Cosmic ray/Soft X-ray background relationship from July 1968 to June 1987

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Abstract. The cross–correlation technique has been applied to obtain quantitative information on the short-term relation between the intensity of the nucleonic component of galactic cosmic rays (CR), as recorded by the Calgary neutron monitor, and the solar soft X-ray background (XBG), measured by satellites. The data consisted of uninterrupted daily sequences from July 1968 to June 1987. Using the 12-month basic (b_i), detrended (d_i), the running mean ($m_i(n)$) and the residual sequences ($r_i(n)$), where $n = 3, 7, 15, 27$ days and $i = 1, ..., 19$, the consecutive CR/XBG cross-correlation functions (ccf-s) were computed with a time lag ranging from - 2 to + 60 days. In 13 cases out of the 19 d_i sequences, a statistically significant anticorrelation was found in the first minimum (for a lag shorter than or equal to 10 days). The m_i and the r_i sequences helped to identify fluctuations on different time scales. In Jakimiec, Antalová and Storini (1999) results for the period July 1968–June 1980 were used to underline differences and analogies between the descending phase of solar activity cycle n. 20 and the ascending phase of solar activity cycle n. 21, i.e., one complete heliomagnetic semicycle. Here we mainly compared the relationship between both parameters during two consecutive descending phases of cycle n. 20 with the one of cycle n. 21.

Key words: the Sun - nonflare (XBG) soft X-ray flux - galactic cosmic rays

1. Introduction

The intensity of the galactic cosmic–ray (CR) flux, as measured by ground–based cosmic–ray detectors, is affected by different forms of solar activity. More precisely, the charged particle flux is modulated by Coronal Mass Ejection–(CME) and coronal hole–induced perturbations travelling in the inner interplanetary medium. In particular, it is of great interest to correlate the CR–modulation phenomena with CME occurrence, which should be responsible for interplanetary shocks and ejecta structures (e.g., Gosling and Hundhausen, 1995; Schwenn, 1996 among others). Unfortunately, CME and coronal hole homogeneous data is not available for a long time interval and proxy data are needed for any detailed study on the topic.

Storini, Antalová and Jakimiec (1995), investigating CR–modulation and solar soft X-ray parameters during the time interval July 1988 – June 1989, observed a progressive increase of the base–line levels of the full-disk X-ray background (XBG) correlated with a series of long–duration X-ray flare events and they concluded that the XBG values could reflect the large–scale coronal variations occurring during the solar activity cycle (Feminella and Storini, 1997; Storini, Massetti and Antalová, 1997). More recently, SOHO–EIT and LASCO observations have demonstrated the existence of transient coronal waves, the so called EIT waves (Delannée and Aulanier, 1999; Hudson, 1999) similar to the well–known chromospheric Moreton waves (Moreton and Ramsey, 1960; Ellison et al., 1960; Smith and Harvey, 1971 among others), propagating away from a flare site, leading to large-scale instability of the solar corona (see, for instance, Harrison, 1996; Lyons and Simnett, 1999; Thompson et al., 1999). Taking into account the above considerations, here we investigated the relationship between the galactic CR flux (as derived from the daily intensity of the nucleonic component registered by the Calgary neutron monitor) and the daily global soft X-ray flux of the non–flaring solar corona (i.e., the solar soft X-ray background; hereafter – XBG) for about 1.5 solar activity cycles (from July 1968 to June 1987). Some results for the first part of the investigated period (July 1968 - June 1980) were discussed by Jakimiec, Antalová and Storini (1999 and references therein). Other aspects of the topic have already been published by Jakimiec, Storini and Antalová (1995, 1997a, b), Antalová, Storini and Jakimiec (1996), as well as, Storini, Massetti and Antalová (1997), Landi et al. (1998) and Storini et al. (1999a, b).

The data and the preliminary treatment of the analysed parameters are described in Section 2. Results from the cross-correlation analysis are presented in Section 3, and Section 4 summarizes the main findings. In Section 5 we give the final conclusions.

2. Sources of data and construction of the data subsets

As in our previous papers, the relationship between CR–modulation and XBG flux was investigated using the daily neutron monitor data of the Calgary detector (Geographic coordinates: N 51.1 W 114.1, 1128 m a. s. l., about 1 GV of cutoff-rigidity; see Venkatesan et al., 1989), normalized to the May 1965 average

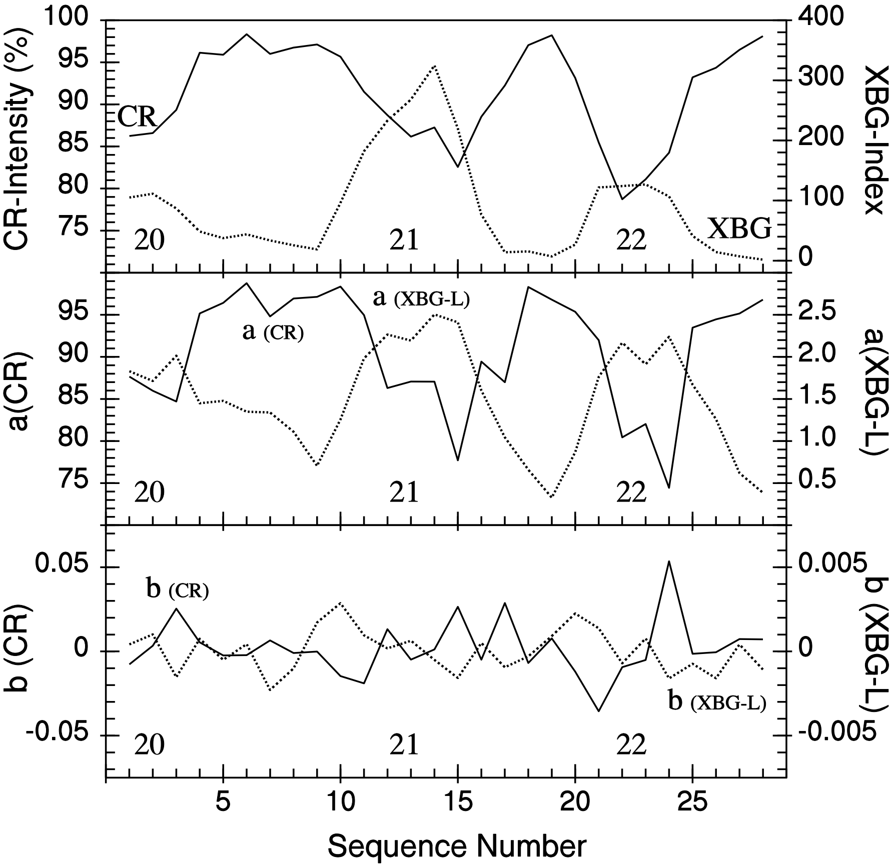

Figure 1. Twelve-month averages of CR and XBG parameters (upper panel), together with the trend of the linear coefficients: a(CR) and a(XBG-L) (middle panel), and b(CR) and b(XBG-L) (lower panel) for the July 1968 - June 1996 time interval.

(i.e., 285554 counts/h = 100% level). In this paper, the CR data gaps were filled considering data from other appropriate neutron monitors. Hence, some small differences can be found when results of this paper are compared with those reported in Jakimiec, Antalová and Storini (1999). According to Donnelly, Grubb and Cowley (1977), Donnelly et al. (1986), Donnelly and Puga (1990), the daily XBG values can be used to describe the solar corona as a whole entity and to follow its evolution during the solar cycle. All the XBG fluxes were evaluated in units of $10^{-8} Wm^{-2}$ (i.e., the GOES A1 class level corresponds to the our XBG unit). We notice that in the solar minimum activity phases there are days with mean XBG values lower than A1, but we assumed in this paper XBG =

1 for all of them and only logarithmic transformed XBG values (XBG-L) were used. We derived the XBG data for the period February 1973 - April 1983 using a scanning procedure of the 5–minute full–sun soft X-ray (0.1–0.8 nm) profiles. Data sources are as in the following list:

Time interval	XBG time profiles
March 1968 - February 1973	SGD 602/part II, p. 26
February 1973 - December 1975	Kreplin et al. (1977), Donnelly (1981) Kreplin and Horan (1992)
January 1976 - December 1979	Donnelly and Bouwer (1981) Bouwer et al., (1982) Puga and Donnelly (1982) Kreplin and Horan (1992)
January 1980 - December 1980	Donnelly and Bouwer (1981) Bouwer et al. (1982)
January 1981 - April 1983	SGD 443/part II - 468/part II
April 1983 - December 1993	SGD 594/part II, p. 36

The complete data set for July 1968–June 1987 (i.e., 228 months), was divided into subsets of 12–month each. The basic data sequences b_i are as follows: b_1(69/70), b_2 (70/71), ..., b_{19} (86/87). These b_i sequences should contain information on CR and XBG variabilities related to: **(i)** the long-term solar cycle activity and **(ii)** the local solar dynamical changes. To separate these two different kind of CR/XBG relationships, for every 12–month sequence the linear trend was estimated as follows: CR = a(CR) + b(CR) × t, and XBG-L = a(XBG-L) + b(XBG-L) × t, where time t = 1, ..., 365, (or 366). Figure 1 shows the obtained a(CR, XBG–L) and b(CR, XBG–L) coefficients together with the 12–month averages of CR and XBG, for a longer period than the one investigated here: July 1968 - June 1996. We notice that the a coefficient reproduces the cycle variability well (see Figure 1, middle panel). When the computed trends were subtracted from the basic data subsets b_i, new subsets of detrended values d_i $(i = 1, ..., 19)$ were obtained, with zero mean values for both parameters. In the d_i sequences the dynamic component of the variables remains in the form of the variable fluctuations and they were the main subject of our investigation. To investigate the response of the CR modulation to the medium- (27 and 15 days), and short–term (7 and 3 days) solar XBG fluctuations the 3–, 7–, 15– and 27–day running mean values were evaluated $(m_i(3), m_i(7), m_i(15)$

Table 1. The comparison of the first minimum values of the CR/XBG ccf-s for the daily detrended (d_i) and the daily basic data (b_i), followed by the corresponding lag (in days). The minima of the appropriate ccf-s less than -0.20 are reported.

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
years	68/69	69/70	70/71	71/72	72/73	73/74	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87
d_i	–	+	-0.48/4	-0.32/3	-0.41/5	–	-0.25/3	-0.35/10	–	-0.24/3	–	-0.38/5	-0.47/8	-0.36/3	-0.50/3	-0.23/8	–	-0.50/6	*-0.48*
b_i	–	–	-0.35/4	–	-0.45/4	–	-0.49/4	-0.34/5	–	-0.54/4	-0.21/5	-0.32/5	-0.46/5	-0.36/3	-0.54/3	-0.27/7	–	-0.57/5	–

and $m_i(27)$ for $i = 1, ..., 19$). When they were subtracted from the detrended ones, we obtained the residual sequences ($r_i(3), r_i(7), r_i(15)$ and $r_i(27)$). The use of the 3-, 7-, 15- and 27-day running mean sequences of both parameters (XBG and CR) allowed us to remove the spurious fluctuations and to take into account parameter variabilities related to a scale longer than the appropriate running-mean points (n–days). More precisely, when the $m_i(n)$ sequences are used the fluctuations shorter than n–days are smoothed. On the other hand, the fluctuations shorter than n–days can be analysed using the residual sequences $r_i(n)$, $i = 1, ..., 19$ and $n = 3, 7, 15, 27$ days.

3. CR/XBG cross-correlation analyses

For every d_i, m_i and r_i sequence the standardized cross-correlation functions (ccf-s) were computed considering – 2 days to + 60 days as the time-lag interval. Table 1 compares the first ccf–minima for detrended d_i and basic b_i data. Examples of the obtained results are shown in Figure 2 – Figure 4 and in Jakimiec, Antalová and Storini (1999). The complete set of plots for the investigated period are reported by Storini, Jakimiec and Antalová (2000).

The 76 ccf-s were estimated for the $m_i(n)$ sequences and the corresponding minima are shown from the second to the fifth columns of Table 2. Analysing the $r_i(n)$, i = 1, ..., 19 sequences, we did not find statistically significant cc–values for n = 3 and 7 (the only exception is in the 68/69 subset $r_i(7) =$ -0.21/3). Therefore, in Table 2, only $r_i(15)$ and $r_i(27)$ are shown in the last two columns. We notice that when the ccf-s of the running-mean sequences contain a high relationship between CR and XBG-L parameters, the ccf-s for

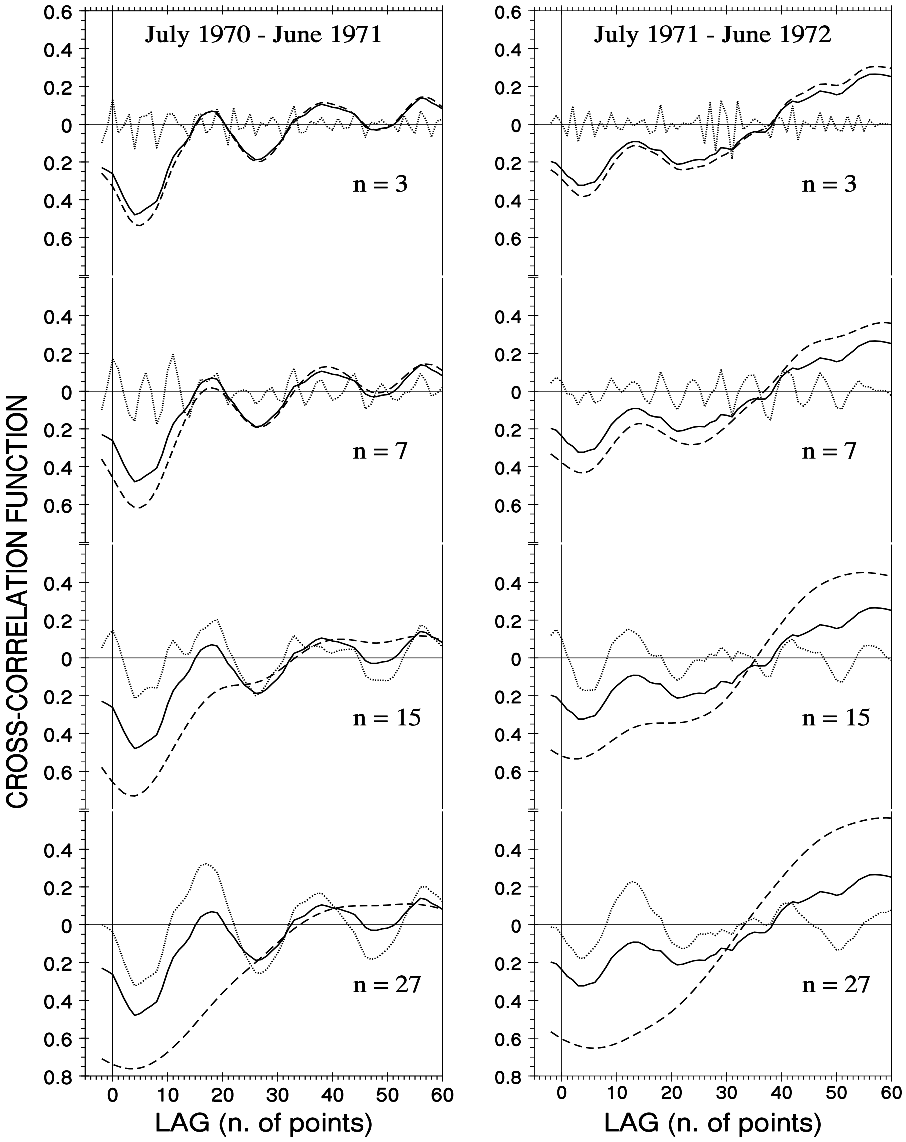

Figure 2. CR/XBG-L cross-correlation functions for July 1970–June 1971 (left panels) and for July 1971–June 1972 (right panels). In each panel, the thick lines illustrate the ccf-s of the detrended daily sequence (d_i), in which all the XBG and CR fluctuations are present. The dashed lines give the ccf values calculated from the appropriate n-point running-mean sequence ($m_i(n)$, where n = 3, 7, 15 and 27 days). In the 70/71, the 1–st minimum is obtained for the $m_3(15)$ (-0.73) and $m_3(27)$ (-0.76). The ccf-s of residuals are shown by dotted lines.

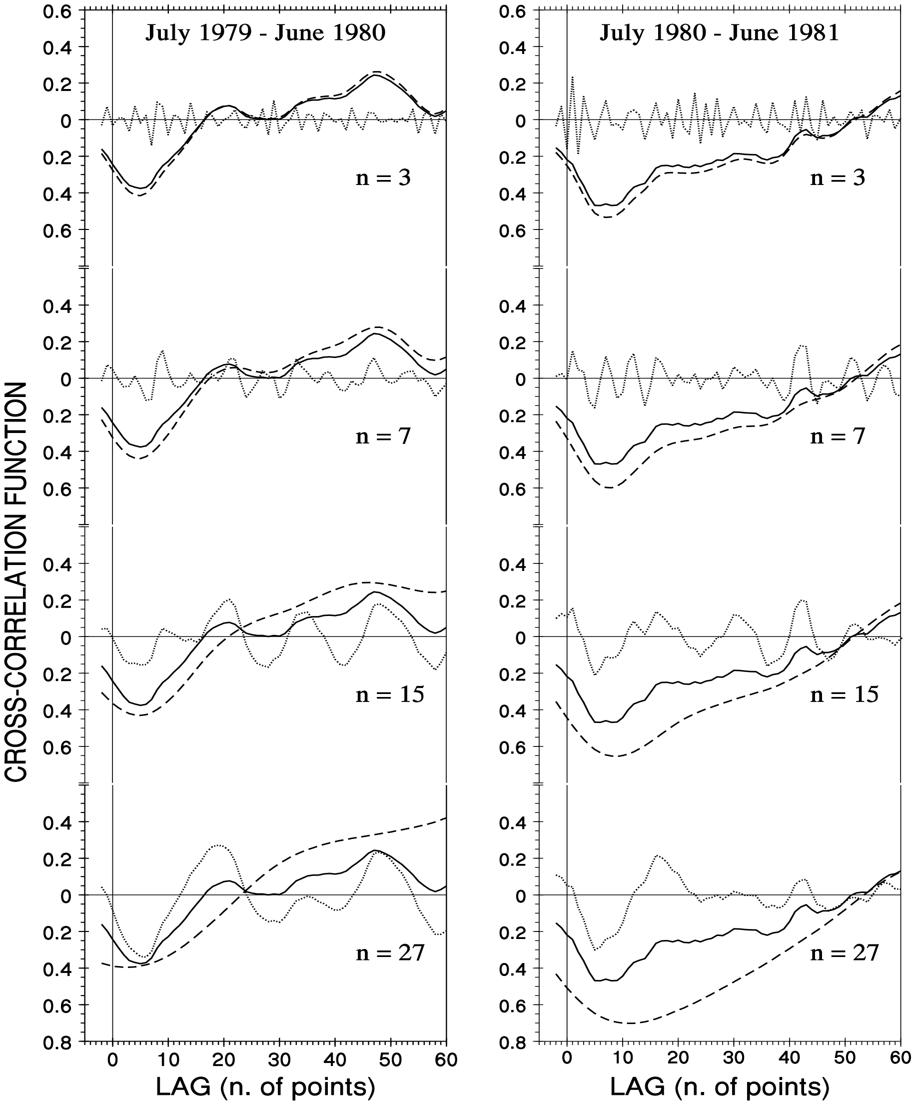

Figure 3. CR/XBG-L cross-correlation functions for July 1979–June 1980 (left panels) and for July 1980–June 1981 (right panels). In each panel, the thick lines illustrate the ccf-s of the detrended daily sequence d_i, where all the XBG and CR fluctuations are present. The dashed lines give the ccf values calculated from the appropriate n–day running–mean sequence. The ccf-s of residuals are shown by dotted lines. In the 79/80 subset, the 1–st minimum from $m_{12}(15)$ has value -0.43. in the 80/81 subset the 1-st minimum is better $m_{13}(27) = -0.70$ than the 2–nd one $m_{13}(27) = -0.57$.

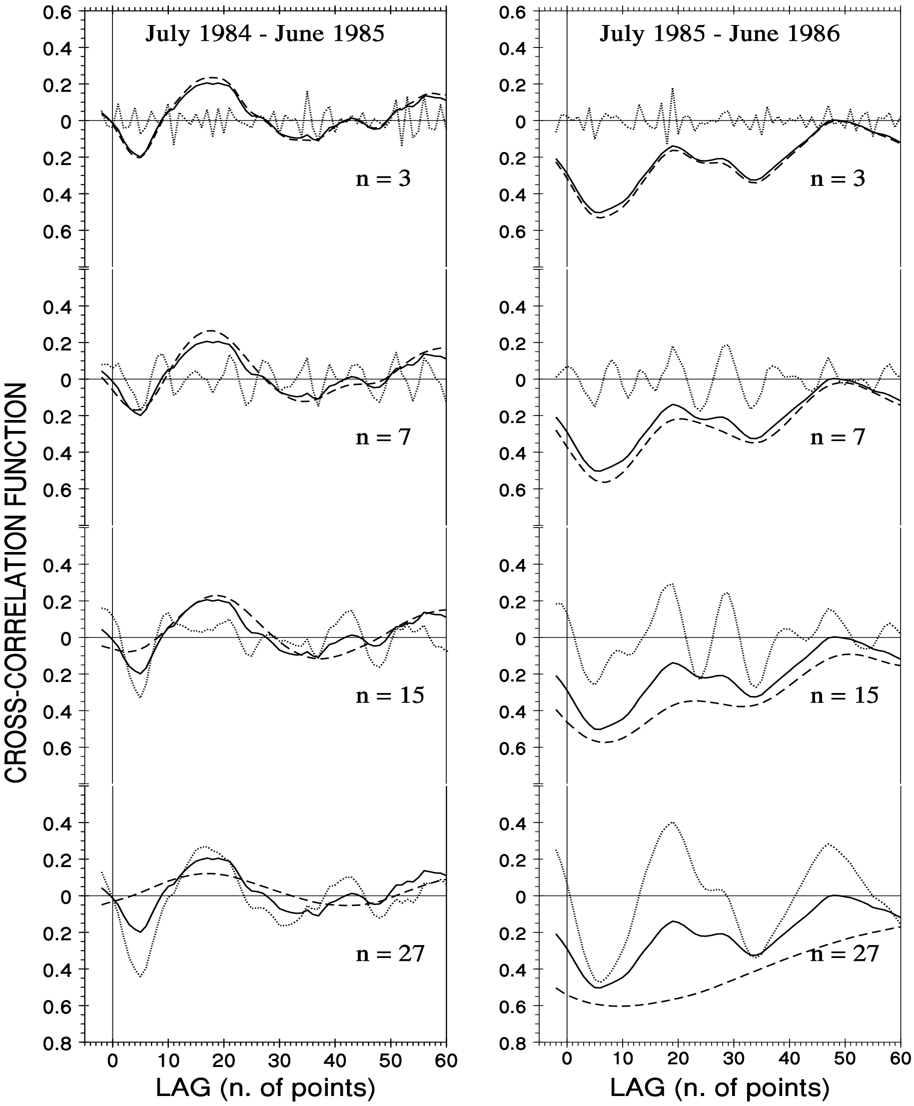

Figure 4. CR/XBG-L cross-correlation functions for July 1984–June 1985 (left panels) and for July 1985–June 1986 (right panels). In each panel, the thick lines illustrate the ccf-s of the detrended daily sequence , where all the XBG and CR fluctuations are present. The dashed lines give the ccf values calculated from the appropriate $m_i(n)$. The ccf-s of residuals are shown by dotted lines. In the 84/85 subset, the 27–day residual ccf shows the best anticorrelation.

Table 2. The minima of CR/XBG ccf-s for d_i – detrended data, $m_i(n)$ – running mean and $r_i(n)$ – residual sequences. The first minima of the appropriate ccf-s ($m \leq -0.20$) are followed by the corresponding lag (in days). In the second line, the secondary minima are given, where the lag is between 11 and 50 days. The anticorrelation from 0 to -0.19 is labelled by - and the positive correlation is labelled by + . *In italics is given the anticorrelation value* when the first and second minima are blended.

$b_i seq$	d_i	$m_i(3)$	$m_i(7)$	$m_i(15)$	$m_i(27)$	$r_i(15)$	$r_i(27)$
years	m/lag	m/lag	m/lag	m/lag	m/lag	m/lag	m/lag
b_1	–	–	–	–	–	-0.28/3	-0.34/3
68/69	–	–	–	–	–	–	–
b_2	+	+	+	+	+	-0.26/6	–
69/70	–	+	+	+	+	–	–
b_3	-0.48/4	-0.54/5	-0.62/5	-0.73/4	-0.76/4	-0.22/4	-0.32/4
70/71	–	–	–	–	–	-0.20/26	-0.26/27
b_4	-0.32/3	-0.38/4	-0.43/4	-0.53/2	-0.65/6	–	–
71/72	-0.21/22	-0.24/22	-0.28/23	–	–	–	–
b_5	-0.43/8	-0.47/8	-0.55/8	-0.67/9	-0.77/9	–	-0.21/4
72/73	-0.22/38	-0.24/38	-0.25/39	–	–	–	–
b_6	–	–	–	–	–	–	–
73/74	–	-0.22/46	-0.25/44	-0.29/42	-0.36/40	–	–
b_7	-0.25/3	-0.29/3	-0.34/3	-0.37/4	*-0.38/3*	–	–
74/75	–	-0.21/36	-0.23/36	-0.32/32	-0.47/20	-0.20/37	–
b_8	-0.35/10	-0.41/9	-0.48/9	-0.55/8	-0.54/5	–	–
75/76	–	–	+	+	+	–	–
b_9	–	–	–	–	-0.22/0	–	–
76/77	–	–	–	+	+	–	–
b_{10}	-0.24/3	–	-0.22/3	–	–	–	–
77/78	–	+	+	+	+	–	–
b_{11}	–	–	–	+	+	-0.21/4/2	–
78/79	–	–	–	–	–	–	–
b_{12}	-0.38/5	-0.42/5	-0.44/5	-0.43/5	-0.40/3	–	-0.34/6
79/80	–	–	–	+	+	–	–

Table 2. continued

$b_i seq$	d_i	$m_i(3)$	$m_i(7)$	$m_i(15)$	$m_i(27)$	$r_i(15)$	$r_i(27)$
years	m/lag	m/lag	m/lag	m/lag	m/lag	m/lag	m/lag
b_{13}	-0.47/8	-0.53/7	-0.60/8	-0.66/9	-0.70/10	-0.21/5	-0.30/5
80/81	-0.26/22	-0.24/36	*-0.33/24*	*-0.41/24*	*-0.57/24*	–	–
b_{14}	-0.36/3	-0.41/4	-0.45/4	-0.43/3	-0.35/1	–	-0.30/3
81/82	+	+	+	+	+	–	–
b_{15}	-0.50/3	-0.56/3	-0.59/3	-0.63/3	-0.65/8	-0.21/3	-0.29/3
82/83	-0.28/24	-0.31/24	-0.33/25	*-0.40/24*	*-0.50/24*	–	–
b_{16}	-0.23/8	-0.25/8	-0.24/8	*-0.22/8*	*-0.22/8*	-0.21/7	-0.32/7
83/84	-0.41/31	-0.44/31	-0.47/33	-0.54/38	-0.61/40	–	-0.20/31
b_{17}	–	-0.20/5	–	–	–	-0.33/5	-0.44/5
84/85	–	+	+	+	–	–	–
b_{18}	-0.50/6	-0.53/6	-0.56/7	-0.57/7	-0.60/9	-0.26/5	-0.47/6
85/86	-0.32/34	-0.34/34	-0.35/34	-0.38/31	*-0.45/31*	-0.23/24	-0.34/34
b_{19}	*-0.48/10*	*-0.51/10*	*-0.55/10*	*-0.55/10*	*-0.68/10*	-0.27/0	–
86/87	-0.55/23	-0.59/23	-0.65/23	-0.72/20	-0.73/19	–	–

the residual sequence $r_i(3)$ are typical for random noise and oscillate around the zero line. The ccf-s for the residual sequences $r_i(3)$ oscillate around the zero line within the interval: -0.20, +0.20. This interval was considered as the interval of insignificant CR/XBG-L correlation. In other words, ccf values lower and equal to -0.20 indicate a statistically significant negative CR/XBG-L relation. Table 2 summarizes for every sequence **the first minima** (the first line) and **the second minima** (the second line) found in the CR/XBG-L ccf-s. When the ccf is very wide and has the blend of the both minima, one can state the negative ccf–values for the lags less than 10 days (see b_{13}, b_{16} or b_{19}) and the significant values *are given in italics* in the first line of Table 2.

4. Discussion of the obtained results

From results reported in Tables 1 and 2 one can see, that the CR/XBG relation is varying during the investigated period. From the present CR/XBG-L cross–correlation analysis, we can derive some useful information on the CR/XBG-L relation over about 1.5 solar cycles. In particular, the advantage of the cross-correlation analysis applied to the running-mean sequences is the possibility of obtaining the CR time delay in response to short– and medium–term solar activity phenomena, which is not possible to do using the usual monthly averages of the parameters.

- Statistically significant CR/XBG anticorrelation for the lags smaller than 10 days can be stated for the data of the 13 subsets from the 19 investigated d_i sequences: $d_3 - d_5$, d_7, d_8, d_{10}, $d_{12} - d_{16}$, d_{18} and d_{19}. This means that mainly during the decay phases of the 20–th and the 21–st solar activity cycles, the CR/XBG anticorrelation is well demonstrated. From these 13 cases the mean value of the lag was around 5 days, which is in good agreement with the lag, found in the past from other solar activity parameters (e.g., Dodson and Hedeman, 1972 and Křivský, 1972 among others).
- The CR/XBG anticorrelation is seen better from results related to the running–mean sequences. The best values of ccf-s are obtained from 15– or 27–day running means, much better than from cc–analysis of the daily basic or detrended sequences. As is known, the 15–day running means represent the all transit of the XBG source from the eastern to western limb of the Sun. It is expected, that cc-analysis of the the $m_i(15)$ subsets will show better the relation of studied parameters, than ccf-s computed from a small part of disk transit (1 – 3 days).
- The first minima from the ccf-s of the residual $r_i(15)$ and $r_i(27)$ subsets were obtained in 10 cases. In $r_i(15, 27)$ the fluctuations with time scale longer than 15 and 27 days are removed (or in other words fluctuations shorter than 15, 27 days are studied). Result suggests that in order to completely explain the CR/XBG–L relation we need to go to a more complicated statistical model.

4.1. Comparing basic, running and residual sequence results

The first minima (increasing n, the better anticorrelation – 9 cases). From the 19 d_i sequences, the first minima are displayed in 13 cases. In the 84/85 subset (see left panels of Figure 4) the 1–st minimum is obtained from $m_{17}(3)$ ccf, as well as from residuals (15, 27). So, we have the 1–st minima in 14 subsets from 19 ones. The expected fact, that the ccf values of the CR/XBG-L analysis would be much better with the increasing number days in the running means (Jakimiec, Antalová and Storini, 1999), is confirmed here in 9 cases, from 14 subsets. As was mentioned above, when we have $m_i(15)$, the all transit of XBG source through Sun is displayed. In given 9 subsets (70/71, 71/72, 72/73, 74/75,75/76, 80/81, 82/83, 85/86, 86/87) large and long–lasting complexes of magnetic fields were observed in the Sun. In seven time intervals, the CR/XBG-L anticorrelation is better than -0.59.

The first minima (increasing n, but anticorrelation is stable – 5 cases). During the 77/78, 79/80, 81/82, 83/84 and 84/85 subsets the anticorrelation was independent of the increasing n. For the 77/78 subset, the anticorrelation was obtained in the $d_{10}(1, 7)$, but for the upper n–values it is lost. In the 84/85 subset the anticorrelation is obtained from $m_{17}(3)$. In these cases we suppose not so optimal conditions for the CR modulation then in 9 cases discussed above.

The second minima (lag interval 11–50 days – 9 cases). Statistically significant anticorrelation arise by using the 71/72, 72/73, 73/74, 74/75, 80/81, 82/83, 83/84, 85/86 and 86/87 data subsets. For the 8 of 19 subsets we stated the existence of the both minima. The unique 73/74 subset has only the 2–nd minimum. The 2–nd minimum was not obtained in 10 cases, but in 7 cases from them, there was the 1–st minimum. The anticorrelation of the 2–nd minimum is better than -0.59 only in the 83/84 and 86/87 subsets. Like for the 1–st minimum, the anticorrelation is better with increasing n (for 5 cases); it is lost for the upper n–values in the years 71–73.

The lack of anticorrelation – 4 cases. No significant CR/XBG relation (in the 1-st minimum) was obtained in the 68/69, 69/70, 73/74 and 76/77 subsets. With the exception of 73/74 (which has the 2–nd minimum), all subsets concern the maximum years of the 20–th cycle and minimum years of the 21–st solar cycle. Around the solar cycle maximum, the polarity of the Sun's magnetic field reverses, causing the more complicated CR–modulation, than during the decay–phase of the solar cycle.

The time lag. In most cases, the first minimum is at lag from 3 to 8 days and with the increasing running points n, the lag is more or less the same. The time lags for the 2–nd minima are less stable than for the first ones. They are ranging between about 19 to 39 days, depending on the subset position in the solar cycle. With the increasing n the lag is more or less the same.

Residual data subsets $-r_i(15,27)$**.** **(i)** From the 78/79 to 85/86 subsets, there are significant ccf–minima of $r_i(15,27)$ with a lag ranging between 3 and 7 days. It implies that during the 21–st cycle the CR/XBG-L relation is partly determined by the short–term fluctuations, which is not true for the period July 1973–June 1978. We believe that this is relevant physical information. For b_1 to b_{12} data sequences the obtained results coincide with the ones reported by Jakimiec, Antalová and Storini (1999). **(ii)** Moreover, we recall that residual sequences gave significant anti-correlations during the maximum phase of cycle 20 and 21, as well as during the descending phase of the 21–st cycle. **(iii)** The 2–nd ccf–minimum of the residuals (searched in the 11–50 days lag interval) was obtained only for the 70/71 (-0.26, 27 days) and 85/86 (-0.34, 34 days) subsets.

Comparing results from detrended and basic data subsets. The comparison of the CR-XBG-L anticorrelation functions of detrended d_i and basic data subsets b_i revealed the following results: **(a)** The minimum values of both sets of data are similar, the differences are inside an error band of 0.20, with the exception of the 74/75 and 77/78. **(b)** However, as we are dealing with daily sequences, the minimum values lower than -0.55 were not found, as it was found for the running–mean sequences (up to -0.77).

5. Concluding remarks

The main result reported in this paper is the difference in the ccf-s during the descending activity phases of two consecutive cycles. We notice that the first cycle (n. 20) is an even–numbered cycle while the second one (n. 21) is an odd-numbered cycle. In the past, several authors claimed a different activity topology in such kind of cycles (i.e. even–odd activity cycle differences in the long–term behaviour of the Sun's life), suggesting the relevance of the heliomagnetic or Hale cycle (about 22 years). In fact, it seems that the transient activity connected with powerful flares during even declining phases is inhibited or reduced (see, for instance, Storini et al., 1999a; Storini and Hofer, 1999), particularly during the latter part of the cosmic ray recovery level, which seems not be true for the odd ones (e.g., Storini, 1997 and references therein). In conclusion, the investigated variability of the CR/XBG-L relationship from July 1968 to June 1987 allowed as not only to learn about its behaviour during a complete heliomagnetic semicycle (Jakimiec, Antalová and Storini, 1999) but also to confirm the existence of a different relationship between the investigated parameters during consecutive declining phases of solar activity.

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