IRRADIANCE OBSERVATIONS OF THE 1-8 Å SOLAR SOFT X-RAY FLUX FROM GOES*

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Abstract. The solar 0.5-8 Å soft X-ray flux was monitored by the NOAA Geostationary Operational Environmental Satellites (GOES) from 1974 to the present, providing a continuous record over two solar activity cycles. Attempts have been made to determine a soft X-ray (SXR) background flux by subtracting out solar flares (using the daily lowest flux level). The SXR background flux represents the quietest SXR flux from heated plasma in active regions, and reflects similar (intermediate-term) variability and periodicities (e.g. 155-day period) as the SXR or hard X-ray (HXR) flare rate, although it is determined in non-flaring time intervals. The SXR background flux peaks late in Solar Cycle 21 (2-3 years after the sunspot maximum), similar to the flare rate measured in SXR, HXR, or gamma rays, possibly due the increasing complexity of coronal magnetic structures in the decay phase of the solar cycle. The SXR background flux appears to be dominated by postflare emission from the dominant active regions, while the contributions from the quiet Sun are appreciable in the Solar Minimum only (A1-level). Comparisons with full-disk integrated images from YOHKOH suggest that the presence of coronal holes can decrease the quietest SXR irradiance level by an additional order of magnitude, but only in the rare case of absence of active regions.

Key words: Solar irradiance – Soft X-rays – GOES spacecraft

1. The GOES satellites

The solar 0.5-8 Å soft X-ray flux is monitored by the full-disk soft X-rays sensors (XRS) onboard the Geostationary Operational Environmental Satellites (GOES), operated by NOAA, since 1974. Earlier versions of the soft X-ray sensors (XRS) were flown on the Solar Radiation (SOLRAD) satellite (Kreplin et al. 1977), starting in 1964, and then on the NASA Synchronous Meteorological Satellite (SMS) series, in 1974. The currently operational spacecrafts are GOES-6 and GOES-7, simultaneously operating in a geostationary EAST and WEST position. Because the GOES spacecrafts are in geostationary orbits they have almost continuous coverage of the Sun. The present GOES are spinning platforms, so that the XRS flux is modulated by solar and nonsolar signals. The main source of nonsolar signals is local particle contamination, detectable on a typical level of \( \approx 10^{-8} \) W m\(^{-2}\). Two bands of X-rays (0.5-4 Å, 1-8 Å) are measured, in 3-second intervals, by two gas-filled ion chambers. Instrumental descriptions and details on the calibration are given in Grubb (1975), Unzicker & Donnelly (1974), Donnelly et al. (1977), and Garcia (1993). The calibration of the XRS sensors is checked by intercomparison between different GOES spacecrafts, or with SOLRAD.


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No trend for a long-term drift in the sensor calibration was found (Bouwer 1983). However, below about $10^{-7}$ W m$^{-2}$ the relative error can increase to about 50% because of low-flux instrumental problems (Bouwer et al. 1982).

The effective temperature $T$ and emission measure $EM$ of an isothermal plasma can be determined from the ratio of the two SXR energy channels measured by GOES, using the analytical expressions which have been derived by Thomas, Starr & Crannell (1985), by folding the theoretical SXR spectra with the GOES detector transfer function. The evolution of the flare properties $T$ and $EM$ provide also constraints on the evaluation of the flare-unrelated background flux (Bornmann, 1990). Intercomparisons of measurements of $T$ and $EM$ between GOES, BCS/SMM, HINOTORI, and PROGNOZ agree within $< 20\%$ (Antonucci et al. 1984; Tanaka 1986; Garcia 1993).

2. Soft X-ray background flux measurements

The following reasons were brought forward to use the 1-8 Å flux to monitor solar irradiance instead of using other solar indices (Bouwer 1983): (1) the source of SXR flux is confined to the solar corona and has no chromospheric quiet Sun contribution (opposed to the 10.7 cm flux), (2) no center-to-limb darkening effects of the SXR flux and higher sensitivity at and behind the limb (compared with the 10.7 cm flux), (3) high dynamic range between solar minimum and maximum (about 3 orders of magnitude), and (4) importance of ionization in ionospheric D region during high solar activity. The long-term temporal variations of GOES X-rays is important not only to the D-region of the ionosphere, but also for modeling the temporal variations of coronal EUV emissions, which are important to the E and F regions of the ionosphere and to the thermosphere. The solar 1-8 Å flux above $\approx 10^{-6}$ W m$^{-2}$ rivals cosmic rays and Lyman $\alpha$ as a source of ionization and excitation in the D region.

The daily background flux should be an indicator of the quiescent X-ray flux from active regions, where variable emission from flares and coronal mass ejections is largely subtracted out. The Soft X-ray flux in the 1-8 Å band is of the order $10^{-6}$ W/m$^2$, which is about a factor of $10^3$ smaller than the white light solar constant of 1368 W m$^{-2}$. Methods to remove the effects of solar flares from a background flux are described in Bouwer et al. (1982) and Wagner (1988): The daily background flux is defined by the minimum hourly value, either taken in the middle 8 hours of the day, or interpolated from the other 16 hours to the middle of the day.

Wagner (1988) determined the daily background X-ray fluxes in the form of monthly averages and annually-smoothed (13-month) values of the 1-8 Å flux for 1974 to 1988 (Solar Cycle 21). He found that intermediate-term variations (on the scale of months) of the 1-8 Å flux roughly mimic those of
other chromospheric and coronal indices such as Ca, K, He 10830 Å, and 10 cm radio flux. The annually-smoothed daily background X-ray flux was found to peak late in the solar cycle, and is best matched by photospheric white-light facular areas. A factor of 85 was found for the SXR background flux between the Solar Maximum in Sept 1981 and the last Minimum in Oct 1986, which is a much smaller variation than found between the most powerful (class X30.0; 3.0·10⁻³ W m⁻²) and the smallest detectable flares (class < A1.0; 10⁻⁸ W m⁻²), differing by a factor of > 3 · 10⁵. Despite this efficient method of subtracting out the principal flare component, the residual SXR background flux and its intermediate-term variability seems still to reflect the flare-associated (post-flare) emission of heated plasma from the flaring active regions. A comparison of the monthly averaged GOES background 1-8 Å flux (Fig.1, middle) with the monthly flare rate counted either in SXR (Fig.1, second row: GOES > M1 class flares) or in hard X-rays (Fig.1, first row: ISEE-3, HXRBS/SMM and BATSE/CGRO > 25 keV flare rate) shows a high degree of correlation between these 3 solar activity indicators, which all show the 155-day variability equally well. Thus, the so-called “SXR background flux” is still dominated by flare-related SXR emission.

3. Long-term variability and periodicities

The nonflare temporal variations of solar activity indicators are usually characterized by 3 time scales: (1) short-term variations (over several weeks, caused by solar rotation and the evolution of active regions), (2) intermediate term variations over several months (caused by episodes of major activity or long-lived active regions), and (3) long-term solar cycle variations (Donnelly et al. 1986).

Bouwer (1983) performed an anharmonic frequency analysis of the 1-8 Å SXR background flux for the data from 1977-1981 and found that the frequencies most closely corresponding to the synodic solar rotation period (27.28 days) are concentrated at 22, 25, and 34 days. Donnelly, Hinteregger & Heath (1986) compared the temporal variations of the 1-8 Å flux with the EUV variability and found that the SXR flux exhibits day-to-day variability related to flare activity rather than to EUV emission, and that the short-term variations in SXR are not well-correlated with the 10 cm flux or EUV, sometimes even out of phase (e.g. the 13-day periodicity), or anti-correlated.

The long-term variations of the SXR background flux is different from most of the other standard solar activity indicators: the SXR background flux tends to peak 2-3 years later in the cycle than the sunspot number (Wagner 1988; reproduced in Donnelly 1989; 1990) for cycle 21.

This delay in the peak is also manifest in other solar activity indicators, such as in the coronal green-line (Fe XIV at 5303 Å) emission (in the Slovak
Fig. 1. The GOES 1-8 Å background flux (monthly averages) in Solar Cycle 21 & 22 (middle) compared with solar flare rates in hard X-rays (top: ISEE-3, HXRBS/SMM, and BATSE/CGRO) and soft X-rays (second row: GOES >M1 class flares), 10-cm flux (forth row), and monthly sunspot number (adapted from Aschwanden & Dennis, 1993).

data; Ribansky et al. 1988), or in the hard X-ray and gamma ray flare rate (Aschwanden & Dennis 1993). The variability of the hard X-ray flare rate is not only a function of the number and size of active regions, but also a
function of the magnetic complexity in active regions. Large, complex active regions with highly sheared (nonpotential) magnetic fields are more likely to produce X-ray flares. The fact that the peak amplitude of the hard X-ray flare rate steadily increases over 3 years after the first sunspot maximum may be interpreted in terms of increasing complexity in coronal structures during the decay phase of the solar cycle. Consequently, solar activity indicators of coronal origin, such as the SXR flare rate or the SXR background flux are expected to mimic the same behavior, and may, therefore, deviate from photospheric and chromospheric activity indicators.

4. The origin of the solar soft X-ray flux

The spectrum from 1-8 Å is a combination of continuum and line contributions, produced by free-free bremsstrahlung, free-bound recombination, and two-photon emission (Mewe 1972; Kato 1976; Mewe & Gronenschild 1981). Generally, the 1-8 Å flux is dominated by continuum emission, and the contribution of line emission varies from 18%, at 30 MK, to 54%, at 6 MK (Thomas, Starr & Crannell, 1985). The excitation of SXR line emission strongly depends on the temperature of the plasma and varies drastically from quiescent active region conditions to flare conditions. In the 1-8 Å range, the SXR flux is dominated by contributions from the hotter corona (> 10⁶ K), while the contributions from the cooler parts of the corona are negligible. Thus, the sensitive temperature range of the 1-8 Å SXR flux is complementary to that of the EUV flux, which is sensitive to cool (< 10⁶ K) plasma in the chromosphere and transition region. The SXR flux is optically thin and does not show a center-limb variation (Mosher 1979) as the 10 cm flux does (Donnelly 1982).

The solar 1-8 Å flux is believed to originate from heated plasma confined in closed magnetic loops in active regions. In earlier models, the disk-integrated SXR flux was simply modeled by summing the SXR emission measure from a variable number n of active region loops (with cross-section A_l and length L_l), neglecting contributions from the quiet sun outside active regions:

$$\Phi \approx a(T) \int N_e^2 dV \approx a \sum_{\text{Active Regions}} [n A_l L_l N_e^2 \Phi(\alpha)/\Phi(0)]$$

where the center-to-limb dependence $$\Phi(\alpha)/\Phi(0)$$ as function of the aspect angle is constant for optically thin SXR, and has a FWHM of \(\approx 205^\circ\) due to the coronal altitude of the SXR-emitting plasma (White 1964; Donnelly et al. 1982). Imaging observations are imperative to disentangle the origin of the various components contributing to the full-disk integrated SXR flux. The analysis of a solar eclipse observation showed that 98% of the disk-integrated SXR flux came from 4 active regions (Bornmann & Matheson
1990). Soft X-ray images from SKYLAB or YOHKOH confirm that the soft X-ray flux outside active regions, especially in coronal holes, is drastically decreased. From YOHKOH observations, a typical temperature of 5.7 MK and an emission measure of $5 \times 10^{28} \text{ cm}^{-5}$ was determined in a bright loop of an active region, while the corresponding values for the quiet corona were found to be 2.7 MK and $1.3 \times 10^{26} \text{ cm}^{-5}$ (Hara et al. 1992). Thus, this active region loop contributes a factor of $\approx 300$ more to the SXR flux than an equal area from the quiet corona.

YOHKOH observations allow us to estimate the solar irradiance level of the quiet Sun in SXR by subtracting out the dominant contributions from active regions. The GOES background level amounts roughly to the C1-class level ($10^{-6} \text{ W m}^{-2}$) during the solar maximum, and drops to the A1-class level ($10^{-8} \text{ W m}^{-2}$) during the solar minimum. Although the contribution from active regions in these SXR background fluxes is minimized, there are additional local fluctuations of the quiescent SXR emission level due to remnants of old active regions, X-ray bright points (supposedly tiny bipolar magnetic regions), arcades of quiet Sun loops, filament channels, emerging flux regions, polar plumes, and coronal holes (zones with open magnetic field lines). K.Strong (private communication) found that X-ray bright points typically have a SXR flux (SXT/YOHKOH count rate per pixel) exceeding the quiet Sun flux by an order of magnitude, while coronal holes typically exhibit a flux an order of magnitude below the quiet Sun flux. Because of the softer response of YOHKOH (5-45 Å) compared with GOES (0.5-8 Å), a scaling law of $F_{YOHKOH} \propto F_{GOES}^{1/3}$ was found for the full-disk integrated SXR flux measured by both instruments, based on statistics during the period of 1993 May 1-20, in the range of GOES B- to M-class levels (K.Strong, private communication). Correcting for their area compared with the full Sun disk, X-ray bright points add little to the full-disk integrated SXR flux, while the presence of coronal holes can reduce the full-disk integrated SXR flux seen by YOHKOH by a few 10%. Given the nonlinear scaling between GOES and YOHKOH full-disk flux, coronal holes are expected to reduce the total quiet Sun flux seen by GOES by up to an order of magnitude, that corresponds to the Z1-class level ($10^{-9} \text{ W m}^{-2}$) during the solar minimum. This low irradiance level cannot reliably be measured by GOES (because of low count statistics and contamination from magnetospheric particles), while SXT/YOHKOH still records a (disk-integrated) count rate of $\approx 10^6 \text{ c/s}$.

5. Concluding remarks

The solar soft X-ray flux exhibits a variability by a factor of more than $10^6$ between the largest flares and quietest periods. Even by subtracting out solar flares, the so-called SXR background flux still varies a factor of $\approx 10^2 - 10^3$.
(depending on the time scale of averaging) between solar maximum and minimum, completely governed by free-free bremsstrahlung and line emission of heated flare plasma confined in active region loops (mainly post-flare emission). Even the quiet component of the corona (without active regions) is estimated to vary by an order of magnitude due to the varying size of coronal holes and quiet Sun loops. Given this variability, there is no such thing like a “solar constant in soft X-ray irradiance”. The understanding of the variability of the full-disk integrated SXR flux crucially depends on the evolution and confinement of heated plasma in flaring active regions.

References


