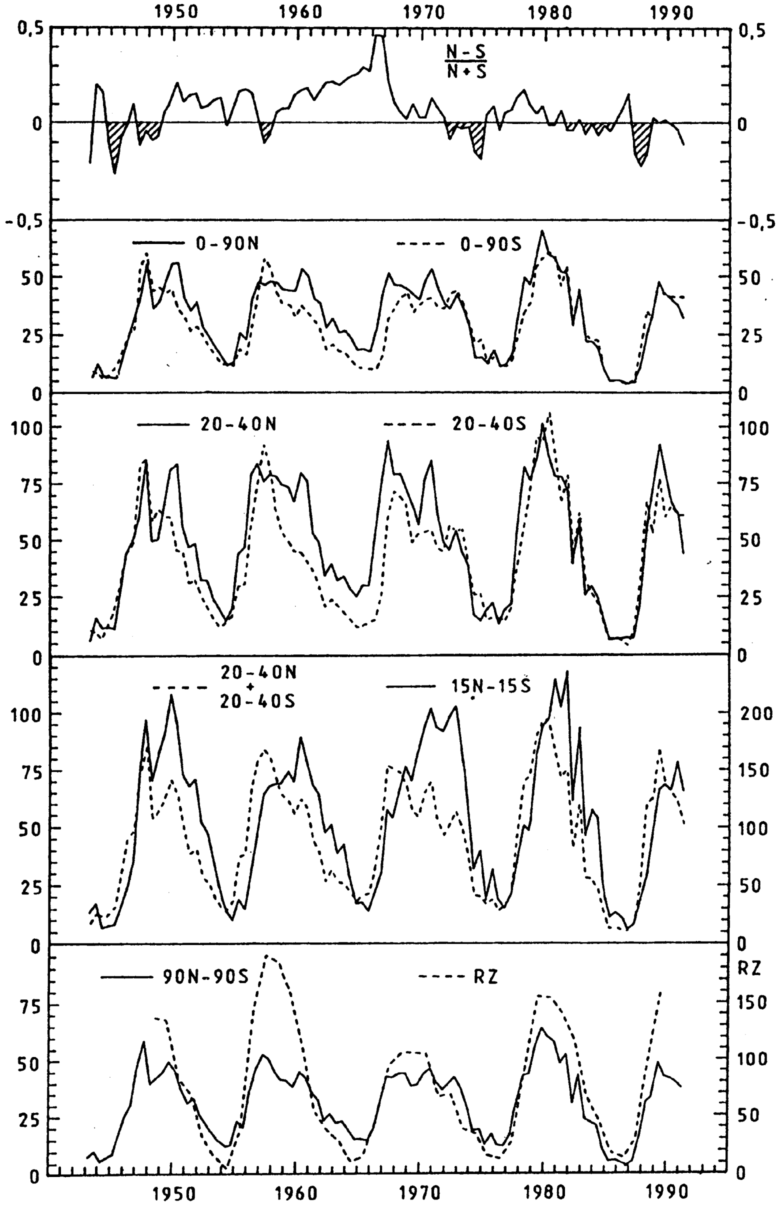

Figure 2. Time variation of the green corona intensity for the chosen zones of heliographic latitudes. The scales express intensities per five degrees of latitude in a given zone. The Zürich sunspot number is plotted in the lower part of the figure for comparison, and the upper part shows the north-south asymmetry calculated from the 0-90N and 0-90S data.

Table 1. The semi-annual averaged coronal intensities as measured in FeXIV 530.3 nm spectral line. The data are expressed in the photometric scale of Pic du Midi coronal observatory and calculated per 5° of the shown latitudinal interval (in the 5th column obtained from both the shown intervals).

Half-year	40N-20N	15N-15S	20S-40S	40N-20N 20S-40S	0-90N	0-90S	90N-90S
43-1	5.6	12.9	10.8	16.4	6.2	9.5	7.7
43-2	16.0	17.0	9.4	25.4	12.5	8.2	10.2
44-1	11.6	6.6	6.4	18.0	6.9	4.9	5.8
44-2	11.6	7.6	13.4	25.0	6.6	8.1	7.4
45-1	10.8	8.0	19.8	30.6	6.1	10.5	8.3
45-2	28.0	16.3	32.4	60.4	15.7	18.2	17.1
46-1	44.8	24.3	44.4	89.2	24.8	25.4	25.4
46-2	50.6	35.4	47.4	98.0	33.4	27.0	30.4
47-1	61.8	74.7	83.0	144.8	43.0	54.6	48.8
47-2	86.2	97.1	86.0	172.2	55.9	60.3	58.9
48-1	49.4	69.8	58.0	107.4	36.5	43.8	39.8
48-2	50.0	81.8	63.6	113.6	39.9	45.5	42.2
49-1	64.4	91.0	60.8	125.2	48.6	42.9	44.9
49-2	81.4	108.7	60.2	141.6	55.9	44.7	49.3
50-1	83.8	95.1	45.2	129.0	56.4	36.4	45.3
50-2	55.4	73.1	45.2	100.6	41.5	33.2	36.7
51-1	46.4	67.8	30.8	77.2	35.8	26.9	30.8
51-2	48.6	71.0	32.4	81.0	39.6	28.7	33.4
52-1	32.2	52.4	25.8	58.0	29.0	24.7	26.1
52-2	32.2	47.3	20.2	52.4	24.0	19.9	21.3
53-1	24.0	35.8	15.6	39.6	20.6	16.1	17.9
53-2	19.4	22.1	11.8	31.2	15.9	12.1	13.8
54-1	14.4	14.1	13.4	27.8	12.1	12.5	12.2
54-2	20.2	10.0	16.8	37.0	13.4	11.4	12.5
55-1	43.8	19.3	29.8	73.6	26.5	18.9	22.9
55-2	46.8	14.6	30.2	77.0	23.1	16.1	19.9
56-1	78.8	29.7	56.2	135.0	41.2	29.7	35.9
56-2	83.8	45.4	74.2	158.0	48.1	43.4	46.2
57-1	75.8	63.7	92.2	168.0	46.9	58.0	52.8
57-2	78.6	67.7	82.6	161.2	48.2	54.1	51.2
58-1	78.4	69.0	63.6	142.0	47.9	42.7	45.1
58-2	74.4	69.1	53.2	127.6	44.8	38.4	41.3
59-1	73.4	74.3	49.4	122.8	44.5	38.2	40.7
59-2	66.6	69.7	44.6	111.2	44.3	32.6	37.9
60-1	79.8	90.1	44.8	124.6	54.2	37.9	45.1
60-2	76.6	79.4	40.6	117.2	51.3	35.1	42.5

Table 1. - continued

Half-year	40N-20N	15N-15S	20S-40S	40N-20N 20S-40S	0-90N	0-90S	90N-90S
61-1	52.4	68.3	36.2	88.6	40.9	31.9	35.8
61-2	49.0	64.0	29.4	78.4	39.3	27.8	32.8
62-1	33.4	47.3	20.2	53.6	28.6	18.5	23.2
62-2	39.6	51.1	23.8	63.4	32.8	21.1	26.3
63-1	31.8	38.4	21.0	52.8	26.5	18.1	22.0
63-2	33.8	42.3	17.6	51.4	27.7	17.4	22.8
64-1	28.4	28.1	15.0	43.4	24.2	14.6	19.1
64-2	24.8	16.8	11.6	36.4	18.9	11.2	15.0
65-1	30.0	17.6	11.6	41.6	19.6	10.7	15.2
65-2	29.4	13.6	13.8	43.2	18.2	10.5	14.4
66-1	50.2	21.6	14.8	65.0	27.8	10.2	19.1
66-2	76.4	30.0	25.2	101.6	43.7	16.3	30.2
67-1	94.0	57.4	60.0	154.0	52.4	33.4	43.1
67-2	79.0	53.4	71.6	150.6	46.8	37.3	42.3
68-1	79.2	66.3	69.2	148.4	46.5	41.5	44.0
68-2	72.8	76.6	65.4	138.2	45.5	43.7	44.3
69-1	65.4	69.6	48.6	114.0	42.8	34.8	38.4
69-2	56.6	82.7	52.4	109.0	40.8	38.4	38.9
70-1	77.0	93.4	53.0	130.0	49.6	40.5	44.2
70-2	85.2	102.0	54.4	139.6	54.3	41.1	46.7
71-1	62.2	93.6	46.0	108.2	46.1	37.1	40.3
71-2	48.8	91.4	44.4	93.2	39.2	36.8	36.8
72-1	45.0	97.7	56.2	101.2	36.6	43.2	39.3
72-2	54.4	103.0	59.4	113.8	43.2	44.8	42.5
73-1	44.8	85.0	54.6	99.4	37.8	39.9	37.7
73-2	38.4	60.6	38.0	76.4	29.6	30.7	29.6
74-1	17.0	31.4	25.4	42.4	16.0	21.7	18.6
74-2	14.4	39.6	26.4	40.8	16.2	23.8	19.6
75-1	19.0	17.9	14.6	33.6	13.6	12.4	12.9
75-2	22.6	32.1	15.8	38.4	19.5	16.2	17.4
76-1	12.6	18.3	14.2	26.8	11.9	12.8	12.1
76-2	19.2	14.7	14.2	33.4	12.6	11.2	11.9
77-1	22.0	20.6	20.0	42.0	17.5	15.1	16.3
77-2	55.2	34.7	39.8	95.0	35.4	26.5	31.0
78-1	82.4	50.9	57.2	139.6	50.7	35.4	43.1
78-2	76.4	48.0	71.0	147.4	47.3	39.1	43.5
79-1	85.0	79.3	95.6	180.6	59.5	54.0	56.5
79-2	101.6	93.3	92.6	194.2	70.7	58.6	64.4

Table 1. - continued

Half-year	40N-20N	15N-15S	20S-40S	40N-20N 20S-40S	0-90N	0-90S	90N-90S
80-1	87.2	96.6	106.2	193.4	60.3	61.1	60.1
80-2	78.2	114.6	87.8	166.0	58.7	59.9	58.3
81-1	78.0	101.9	65.8	143.8	52.8	45.9	48.4
81-2	72.0	117.9	78.8	150.8	52.1	55.8	52.6
82-1	39.0	60.4	43.0	82.0	29.4	31.8	30.0
82-2	57.6	93.9	62.0	119.6	45.7	43.5	43.4
83-1	25.4	44.9	31.8	57.2	22.9	25.9	24.0
83-2	29.8	57.0	26.2	56.0	22.9	23.1	21.9
84-1	25.0	53.6	22.0	47.0	20.4	23.3	20.8
84-2	14.8	22.6	12.4	27.2	10.9	11.1	10.5
85-1	6.0	11.0	6.8	12.8	5.5	6.0	5.6
85-2	7.0	12.9	7.2	14.2	6.2	6.0	5.9
86-1	6.6	10.9	5.0	11.6	5.4	4.6	4.8
86-2	7.0	5.6	3.8	10.8	4.4	3.2	3.7
87-1	6.6	8.0	11.4	18.0	5.1	7.1	6.1
87-2	20.4	18.1	34.2	54.6	12.1	19.2	15.7
88-1	53.8	28.1	66.4	120.2	25.9	35.6	31.1
88-2	73.0	46.0	52.0	125.0	34.7	32.7	33.7
89-1	92.6	65.7	76.8	169.4	48.6	48.9	48.8
89-2	79.4	68.1	59.4	138.8	43.6	42.3	42.3
90-1	66.0	65.6	64.8	130.8	41.1	41.6	41.3
90-2	62.0	78.6	60.4	122.4	39.0	41.8	39.5
91-1	42.8	64.7	60.2	103.0	32.7	41.4	36.6

The north-south asymmetry is presented separately in Table 2. Figure 1 shows the time variation of the semi-annual averaged green corona intensities at four coronal observatories with the longest continuous series of measurements - Pic du Midi (PM), Norikura (NO), Kislovodsk (KI) and Lomnický Štít (LS). The intensities (see the ordinate) measured at the individual observatories are expressed on their own photometric scales. The pronounced differences of the intensity ratios between the observatories are evident, as well as the instability of these ratios in time, related to the instability of the photometric scales at one or the other observatory. To estimate better the inconsistent situation in the 21st solar cycle the data of Sacramento Peak taken from Altrock (1990) have been added in the form of 27-day averages. The homogeneized set of the green emission corona FeXIV 530.3 nm intensities, expressed on the PM scale, is presented in the upper part of Figure 1. We believe that this curve can be

Table 2. The north-south asymmetry as derived from brigtness of the the green emission line FeXIV 530.3 nm corona

Half-year	N-S/N+S	Half-year	N-S/N+S	Half-year	N-S/N+S
43-1	−0.210	59-1	+0.076	75-1	+0.046
43-2	+0.208	59-2	+0.152	75-2	+0.092
44-1	+0.169	60-1	+0.177	76-1	−0.036
44-2	−0.102	60-2	+0.188	76-2	+0.059
45-1	−0.265	61-1	+0.124	77-1	+0.074
45-2	−0.074	61-2	+0.171	77-2	+0.144
46-1	−0.012	62-1	+0.214	78-1	+0.178
46-2	+0.106	62-2	+0.217	78-2	+0.095
47-1	−0.119	63-1	+0.200	79-1	+0.048
47-2	−0.038	63-2	+0.228	79-2	+0.094
48-1	−0.091	64-1	+0.247	80-1	−0.007
48-2	−0.066	64-2	+0.256	80-2	−0.010
49-1	+0.062	65-1	+0.294	81-1	+0.070
49-2	+0.111	65-2	+0.268	81-2	−0.034
50-1	+0.216	66-1	+0.463	82-1	−0.039
50-2	+0.111	66-2	+0.457	82-2	+0.025
51-1	+0.145	67-1	+0.221	83-1	−0.061
51-2	+0.160	67-2	+0.113	83-2	−0.004
52-1	+0.080	68-1	+0.057	84-1	−0.066
52-2	+0.093	68-2	+0.020	84-2	−0.009
53-1	+0.123	69-1	+0.103	85-1	−0.043
53-2	+0.136	69-2	+0.030	85-2	+0.016
54-1	−0.016	70-1	+0.025	86-1	+0.080
54-2	+0.081	70-2	+0.138	86-2	+0.158
55-1	+0.167	71-1	+0.084	87-1	−0.164
55-2	+0.179	71-2	+0.032	87-2	−0.227
56-1	+0.161	72-1	−0.083	88-1	−0.158
56-2	+0.051	72-2	−0.018	88-2	+0.030
57-1	−0.106	73-1	−0.027	89-1	−0.003
57-2	−0.058	73-2	−0.018	89-2	+0.015
58-1	+0.057	74-1	−0.151	90-1	−0.006
58-2	+0.077	74-2	−0.190	90-2	−0.035
				91-1	−0.117

considered sufficiently representative when comparing the green corona brightness with other large-scale and long-term indices of solar and heliospheric activity (the curve in terms of absolute coronal units is given in the 8th column of Table 1). The sunspot number curve Rz is also presented in the upper part of Figure 1 for comparison.

Figure 2 shows the time variation of the green corona intensity for the separated belts of heliographic latitude. This kind of presentation seems reasonable for distinguishing coronal relations to some specific properties of the heliosphere and of solar-terrestrial relations. The PM scale has again been used in Figure 2, however, the ordinates represent the semi-annual intensities averaged per 5 degrees of position angle in a given latitudinal interval. The north-south asymmetry N-S/N+S (calculated from the 0-90N and 0-90S data) is also shown. We do not to wish to analyse the N/S asymmetry in this paper. We should only like to draw attention to the surprising fact of a pronounced N/S asymmetry in the decisive part of the whole 1943-91 period. Particularly during 1949-71 there should be some remarkable response of it in the heliosphere. Distinct differences of the increasing phase of the solar corona cycles as seen in the equatorial and higher-latitude zones (the second part of the figure from below) and their responses in cosmic-ray modulation are partly discussed by Parisi et al. (1992). The data of Figure 2 are given in Tables 1 and 2.

Data similar to those presented in this paper have been published by Kulčár et al. (1990) for the period 1947-1976. Moreover, the referenced paper gives the monthly averaged data thanks to the basic work carried out in preparing Atlas of green corona synoptic charts (Letfus and Sýkora, 1982). To insist on monthly data for the last 15 years, would be a little unrealistic and hardly justified owing mainly to the time-consuming quantity of work that would be required to reduce the existing daily measurements to a common photometric scale. We are of opinion that the semi-annual values are sufficient for a large number of studies of large-scale and long-termed manifestations in the solar corona. If the computer requires a higher data density to correlate the solar corona with the features observed in the heliosphere, it would seem simple to obtain, for example, the monthly data by interpolation. We are convinced that the final result would be influenced but little.

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