SOLAR CYCLE VARIATIONS OF THE SOFT X-RAY BACKGROUND FLUX AND ITS RELATION TO FLARE OCCURRENCE

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ABSTRACT

The X-ray background flux (XBF) based on GOES 1–8 Å measurements for the period 1975–2000 is studied. We come to the conclusion that in the XBF the flare contribution is not eliminated but the XBF is dominated by flare and post-flare emission of intense events. Furthermore, we suggest that the characteristic lag of the X-ray background flux with regard to Sunspot Numbers reported for cycle 21 is a secondary effect related to the substantial contribution of large flares to the XBF.

1. INTRODUCTION

At the extreme ends of the spectrum (radio, X-rays) solar irradiance is very low but the amplitude of solar variability is most pronounced, since at these wavelengths the radiation of flares can be quite intense (cf., reviews by Hudson, 1988; Lean, 1997). We employ the full-disk soft X-ray flux recorded by GOES in the 1–8 Å passband to study the global evolution of the soft X-ray background flux for solar cycles 21, 22 and 23 up to the end of year 2000. Since the soft X-ray background flux varies by several orders of magnitude throughout a solar cycle, it provides a very sensitive means to solar activity. The background flux has been introduced in order to represent the slowly evolving flux level that is independent of strong flare effects (Bouwer et al., 1982). However, it was noted in previous studies (Pearce et al., 1992; Wilson, 1993; Aschwanden, 1994) that the background flux is still related to the flare-associated soft X-ray emission. Furthermore, it was shown that in solar cycle 21 the peak of the soft X-ray background flux was significantly delayed with regard to Sunspot Numbers (Wagner, 1988; Pearce et al., 1992; Aschwanden, 1994), whereas this peculiarity did not recur in cycle 22 (Wilson, 1993). In this paper, we investigate in detail the contribution of flares to the background flux.

2. SOLAR SOFT X-RAY FLUX

The soft X-ray background flux is based on the 1–8 Å flux measured by the full-disk X-ray sensors aboard the Geostationary Operational Environmental Satellites (GOES). The 1–8 Å soft X-ray flux from the Sun is a combination of continuum and line emission, produced by free-free bremsstrahlung, free-bound recombination and two-photon emission (Mewe, 1972; Mewe and Gronenschild, 1981). In general, the 1–8 Å emission is dominated by free-free bremsstrahlung. The excitation of soft X-ray lines strongly depends on the temperature of the plasma and varies extremely from quiescent active regions to flare conditions (e.g., Thomas, Starr, and Cranell, 1985; Aschwanden, 1994). The 1–8 Å flux is believed to originate from heated solar plasma that is confined in closed magnetic loops in active regions. The emission is dominated by contributions from the hotter coronal plasma with temperatures $T \geq 10^6$ K (Bouwer, 1983; Aschwanden, 1994).

Several important reasons have been brought forward to use the 1–8 Å soft X-ray irradiance as an index for solar activity (Bouwer, 1983): (a) the source of the SXR emission is confined to the solar corona and has no chromospheric contribution from the quiet Sun (opposed to the 10.7 cm radio flux), (b) since the SXR emission is optically thin it is not subject to center-to-limb darkening, and thus has also high sensitivity at and behind the solar limb, (c) the SXR flux is an important source of ionization in the D-region of the Earth ionosphere, and (d) the background SXR flux has a high dynamic range between minimum and maximum solar activity and thus provides a very sensitive means for solar coronal activity.

3. DATA

In this analysis we use monthly averages of the soft X-ray background flux together with monthly mean Sunspot Numbers and monthly numbers of SXR flares for the period January 1975 to December 2000. The analysis fully covers cycle 21 (June 1976–August 1987) and cycle 22 (September 1988–August 1991).
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Figure 1. Monthly averages of Sunspot Numbers (top) and X-ray background flux (bottom) for the time range 1975–2000.

Figure 2. Annually smoothed monthly mean Sunspot Numbers (top) and X-ray background flux (bottom) for the time range 1975–2000. Solid (dotted) lines indicate the solar cycle maxima (minima).

1986), cycle 22 (September 1986–April 1996) as well as cycle 23 up to its early declining phase (maximum: April 2000). Monthly mean and annually smoothed monthly mean Sunspot Numbers are taken from the Sunspot Index Data Center (SIDC), RCW Belgium, World Data Center for the Sunspot Index. The X-ray background flux is based on the 1–8 Å flux measured by GOES. Monthly averages of the X-ray background flux for the period January 1975–June 1988 are given in Wagner (1988). Starting from January 1987, daily background flux data are compiled in the Solar Geophysical Data (SGD) at the National Oceanic and Atmospheric Administration (NOAA), from which we derived monthly averages for the time range 1987–2000. Monthly numbers of SXR flares (for different importance classes) are derived from the GOES SXR flare compilation in the SGD.

In the X-ray background flux (XBF), the principal flare component has to be removed in order to represent the slowly evolving flux level (cf., Bouwer et al., 1982; Wagner, 1988). The non-flare variations of solar activity are generally characterized by three time scales (e.g., Donnelly, 1986): (a) short-term variations (order of weeks) due to solar rotation and the evolution of active regions, (b) intermediate term variations (order of months) due to episodes of major activity and long-lived active regions, and (c) long-term solar cycle variations.

It has to be noted that the definition of the XBF used by the SGD is slightly different from those employed by Wagner (1988). Wagner (1988) determined the daily XBF by calculating hourly flux averages and dividing each day into three 8-hour periods. Within each 8-hour bin the minimum value is derived and a linear interpolation between the minima of the outside bins for a point halfway between these two bins is performed. The daily X-ray background flux is then defined as the minimum of the middle bin and the interpolated minimum from the outside bins. In the SGD listings, daily XBF data are derived by averaging the GOES 1-min data for three 8-hour periods through the day, and then the lowest of the three averages is used as the X-ray background level for the day. The period January 1987 to June 1988, for which we have overlapping XBF data from Wagner (1988) and the SGD reveals only minor differences in the derived monthly X-ray background flux for the two different definitions.

4. RESULTS

Fig. 1 shows the evolution of monthly mean Sunspot Numbers and the monthly mean background flux during the period 1975–2000. Fig. 2 plots the same indices but smoothed with a 13-months running mean. Cycle maxima and minima are indicated by vertical lines. The XBF changes from about \(10^{-8}\) W m\(^{-2}\) (GOES A-level) during solar minimum to a few times \(10^{-6}\) W m\(^{-2}\) (GOES C-level) during maximum activity. In comparison, the smallest GOES detectable flares are class A, whereas the largest are \(\sim X20\) (i.e., \(2 \times 10^{-3}\) W m\(^{-2}\)). Thus, over the solar cycle the XBF changes \(\gtrsim 2\) orders of magnitude, whereas the difference between the smallest and largest SXR flares is \(\gtrsim 5\) orders of magnitude. During solar maximum, the SXR background flux ("X-ray irradiance") is \(\sim 9\) orders of magnitude smaller than the total solar irradiance of \(1366\) W m\(^{-2}\).

From Fig. 2 it is evident that in solar cycle 21 the XBF peaks about 1–2 years later than the Sunspot Numbers. The phenomenon that in cycle 21 the XBF was significantly delayed with regard to the sunspot cycle was already noted in previous studies (Wagner, 1988; Pearce et al., 1992; Aschwanden, 1994). However, from Figs. 1 and 2 no such delay between
sunspot cycle and XBF is evident for solar cycle 22 (see also Wilson 1993).

In Fig. 3, we plot the monthly numbers of SXR flares for different importance classes: $\geq C1$ (top panel), $\geq C6$ (middle panel) and $\geq M2$ (bottom panel). Since the detectability of weak SXR flares depends on the SXR background flux, which changes over the solar cycle, we did not consider flares smaller than C1. The ratio of the total number of flares between the groups $\geq C1$ and $\geq C6$ is about 4:1, between $\geq C1$ and $\geq M2$ it is about 16:1.

Fig. 3 clearly reveals that in cycle 21 also the numbers of SXR flares are delayed with respect to Sunspot Numbers; the peak occurs $\sim$2 years later. In solar cycle 22 it is interesting to note that the double-peak feature with the Gnevyshev gap (which is an indicator of the magnetic field reversal) shows up in Sunspot Numbers, SXR background flux and SXR flare occurrence. For Sunspot Numbers and XBF, the first peak is higher than the second one, whereas for the number of SXR flares the relative intensity is reversed when also weak events are considered ($\geq C1$, see top panel in Fig. 3). However, if only very energetic events are considered ($\geq M2$, see bottom panel in Fig. 3) the relative intensity of the peaks mimics those of Sunspot Numbers and XBF.

In Fig. 4, the scatter plots of the smoothed monthly XBF and smoothed monthly SXR flare numbers (for different importance classes) versus Sunspot Numbers are shown for solar cycles 21 and 22, respectively. For clearer representation of the evolution in time, the rising phase of each cycle is indicated by black, the declining phase by gray color. The resulting patterns are very different for both cycles. For cycle 21, loop-like structures appear in the scatter plots which are an indicator for a time shift of XBF as well as SXR flare numbers with regard to Sunspot Numbers: the larger the time shift, the wider the loop. This behaviour is most extreme for $\geq C1$ flares. The comparison of the pattern for the XBF with the SXR flare numbers shows that the pattern of the XBF is most similar to that of flares $\geq M2$.

No obvious loop structures show up in the scatter plots for cycle 22 (see Fig. 4). The smoothed monthly XBF versus Sunspot Numbers lie along a line in the double logarithmic plot. Thus, the relation between XBF ($y$) and Sunspot Numbers ($x$) can be well represented by a power-law, $y = ax^b$, where the fit gives $a = 0.6 \cdot 10^{-9}$ and $b = 1.5$ (the fit was applied to the logarithmic data, i.e. $\log y = \log a + b \log x$). The correlation coefficient (in log-log space) gives $r = 0.97$. In Fig. 5 we show the monthly XBF versus monthly Sunspot Numbers together with the outcome of the fit separately for cycles 21, 22, and 23 up to its early
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Figure 5. Scatter plots of monthly XBF against Sunspot Numbers for cycles 21, 22 and 23. The line indicates the fit to the data of the functional form
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\log y = \log a + b \log x
\]
decline phase. For cycle 21 we obtain \( a = 1.8 \cdot 10^{-9}, \) \( b = 1.3 \) and \( r = 0.93. \) Cycle 23 gives \( a = 2.5 \cdot 10^{-9}, \) \( b = 1.2, \) and \( r = 0.93. \)

In cycle 22, also the smoothed monthly numbers of SXR ﬂares \( \geq C6 \) and \( \geq M2 \) form a line in log-log space when plotted against Sunspot Numbers (see Fig. 4). For ﬂares \( \geq C1, \) a ﬂattening for large Sunspot Numbers can be seen. This phenomenon is very probably a selection effect: The detection of SXR ﬂares is constrained by the background radiation, which varies over the solar cycle. Thus, the X-ray background level is critically important in determining the number of ﬂares that occur in a particular importance class (see also Feldman, Doschek and Klimchuk, 1997). As can be seen in Fig. 1 (bottom panel), during solar maximum the monthly averaged XBF may reach almost C3 level.

5. DISCUSSION AND CONCLUSIONS

The XBF may be due to emission from many ﬂare events or/and due to a steady coronal heating mechanism. If small-scale ﬂares (“nanoflares” – Parker, 1988) are responsible for heating the corona and thus for the enhanced X-ray emission, then a nonlinear relation between the occurrence frequency of SXR ﬂares in a particular importance class and the background ﬂux is expected. For a relative high XBF, say \( \geq C1 \) level, the occurrence rate of low-energetic events (B class, A class, < A class) has to be enhanced, too. These low-energetic events act as main contributors to the build-up of this background level but cannot be detected separately due to the enhanced XBF (see also Feldman, Doschek and Klimchuk, 1997). It is worth noting that for Hα ﬂares, who are contrary to SXR ﬂares detectable with the same efﬁciency in minimum and maximum activity, it was reported that in cycle 21 many more subﬂares occurred than in cycle 22 (Temmer et al., 2001).

High correlations exist between XBF and Sunspot Numbers \( (r \approx 0.9) \) as well as SXR ﬂare numbers and Sunspot Numbers \( (r \approx 0.8). \) Comparison of Figs. 2 and 3 as well as the patterns in Fig. 4 suggest that the XBF is strongly dominated by large events \( (\geq M2). \) This outcome supports previous reports that the flare component is not fully subtracted out in the XBF (Aschwanden, 1994), but the XBF is dominated by ﬂare and post-ﬂare emission from intense events. This also explains the ﬁnding that in solar cycle 21 not only the XBF but also the SXR ﬂare occurrence lags behind sunspot activity.

Wheatland and Litvinenko (2001) presented a model for the dynamic energy balance in the corona over the solar cycle. The model predicts that the free energy in the corona lags behind the variation in the energy supply to the system. From this model a characteristic delay of ﬂare occurrence with respect to Sunspot Numbers of \( \sim 1 \) year was derived. Temmer, Veronig and Hanslmeier (2003) analyzed SXR and Hα ﬂare occurrence, and found that the delay between ﬂare activity and sunspot activity is more pronounced for large events. Moreover, a characteristic delay could only be found in odd-numbered cycles, which suggests a connection to the 22-year magnetic cycle of the Sun. We conclude that the extreme delay of the XBF in cycle 21 is a secondary effect related to the substantial contribution of large ﬂares to the XBF.

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REFERENCES