Solar soft X–ray parameters: 1969-1976 autocorrelation functions

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Received: May 21, 1997

Abstract. The autocorrelation analysis of solar soft X-ray parameters was performed with a time lag ranging from 1 to 32 days (acf_j, with j=1, ..., 32) for the 1969-76 period. Consecutive sequences containing daily data for a 2-year interval were considered. From the comparison of the autocorrelation functions for both flare (TOT) and nonflare (XBG) soft X-ray variables we selected the different recurrent tendency over the years. During the maximum (1969-71) and minimum (1975-76) phases of the 20^{th} solar cycle the recurrency of all the SXR parameters is included between 18 and 23 days, but during the decreasing activity phase (1972-74) recurrencies approach the expected 27-day synodic rate of rotation. The nonflare X-ray corona has a particularly stable 27-day recurrency (from 1971-72 to 1974-75), but the flare TOT variable displays the 27-day recurrency only in the 1972-73 sequence (Figure 5). The most stable 25-day TOT recurrency was observed in 1973-75. Our results of the atypical 'solar periodicity' of TOT values (i.e., $acf_{lm} < 27$ days) are in agreement with past findings based on other solar activity indices and cycles. However, we have also noted, on a short time scale (1 day), that there exists a strong coherence ($acf_1 \sim 0.8$) of the XBG variables for all the investigated intervals. While this coherence is high ($acf_1 \sim 0.7$) in the TOT variable only for 1973-75, when long-lived coronal holes covered a large fraction of the solar surface, in the other periods the parameter acf_1(TOT) ≤ 0.55. The above findings were never explicitly emphasized in solar soft X-ray studies.

Key words: the Sun - flares - nonflare (XBG) soft X-ray parameter

1. Introduction

There is a considerable evidence in favour of modulation of the various solar indices due to the 27-day synodic rotation. The phenomenon is understandable

Contrib. Astron. Obs. Skalnaté Pleso **27**, (1997), 104– 114.

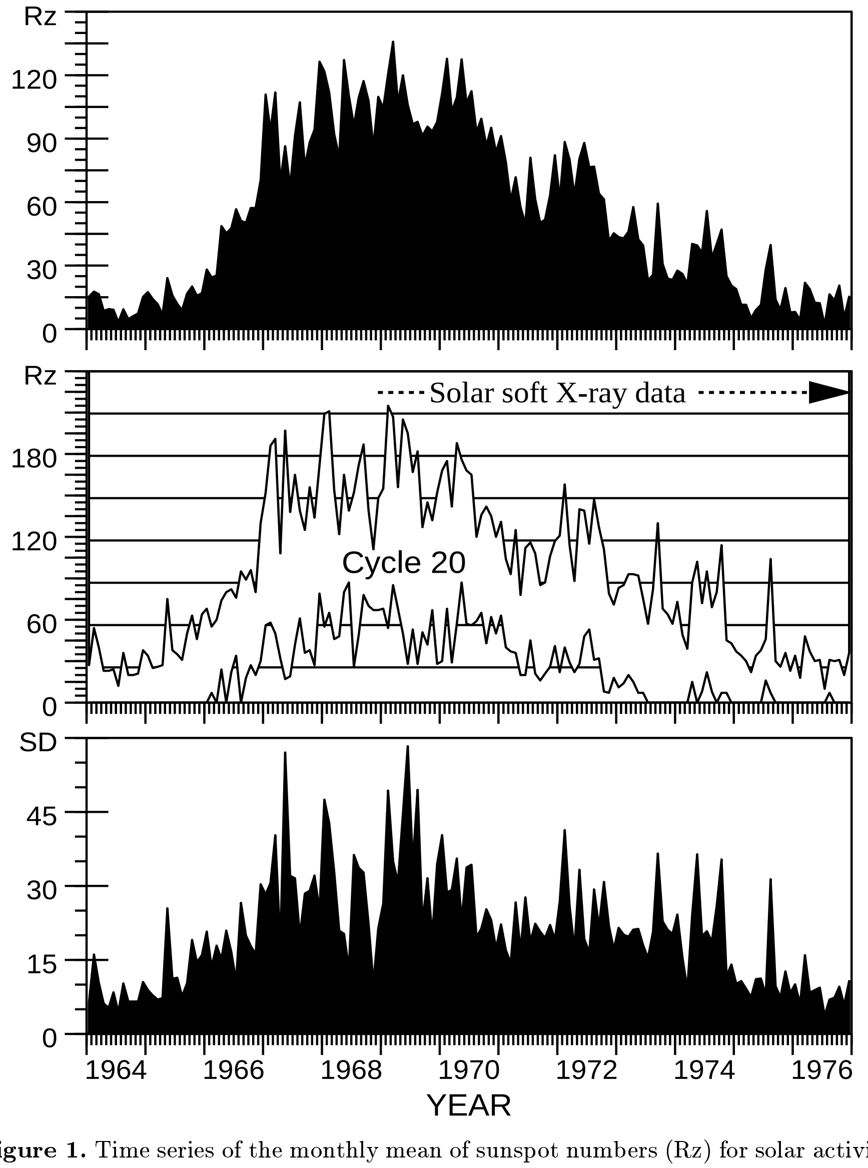

Figure 1. Time series of the monthly mean of sunspot numbers (Rz) for solar activity cycle no. 20 (upper panel), together with those for the extreme values found in the daily Rz data set (middle panel) and that for the computed standard deviation (SD, lower panel) derived from daily data within each month. The period covered by the solar soft X-ray data is indicated by a dashed arrow in the middle panel.

considering that several solar features often have a life-time longer than a month (i.e., persistent active centers and coronal holes). However, the amplitude of this periodicity is not stable over an entire solar activity cycle, being more pronounced during the late declining phase (e.g., Pap, Tobiska and Bouwer, 1990 and references therein).

Nearly continuous daily data for solar soft (0.1 – 0.8 nm) X-ray radiation are available from 1969 on. In this paper we analyze solar soft X-ray (SXR) parameters during the years 1969-1976 to look mainly for the time behavior of the near-synodic recurrent periodicities. We consider the nonflare SXR data as a proxy of global coronal structures and the occurrence of soft X-ray flares as a proxy for *coronal magnetic storms* (Harrison, 1996).

The data and preliminary treatment used to remove the long-term trend from the SXR parameters are described in Section 2. The autocorrelation analyses are presented in Section 3. Section 4 summarizes the results and gives the final conclusions. The preliminary results on this topic were presented at the 17th NSO/Sacramento Peak - SOLERS22 Workshops (1996).

2. Data used and preliminary treatment

Our study is based on the solar soft (0.1 – 0.8 nm flux) X-ray background, derived from several satellite measurements, and on the corresponding list of solar soft X-ray/H-alpha flares for the years 1969-1976 (i.e., the maximum and decline phases of solar activity cycle no. 20). The data were obtained from *Solar Geophysical Data* (SGD 1969-1976; 1994) and from Donnelly (1981). To illustrate solar activity in cycle no. 20, Figure 1 shows: - the monthly mean of sunspot numbers (Rz, upper panel), - the range of the sunspot number variability (middle panel), and - the standard deviation series derived from daily data within each month (lower panel). The period covered by the solar soft X-ray data is indicated by a dashed arrow in the middle panel of Figure 1. The analyzed time sequences contain the daily values of the following two soft X-ray variables:

– XBG (in units of $10^{-8} Wm^{-2}$), the daily average of the unresolved full-sun soft X-ray background as observed by SOLRAD 9 (from January 1969 till February 1973), EXPLORER 37 (from February 1973 till April 1974), SMS-1, SMS-2 and GOES-1 (July 1974 - December 1976). The XBG data for the period February 1973 - December 1976 were derived using the scanning procedure of the 5-minute SXR profiles reported by Donnelly (1981; see, also, Bouwer et al., 1982; Puga and Donnelly, 1982 and Donnelly, Grubb and Cowley, 1977). In the period May - June 1974 in which SXR observations are lacking completely, the data were substituted by data derived from the daily mean of the 10.7-cm radio flux (which correlates well with SXR; Donnelly, Puga and Busby, 1986) and also from the occurrence of Sudden Ionospheric Disturbances (SIDs - which are sensitive to the SXR flux). Moreover, the SID list was also compared with that for H-alpha flares, as published in SGD.

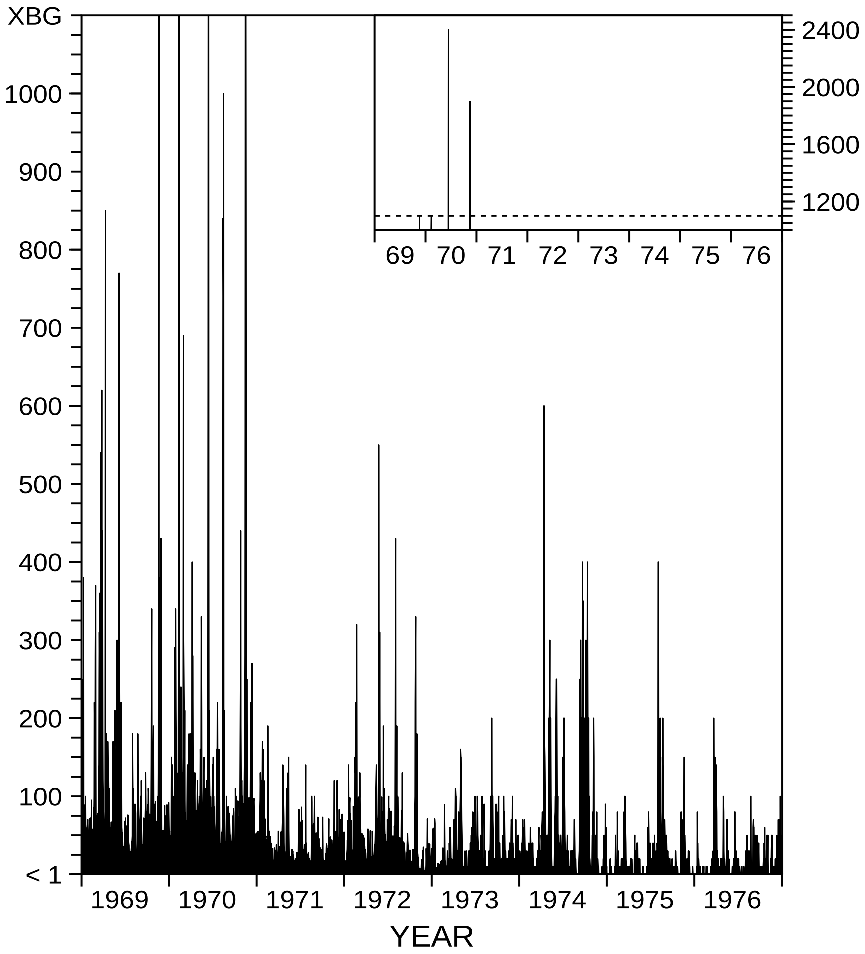

Figure 2. Time series of the nonflare soft X-ray daily values (XBG – in units of $10^{-8}Wm^{-2}$), from 1969 to 1976. Out-of-scale values are shown in the upper right corner.

– TOT (in units of $10^{-6}Wm^{-2}$), the daily flare index for all soft X-ray flares (larger than B5 and disregarding their time duration), as used by Antalová et al., 1995; Jakimiec, Storini and Antalová, 1995; Storini, Antalová and Jakimiec, 1995; Antalová, Storini and Jakimiec, 1996.

Figures 2 and 3 show the time series of both soft X-ray parameters (on a daily basis). The out-of-scale values are shown in the upper right panel. We first investigated the data distributions and found that each soft X-ray variable displays a high skewness. Hence, the logarithmic transformed values for both soft X-ray variables were considered. We formed seven consecutive subsets of

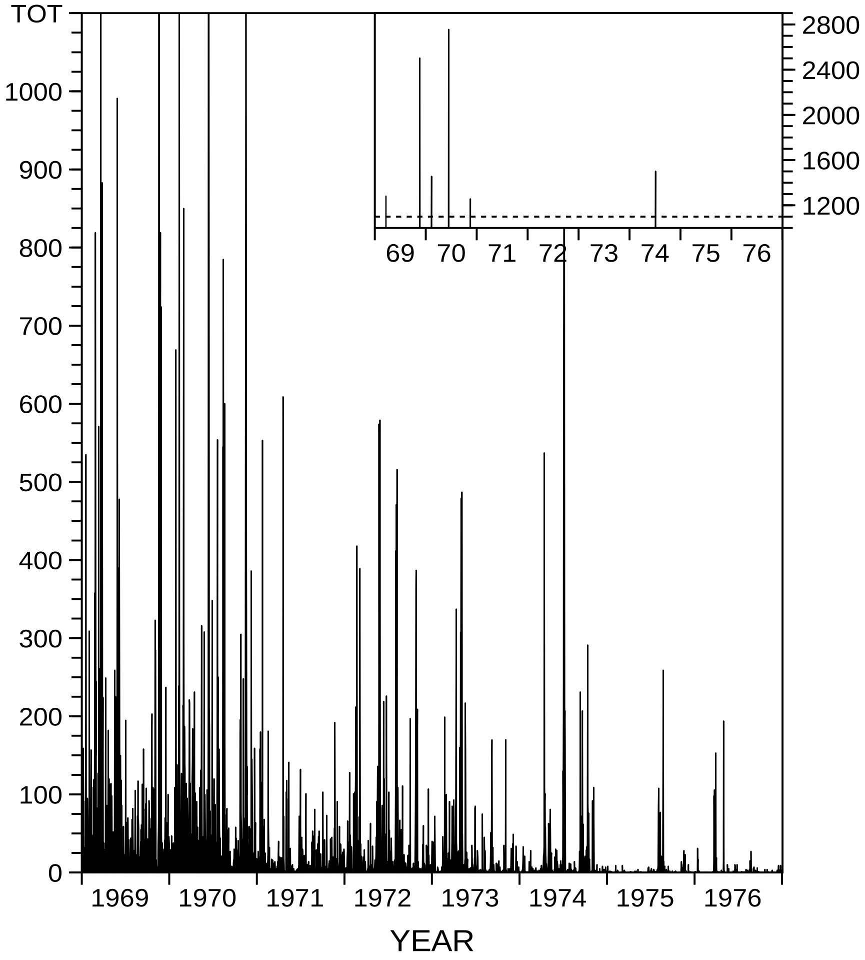

Figure 3. Time series of the flare soft X-ray daily values (TOT – in units of $10^{-6} W m^{-2}$, see the text), from 1969 to 1976. Out-of-scale values are shown in the upper right corner, as in Figure 2.

daily values, each spanning two years: 1969-70, 1970-71 up to 1975-76. As the eleven-year cycle of solar activity is reflected in the decaying trend of the data used, a polynomial data fit of the 2nd order was produced for each variable and sequence. However, it was found that in all sequences the linear trend was enough to eliminate the long-term data behavior. By removing the long-term (year) trends we obtained the detrended sequences of our soft X-ray parameters (XBG and TOT) for every subset, which express their fluctuating character well.

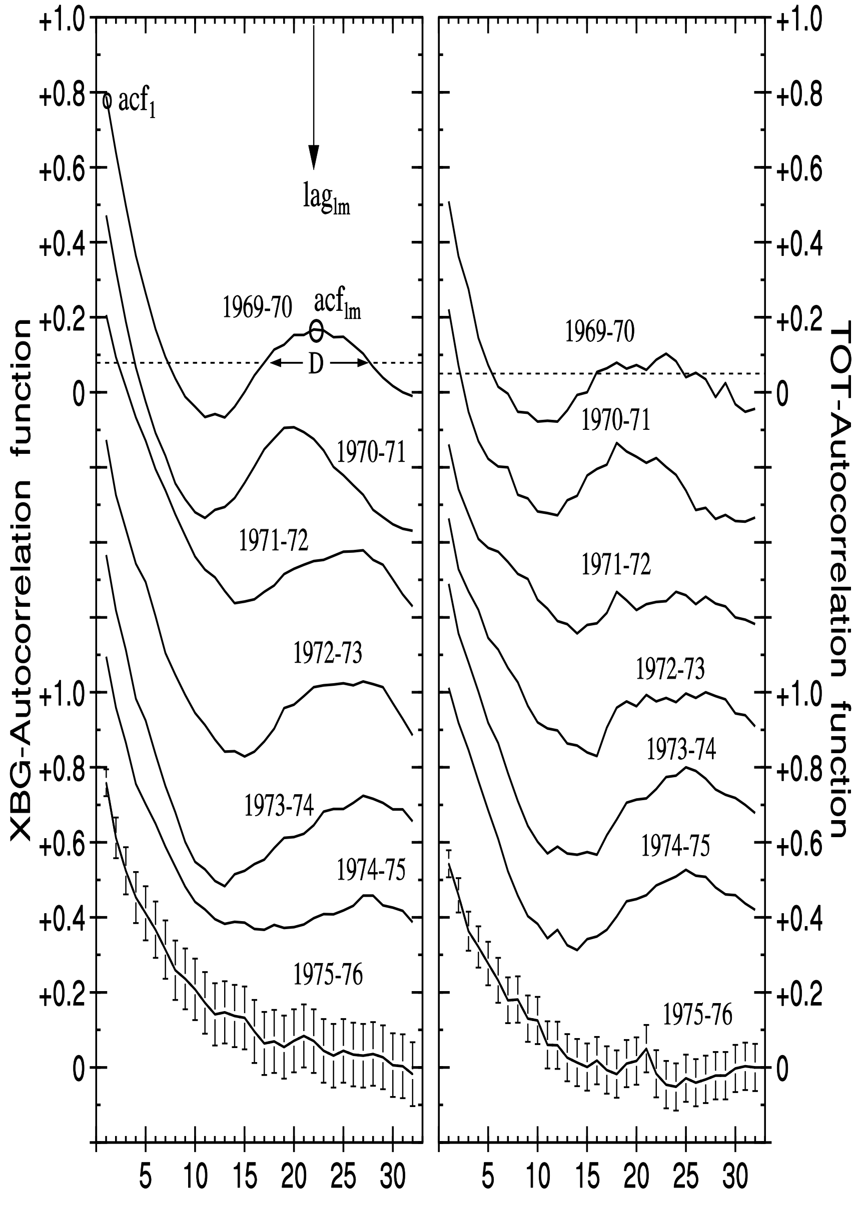

Figure 4. Acf-s of detrended non-flare XBG (left panel) and flare TOT (right panel) data for the 1969-70 (top) to 1975-76 (bottom) sequences. The true scale is given for the first and for the last acf-s. The scale of every successive acf is moved down by 0.3, starting from the top. Standard error (s.e.) bars are shown only for the 1975-76 acf-s. In the first acf (1969-70) the meaning of four acf-parameters is clarified as follows: acf_1 – small circle, acf_{lm} – large circle, lag_{lm} – a vertical arrow and D – horizontal bidirectional arrows. The dashed lines, reported for the 1969-70 sequences, give the assumed s.e. value for the acf recurrent values.

3. Autocorrelation functions of detrended data

For both soft X-ray variables (XBG and TOT) and for every detrended sequence we computed the autocorrelation functions (acf-s) with a time lag ranging from 1 to 32 days. Figure 4 shows the XBG (left panel) and TOT (right panel) acf-s obtained. The vertical bars illustrate standard errors for the 1975-76 acf-s. The other functions have similar standard error bars and they were omitted to avoid confusion. From Figure 4 we selected four acf-characteristic parameters:

- – acf_1, the acf value for the 1-day lag;
- – $acf_{\rm lm}$, the local maximum of acf values within the 15-32 day range;
- – $lag_{\rm lm}$, the time lag of this acf local maximum (in days);
- – D, the time lag extension or time duration (in days) of the period for which the acf values are greater than one standard error (assumed as 1 s.e. = 0.08 for XBG, and 1 s.e. = 0.05 for TOT) in the 15-32 day range.

Considering that $acf_{\rm lm} \geq 1$ standard error, it can be said that the local maxima are significant with an α level = 0.16 (or with a 84 % confidence level). We notice that in many cases the $acf_{\rm lm}$ statistical significance is better (up to α = 0.05, i.e. 95 % confidence level) than the one assumed.

Besides the above four acf-parameters (which are the characteristics of the local maximum of acf-s) we computed two others, which give a measure of the recurrency effect:

- – M, equal to $acf_{\rm lm}$ times D, exhibiting the $acf_{\rm lm}$ importance on an absolute scale.
- – S, equal to $acf_{\rm lm}$ divided by acf_1, giving the $acf_{\rm lm}$ importance on a relative scale.

Figure 5 illustrates the six acf parameters defined above. Figures 4 and 5 indicate that:

• XBG – **(i)** the acf_1 (acf_2) values are about 0.80 (0.65) with conspicuous stability during the period 1969-1976; **(ii)** the acf-s display some recurrent tendencies for *lags* longer than 20 days, and the $acf_{\rm lm}$ values show a dual-peak run with a higher maximum in the years 1970-71 than in 1974-75; **(iii)** the $lag_{\rm lm}$ ranges from about 20 (1970-71) up to 27 (1972-75) days; **(iv)** the D range is included between 9 and 13 days (1969-1975), except for 1975-76 (D = 1); **(v)** the trend of M underlines the dual-peak shape of the recurrence effects, where the first peak (1969-73) is stronger than the second (1973-76); **(vi)** the S also displays two maxima, with the first (1970-71) more pronounced ($\sim$ 25 % of the acf_1).

• TOT – **(i)** the acf_1 values increase from about 0.5 in 1969-72, to 0.7 in 1973-75, decreasing again to almost 0.5 in the years 1975-76; **(ii)** the $acf_{\rm lm}$ has

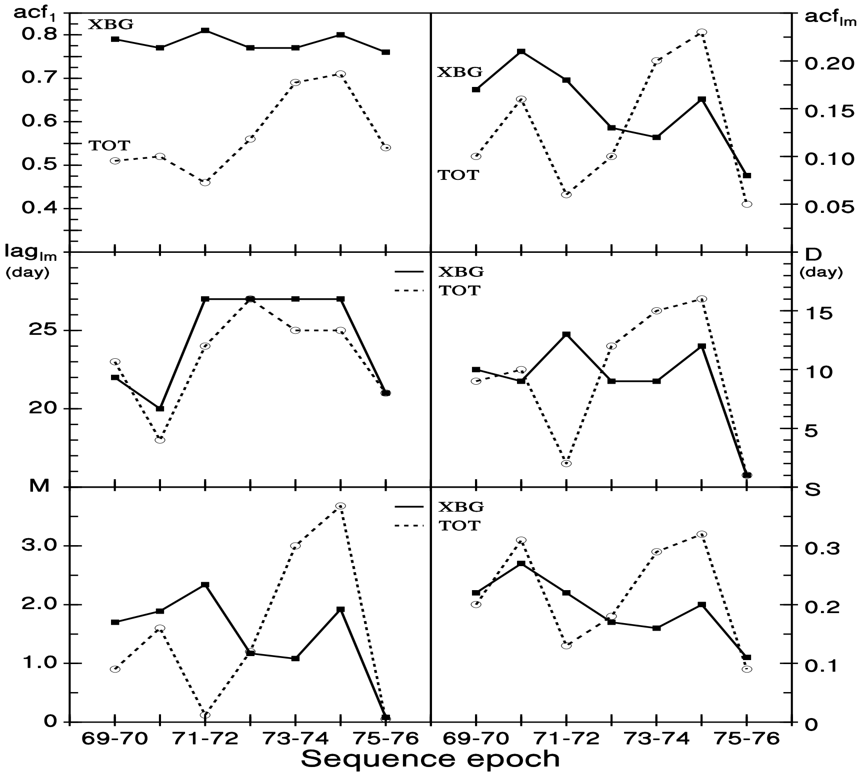

Figure 5. - Six acf parameters computed from both soft X-ray variables (XBG and TOT) and their changes from 1969-70 to 1975-76 sequences. Left panels show parameters: acf_1, $lag_{\rm lm}$ and M; right panels show parameters: $acf_{\rm lm}$, D and S.

a dual-peak shape, with a higher second maximum in 1973-75 than in 1970-71. No recurrent tendency is found for 1975-76, with $acf_{\rm lm}$ = 0.05 (assumed 1 s.e. = 0.05 for TOT); **(iii)** the $lag_{\rm lm}$ range varies between 18 (1970-71) and 27 days (1972-73), while the most stable $lag_{\rm lm}$ (25 days) was observed in 1973-75; **(iv)** the D is very variable from a very short period of 1 day (1975-76) or 2 days (1971-72) to 16 days (1974-75), showing again a dual maximum in the trend of D with a higher value in the second peak (1973-75); **(v)** from M we can see that the recurrence effect is characterized by a very large second peak during the solar cycle late declining phase (1973-75); **(vi)** the S, instead, displays two comparable maxima (32 % of the acf_1); the first maximum of S occurs in the 1970-71 and the second in the 1973-75 interval.

4. Discussion

The autocorrelation analyses (acf_j, with j=1, ..., 32 days) of daily SXR parameters (0.1–0.8 nm) during the maximum and decreasing phases of the 20^{th} solar cycle indicate the following:

– there is a strong coherence in the nonflare SXR corona, represented by XBG. The acf_1(XBG) $\sim$ 0.8 *being constant* (within the given accuracy) for the all 1969-1976 period (left upper panel of Figure 5). In other words, there are no relevant XBG changes on a short-time scale. We conclude that appreciable variations in the global coronal structures emerge only when we are comparing coronal features several days apart. On the other hand, during the years of high solar activity (1969-1972) the X-ray flare parameter (TOT) displays the dynamical presence of long-lived and new flaring regions (acf_1(TOT) $\sim$ 0.5) on a short-time scale, while during the solar cycle late declining phase (when only long-lasting active centers survive in the areas between coronal holes) the acf_1(TOT) increases and maximizes (acf_1(TOT) $\sim$ 0.7 in 1973-1975). Near the solar activity minimum (1975-76) the acf_1(TOT) recedes towards the $\sim$ 0.5 level (left upper panel of Figure 5).

– *the* $acf_{\rm lm}$ values, due to superposed noise, are not very high (0.05-0.25), but at the boundary of significance (right upper panel of Figure 5). Donnelly, Puga and Busby (1986), and Donnelly (1987) analyzing, inter alia, the daily Fe IX intensity during the 21^{st} cycle, obtained similar results for lags of $\sim$ 28 days. However, we have shown that this significance in the SXR parameters depends on the cycle phases (right upper and lower panels of Figure 5), with a dual-peak behavior from the maximum to the minimum activity phases. It will be interesting to find out if this peculiar feature exists in other cycles, including that for the increasing activity phases. Moreover, notice that only with two exceptions, 1970-71 and 1975-76, the recurrent acf values have a broad time duration D (right middle panel of Figure 5; see also Donnelly, 1987).

– the obtained recurrence *lags* (left middle panel of Figure 5) agree with the findings reported for the 21^{st} cycle, i.e. *a lag* shorter than the 27-day during the maximum activity phase and *a lag near the synodic period* during the declining phase. In fact, Wilson (1982) noted dip minima with a periodicity close to 24 days, analyzing the ACRIM irradiance from April to October, 1980. A link was found between irradiance decreases and sunspot flux deficit in solar active regions. Moreover, Bouwer (1983) analyzing solar soft X ray emission for the years 1977-81 found that *frequencies most closely corresponding to the solar rotation are not normally distributed about a 27-28 day mean but occur about 22, 25 and 34 days.* Rottman (1983) noted that when solar activity is concentrated at well–defined solar longitudes, a $\sim$ 27-day periodicity appears in the solar irradiance. Pap (1985) explained the above features by invoking a different periodicity for *young sunspot groups* (or 'active' sunspot groups, characterized by a fast development and a complex magnetic configuration: 23.5-day periodicity) and *old sunspot groups* (or 'passive' sunspot groups with a simple magnetic structure: 28-day periodicity). During the rising and maximum activity phases of each solar cycle there is a predominance of *young* spots, while during the declining phases new spot groups are rare, and *old* spot groups characterize the recurrent effects. We show that this seems to be true for the XBG parameter in the interval 1971-75. In the TOT parameter this behavior sets in, more slowly, suggesting that the ratio between *new* and *old* flaring centers decreases nearly monotonically up to 1972-73; after that time there is a period (1973-75) in which a close 25-day recurrence is observed. This could be done by the magnetic field interplay between well-extended coronal holes and the nearby active centers. At the time near the solar minimum (1975-76) no significative periodicities existed (Figure 4 and right upper panel of Figure 5) because few sunspot groups and active regions survive on the solar disk (e.g., Pap, 1986; Fröhlich and Pap, 1989).

5. Conclusion

Our results, while confirming past findings based on several mathematical techniques and different solar parameters (Hansen, Hansen and Loomis, 1969; A-postolov and Letfus, 1975; Wilson, 1982 and 1984; Bouwer, 1983; Donnelly et al., 1983 and 1985; Pap 1985 and 1986; Donnelly, Hinteregger and Heat, 1986; Donnelly, 1987; Rušin, Rybanský and Zverko, 1987 and 1988; Pap, Tobiska and Bouwer, 1990; Bouwer, 1992 among others), clearly show, by means of the autocorrelation technique, that the behavior of the medium-term X-corona (i.e. within a synodic solar rotation) depends on the solar cycle phase. Instead, on a short-term scale (1 day) this dependence exists only for the X-flaring corona, with the X-background nearly stable from the maximum to the minimum activity phases. Work is in progress to update our results until the end of the ascending phase of solar activity cycle no. 21.

Acknowledgements. This work was carried out within the scope of the CNR/SAV (1995-97) and CNR/PAN (1997-99) agreements and it was partly supported by the KBN Grant of the Wroclaw University (1007/S/IA/96) and by Slovak VEGA Grants *2/1353/97* and *2/2007/97*. Part of the work was done while M.S. was visiting scientist at the Astronomical Institute of the Slovak Academy of Sciences (Tatranská Lomnica, in spring 1997).

References

Antalová, A., Kudela, K., Venkatesan, D. and Rybák, J.: 1995, *Adv. Space Res.* **16**, (9)233

Antalová, A., Storini, M. and Jakimiec, M.: 1996, in *Solar Drivers of Interplanetary and Terrestrial Disturbances, 16th NSO/Sac Peak Workshop*, ed.: K.S. Balasubramaniam, S.L. Keil and R.N. Smartt, ASP Conf. Series, 95, Book Crafters Inc., San Francisco, 437

Apostolov, E. M. and Letfus, V.: 1975, *Bull. Astron. Inst. Czechosl.* **26**, 193

Bouwer, S. D: 1983, *J. Geophys. Res.* **88**, 7823

Bouwer, S. D: 1992, *Solar Phys.* **142**, 365

Bouwer, S. D., Donnelly, R. F., Falcon, J., Quintana, A., and Caldwell, G.: 1982, *A summary of solar 1-8 Å measurements from the SMS ans GOES satellites, 1977-1981*, NOAA Technical Memorandum, ERL SEL-62, Boulder

Donnelly, R. F.: 1981, *SMS-GOES solar soft X-ray measurements. Part I. SMS-1, SMS-2, and GOES-1 measurements from July 1, 1974, through December 31, 1976*, NOAA Technical Memorandum ERL SEL-56, Boulder

Donnelly, R. F.: 1987, *Solar Phys.* **109**, 37

Donnelly, R. F., Grubb, R.N. and Cowley, F.C.: 1977, *Solar X-ray measurements from SMS-1, SMS-2, and GOES-1, information for data users*, NOAA Technical Memorandum ERL SEL-48, Boulder

Donnelly, R. F., Heath, D. F., Lean, J. L. and Rottman, G. J.: 1983, *J. Geophys. Res.* **88**, 9883

Donnelly, R. F., Harvey, J. W., Heath, D. F. and Repoff, T.P.: 1985, *J. Geophys. Res.* **90**, 6267

Donnelly, R. F., Hinteregger, H. E. and Heath, D. F.: 1986, *J. Geophys. Res.* **91**, 5567

Donnelly, R. F., Puga, L.C. and Busby, W.S.: 1986, *Temporal characteristics of solar EUV, UV and 10830 Å full-disk fluxes*, NOAA Technical Memorandum ERL SEL-146, Boulder

Fröhlich, C. and Pap, J.: 1989, *Astron. Astrophys.* **220**, 272

Hansen, R. T., Hansen, S. F. and Loomis, H. G.: 1969, *Solar Phys.* **10**, 135

Harrison, R.A.: 1996, *Solar Phys.* **166**, 441

Jakimiec, M., Storini, M. and Antalová, A.: 1995, 24^{-th} ICRC, Vol.**4**, International Union of Pure and Applied Physics, Roma, 852

Pap, J.: 1985, *Solar Phys.* **97**, 21

Pap, J.: 1986, *Astrophys. Space Sci.* **127**, 55

Pap, J., Tobiska, W.K., and Bouwer, S.D.: 1990, *Solar Phys.* **129**, 165

Puga, L.C. and Donnelly, R.F.: 1982, *NOAA Technical Memorandum*, ERL SEL-65, Boulder

Rottman, G.J.: 1983, *Planet. Space Sci.* **31**, 1001

Rušin, V., Rybanský, M. and Zverko, J.: 1987, *Bull. Astron. Inst. Czechosl.* **38**, 181

Rušin, V., Rybanský, M. and Zverko, J.: 1988, in *Solar and Stellar Coronal Structures and Dynamics*, ed.: R.C. Altrock, NSO/Sacramento Peak, Sunspot, 400

SGD *Solar Geophysical Data*: 1969 – 1976, Parts I and II

SGD *Solar Geophysical Data*: 1994, No. 602, part II

Storini, M., Antalová, A. and Jakimiec, M.: 1995, *J. Geomagn. Geoelectr.* **47**, 1085

Wilson, R. C.: 1982, *J. Geophys. Res.* **87**, 4319

Wilson, R. C.: 1984, *Space Sci. Rev.* **38**, 203