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Research Article

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The variance of solar soft X-ray fluxes

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Abstract The timeseries of GOES soft X-ray data contains clues about the nature of the heating mechanism(s) of the solar corona. This paper focuses on a basic statistical analysis: the correlation of the mean flux S and its variance $var(S)$. Using Taylor’s law $var(S) = a\langle S \rangle^\alpha$, we can distinguish different degrees of coherence in the variability via the fitted value of the exponent; $\alpha = 1$ implies Poisson statistics. For the GOES 1–8 Å timeseries we find α to be substantially greater than unity for the entire dynamic range of the observations, which cover an eight-year period embracing both quiet times and flare-active times. A single value of $\alpha = 3.06 \pm 0.05$ characterizes the whole data set, 2018–2025, with no evidence for variability in time or any dependence on the base-level flux. This indicates that flares dominate the statistics to well below GOES A-class levels. The fact that the same correlation applies to quiet times as well as active times suggests that there is no need for a different physics to explain the heating of the quiescent corona. This finding does not exclude episodic heating mechanisms, but the heating events do not occur randomly.

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1. Introduction

The GOES soft X-ray observations have a central role in any discussion of solar flares. Not counting the Carrington event and white-light flare observations, the chromospheric H α line emission was the staple observable of the flare process until the space age. From 1975 the systematic X-ray observations from the Geostationary Observational Environmental Satellites – GOES – soon became the definitive characterization of flare magnitude. The technology has changed (Woods et al. 2024) but the 1–8 Å band has remained constant and the database relatively well standardized. Machol et al. (2026) describe how this has worked

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over the long history of this measurement. We note that $H\alpha$ and soft X-rays have a close relationship physically, even though one is chromospheric and one is coronal (e.g. Thomas and Teske 1971).

Given this long history of observation, and the central role that soft X-rays play physically, there have been many studies of flare statistics. These have focused on occurrence distribution functions, which describe the frequency of flare occurrence as a function of flare magnitude (usually from the peak 1–8 Å irradiance as expressed in terms of the well-known GOES class system (e.g. Machol et al. 2026)). See Aschwanden and Freeland (2012); Hudson et al. (2024) for recent studies. Related to this, there is a body of work on waiting-time distributions (Wheatland, Sturrock, and McTiernan 1998; Katz 2024). These studies often use other event proxies, rather than GOES soft X-rays, but for Sun-as-a-star observation each of them can be linked to event energy.

In this article we explore another statistical tool, the dependence of the time-series variance as a function of the fluxes from the GOES 1–8 Å timeseries, with mean value $\bar{S}$. We interpret this via Taylor’s law, Equation 1.

$$var(S) \propto \bar{S}^\alpha, \quad (1)$$

where $\alpha = 1$ for simple Poisson statistics. Taylor’s law is an empirical relationship known from the field of ecology (Taylor 1961) and applied successfully to a wide range of natural phenomena. It is termed “fluctuation scaling” in physics (Eisler, Bartos, and Kertész 2008). The value of the exponent α depends upon the underlying physics. Surprisingly, there may be no other literature on this scaling description as applied to GOES data, other than a mathematical study by Fryzlewicz, Delouille, and Nason (2007).

The fundamental interest in this investigation lies in the exploration of the non-Poisson statistics of the GOES data. This reflects the physics of the mechanisms required to maintain the high temperature of the corona (e.g. Klimchuk 2006). Among the many theories proposed, one can distinguish episodic mechanisms (Sturrock et al. 1990), analogous to stick-and-slip descriptions of friction, from steady ones. Famously Parker (1988) proposed “nanoflares” as a framework for coronal direct heating by the random occurrence of small magnetic reconnection events. Interpreted literally, this idea conflicts with the occurrence distribution functions observed for solar flares (Hudson 1991; Wheatland, Sturrock, and McTiernan 1998).

The direct application of Equation 1 to the GOES time series meets an interesting problem: the flat occurrence distribution function of solar flares (Hudson 1991) does not have a well-defined mean. Accordingly the variance estimation requires rebinning of the timeseries onto a specific time scale. The GOES time series generally show broad-band variability at low flux levels, plus flares. We adopt two binning scales here: hourly, in order to distinguish flare-dominated from quiet-time behavior, and daily, to suppress the variance due to the flare process itself. We discuss the results for the native 1-s GOES sampling but obtain the main results from 1-min integrations.

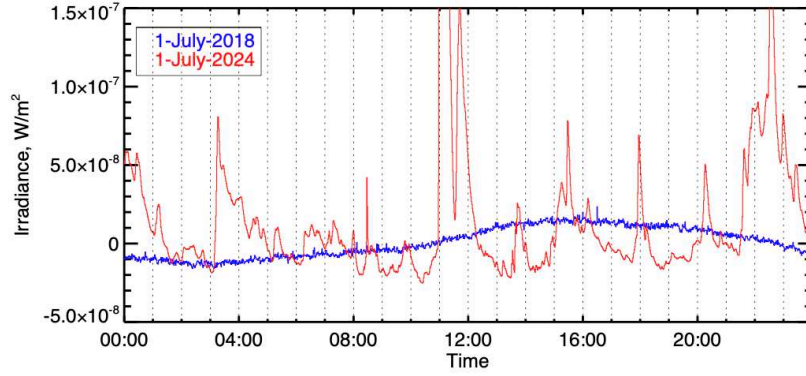


Figure 1.: Two representative days, showing the nature of the variability we characterize. The blue (quiet) and red (active) lines are residuals against the median value for each day, shown this way to facilitate intercomparison on a common scale. The dotted lines show the one-hour bins as adopted for measuring the variance at this time scale, and these plots show one-minute integrations.

2. Data

2.1. Hourly binning

We generate annual correlation diagrams of one-hour data intervals and plot the variance against the mean value for each interval, using exclusively the modern GOES-R data over 2018-2025. This specific choice of one hour, by inspection of typical GOES time series, will often have intervals that do not contain a recognized flare. Based on soft X-ray imaging data, such “quiet Sun” intervals occur in the absence of solar active regions and may reflect the global corona, as opposed to flare intervals that obviously do not. The GOES timeseries in Figure 1 show the nature of the data, comparing representative solar-quiet and solar-active days, along with dotted lines to mark off hourly bins.

The quiet day (blue line in Figure 1) shows almost no organized variability except for the nearly diurnal slow variation. This results from unwanted signal due to geomagnetically trapped electrons (the Van Allen belts) often detected at geosynchronous orbit. These fluxes which may also show broad-band variability as discussed previously in a different context by Hudson (2025). By comparison, the active day (red line) has enormous swings due entirely to solar X-rays, with five identified flares (C2.0-M2.1) plus much other variability. The quiet day may also have broad-band solar variability (microflares detectable in imaging data may not be detectable in Sun-as-a-star data), but at a lower level buried in known and unknown sources of low-level variability that have a Poisson appearance. We discuss this issue further in an Appendix.

The plots in Figure 1 show one-minute integrations, but the current data from GOES-16 through GOES-19 actually have 1-sec resolution. Figure 2 shows a variance/mean plot for 2018 for the 1-s data. We can see that most of the variance looks like noise and is indeed not solar in origin, as discussed in more

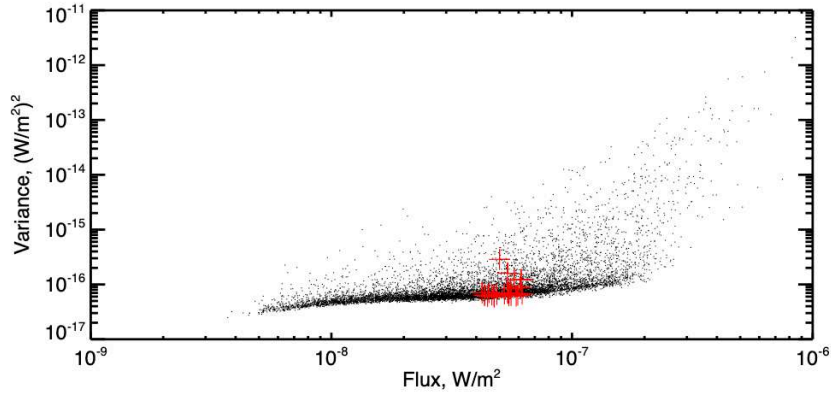


Figure 2.: Variance *vs* mean flux values for 1-s sampling of GOES 1-8 Å data, showing all 1-h intervals in 2018. The red points show the 24 samples for 1-July-2018, as illustrated in Figure 1. The flux range corresponds to flare classes A0.1 to C1. The heavy concentration of points at the bottom is noise, but about 10% of the points extend to the upper right and represent detections of solar photons. No NOAA flares were listed on this day.

detail in the Appendix. The red points in the figure show the 24 hourly samples from 1-July-2018, the representative quiet day. There is some excess variance, with many individual points (approximately 10%) having excess variances above the well-organized grouping of points at low variances. This grouping is dominantly noise signal, with mean apparent fluxes over the range from approximately A0.5 to B2 in terms of GOES class. At these noise levels the GOES data also contain contributions from microflares. More sensitive Sun-as-a-star data can detect these tiny events (Sylwester et al. 2008), and of course they also appear in soft X-ray and EUV imaging observations.

Figure 3 shows correlation diagrams for quiet and active years of the current solar cycle, using the means and variances of the hourly intervals. A distinctive pattern appears: the sharp right-hand edge of the occurrence pattern. The same pattern obtains for both years, but while the 2018 variation is largely in the GOES A-class range (mostly from flares not reported as such by NOAA), the 2025 data concentrate at higher mean values (equivalent to GOES classes above B5) because of the solar-cycle variation of the background soft X-ray flux level. The sharpness of the edge results from the fact that a 1-hour sample containing the onset of a flare will have a large variance, whereas a sample containing the gradual phase will have a smaller one, owing to the basic asymmetry of flare development: fast rise and slow decay. This pattern can be captured empirically, as done for example by Davenport et al. (2014) for stellar flares. But the basic point can be illustrated with a rudimentary model flux variation such as $S(t) = 1 - t/t_0$, an instant rise followed by a linear decay on time scale t_0 . This implies $\text{var}(S) \propto (1 - t/t_0)^3$, extended in time and therefore consistent with the asymmetry in the correlation plot.

The hourly correlation plots show a consistent pattern in all years, which we capture approximately with Figure 4. This shows the correlation of the

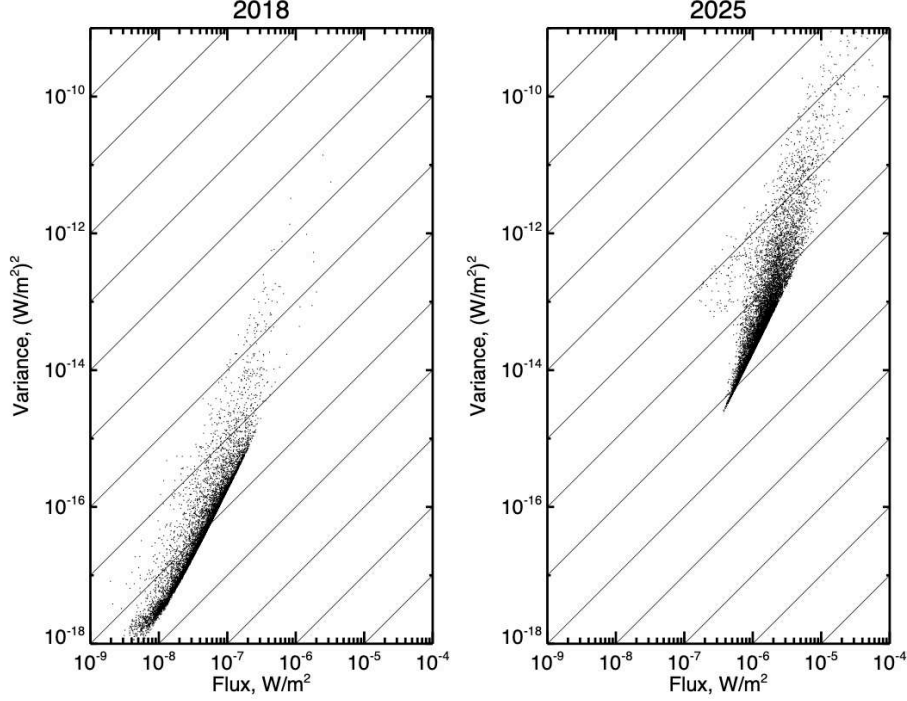


Figure 3.: Correlation diagrams for 1-minute sampling over 2018 (solar minimum) and 2025 (solar maximum), plotting variance vs. mean for all of the 1-hour intervals in each year (nominally 8808 points). The diagonal lines show the $\alpha = 1$ pattern expected from a Poisson process. In terms of GOES flare class, these plots cover A0.1 to X1.0.

means of variance and flux by year, ignoring the obvious bias from the sharp edge of the scatter diagrams. This naive fit shows a power law $var(S) \propto \bar{S}^\alpha$ with $\alpha \approx 2.0$, distinctly different from the Poisson expectation of $\alpha = 1$. This correlation extends from the greatest flares down to the Class A level of peak fluxes, 10^{-9} W/m^2 . We can refine this result by using 1-day binning, as described in the next section.

2.2. Daily binning

A similar analysis based on daily averages will strongly tend to be dominated by the flare component of the time series, rather than a physically different contribution. Figure 5 (analogous to Figure 3) shows results for quiet and active years. As with the hourly binning, we only use datasets with no missing data points; this means relatively more data rejection for the full-day sampling. The 2025 panel shows a relatively tight correlation, $var(S) \propto \bar{S}^{3.50 \pm 0.12}$, with a minimum daily flux level at about GOES class B5. In earlier years the correlation is not so tight, has a smaller slope, and reveals additional variance at the quietest times.

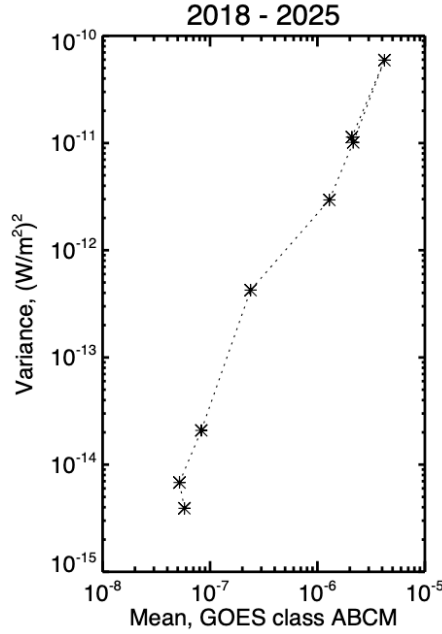


Figure 4.: A crude summary of the overall variance/flux correlation trend, based on the hourly integrations in the 8 annual datasets.

With daily averages we find that the effect of the asymmetric sampling of flare time profiles disappears, and we can make more representative estimations of the slopes for each year. Table 1 lists the slopes of the annual datasets, including some points from both primary and secondary GOES spacecraft because of the relatively low success rate for completely continuous data days in the early years of the study. The weighted-mean result for all years together is $\alpha = 3.06 \pm 0.05$. The time-series plot of these yearly results, Figure 6, shows no evidence for time variability on solar-cycle time scales, even though the GOES background level varies by two orders of magnitude.

3. Interpretation

The variance of the GOES time series at the 1-s native sampling of the current GOES/XRS data is dominated, at low flux levels, by noise of non-solar origin (see Appendix B). Accordingly our analysis in this article deals only with 1-min integrations. Appendix A shows the individual flux/variance correlations for each year in our analysis, using 1-day binning to extract variances and means.

We have clear conclusions from the behavior of the variance: it is distinctly not Poisson, even at the lowest levels where we might expect different physics and a different variance behavior from the global corona, as opposed to the active regions and flares. Second, there is no obvious solar-cycle dependence, and so the flare-dominated nature is a stable feature of the solar soft X-ray emission

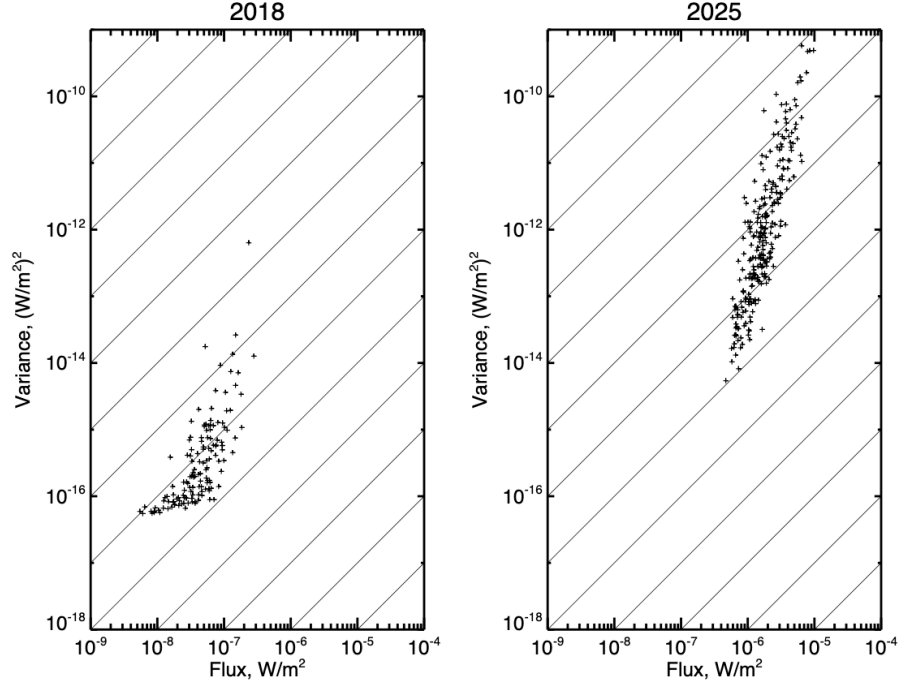


Figure 5.: Correlation diagrams for daily sampling, again comparing 2018 (solar minimum) and 2025 (solar maximum), plotting variance vs. mean for the valid 1-day intervals in each year (nominally 365 points, but substantially fewer because of the likelihood of data errors). The diagonal lines show the $\alpha = 1$ pattern expected from a Poisson process. In terms of GOES flare class, these plots cover the range A0.1 to X1.0. See Appendix A for all 8 annual correlation plots.

Year	Satellite	Samples	Slope
2018	GOES-16	50	2.92 ± 0.32
2019	GOES-17	56	2.82 ± 0.20
2020	GOES-17	103	2.65 ± 0.12
2021	GOES-17	150	2.87 ± 0.11
2022	GOES-18	168	3.02 ± 0.12
2023	GOES-18	189	3.44 ± 0.13
2024	GOES-18	197	3.14 ± 0.12
2025	GOES-18	232	3.50 ± 0.12

Table 1.: Correlation slopes for annual data sets

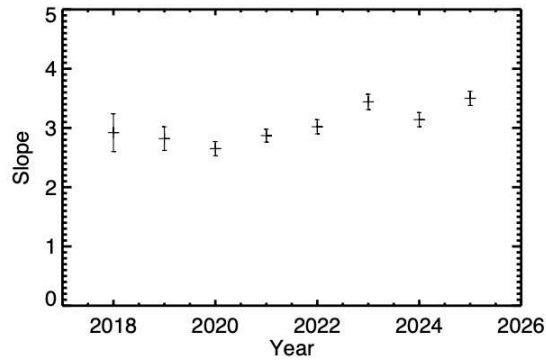


Figure 6.: The year-by-year estimates of the exponent α (Equation 1) of the flux/variance correlation.

in general. From these data alone we cannot describe the physical nature of the deviation from Poisson statistics. The large value of α implies correlations in the time domain, which the pattern of flare occurrence (Hudson 1991) and waiting times (Wheatland, Sturrock, and McTiernan 1998) also shows. These correlations could be present in some form of episodic heating (nanoflares; see *e.g.* Klimchuk, 2006) or any other mechanism (for instance, flares frequently exhibit quasi-periodic variations with large amplitudes (Parks and Winckler 1969; Simões, Hudson, and Fletcher 2015)).

4. Conclusion

We have applied a little-used tool for statistical analysis of GOES soft X-ray data, the correlation between the variance of a data set and its mean. This tool is widely used elsewhere in studying natural phenomena, and was first systematically applied to population statistics in ecology. The GOES data follow Taylor’s law (Equation 1), as Taylor (1961) and many others have found for numerous phenomena throughout nature.

The entire GOES timeseries presents a quandary: because of the power-law nature of the occurrence distribution function, the mean is not well-defined. Alternatively, we can test Taylor’s law instead for the mean properties of specified intervals. In this article we arbitrarily use one-day intervals, which are long enough to capture the time scales of the variation due to individual flares. The resulting correlation plots have a uniform character across the solar cycle and for a wide corresponding range of flux levels: the net power-law slope $\alpha = 3.06 \pm 0.05$ strongly conflicts with the expectation for random occurrence with Poisson statistics. This value confirms the presence of coherence in the occurrence pattern of flares, and suggests the existence of a new scaling law for flare activity. The proximity of our result to an exact value of 3 strengthens this suggestion, which warrants further research. The primary result of these correlations is that a single physical phenomenon – the solar flare – dominates

all solar soft X-ray emission detected by GOES, even down to magnitude scales substantially below those for which flares are typically recognized and classified.

This finding does not exclude Parker’s nanoflare hypothesis as an explanation for heating the global corona, but does require that the nanoflares follow a coherent pattern and suggests the need for a theoretical description of how this may work. From the GOES point of view, such tiny events may contribute to the variance that could be observed by more sensitive observations that can respond below the GOES A-class level, where other sources of variance begin to dominate.

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5. Appendix A: Full coverage

Figures 7 and 8 show annual plots completing an 8-year overview of the rise phase and maximum of Solar Cycle 25. These plots show correlations between GOES/XRS 1-8 Å flux and its variance on one-hour integrations.

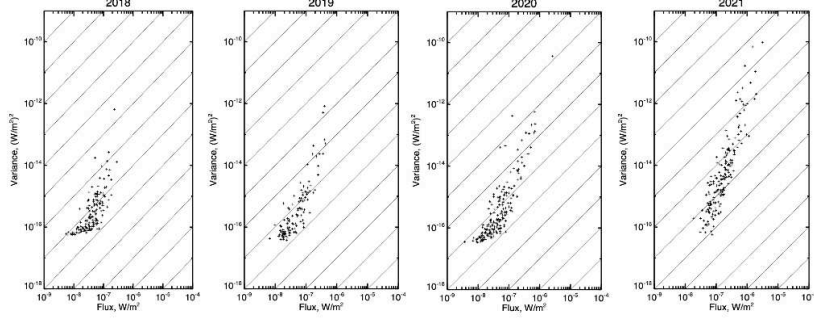


Figure 7.: Same format as Figure 3 but showing the years 2018-2021, the rise phase of Cycle 25.

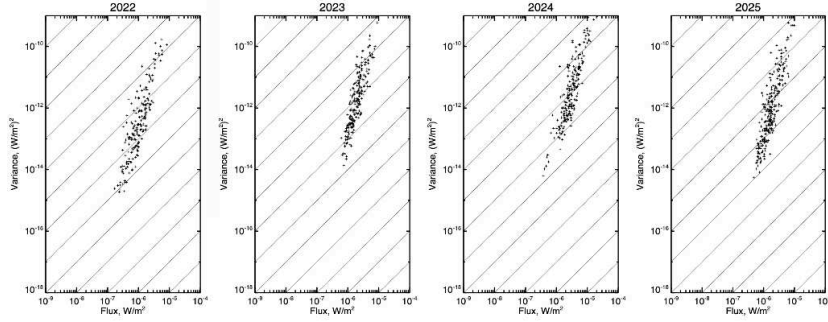


Figure 8.: Same as Figure 7 but for the years 2022-2025, the maximum phase of Cycle 25.

6. Appendix B: GOES-R at low flux levels

The analysis of GOES variance in this article makes use of the standard data product, *i.e.* the public-domain data files provided by NOAA¹. This precludes a full analysis of the data variance at low flux levels; this background has a complicated origin that could better be addressed via the raw data and its ancillary information. This Appendix describes what a user can safely conclude from the standard data product (see also Hudson 2025).

¹<https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes>

Figure 9 plots three days around the selected quiet day 1-July-2018, as shown earlier in Figure 1. Now with three days we confirm the presence of a non-solar contribution, as betrayed by a clear diurnal pattern. Additionally, the comparison between the 0.5–4 Å (XRSA) and 1–8 Å (XRSB) channels (rough equality) shows that the background counts are not photons, but particles – a solar X-ray spectrum would have a much smaller XRSA flux.

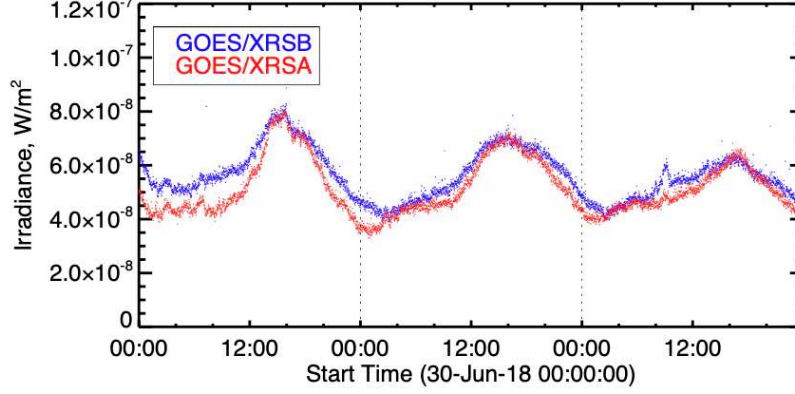


Figure 9.: Three days of GOES 0.5–4 Å (XRSA) and 1–8 Å (XRSB) fluxes, one-minute averages, at solar minimum and near the time of full Moon (in thinking about possible systematic effects!).

The particle data come from Van Allen Belt electrons (e.g. Machol et al. 2026), and coincidentally have a very stable presence in this case. Note that a correction for the presence of electrons already exists in the Level-2 data plotted here; the GOES spacecraft have an independent detection capability for these electrons, but it unfortunately this correction has systematic discrepancies. For a peek at electron background on disturbed days, see the discussion in Hudson (2025). The variance of the total signal S therefore includes several terms:

$$\text{var}(S) = \text{var}(F_{\odot}) + \text{var}(F_e) + N_{\odot} + N_e \quad (2)$$

where S is the data, a fluence from a given time interval; $F_{\odot}$ and F_e are photon and particle fluences, and $N_{\odot}, N_e$ are the detected photon and electron counts, which have Poisson statistics. Correlations among these terms might make it possible to understand the variance in solar irradiance at a level below the GOES class 0.1A level (*i.e.*, the possibly distinct emission from the quiet corona).