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Do Stellar X-ray Observations Provide Evidence For Solar-like Cycles?

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Abstract.
Utilizing 10 years of Yohkoh data, spanning nearly a complete solar cycle, we investigate the statistical variations of solar X-ray fluxes in the stellar context. The Yohkoh soft X-ray data can be described by the combination of a smoothly varying function representing the solar cycle plus a lognormal distribution representing the day-to-day variability in the lowest energy bands. Using data from the SXT filter which most closely resembles the ROSAT PSPC or Einstein IPC bandpasses, we examine the distribution of two "snapshot" samples of the Sun's X-ray emission taken at varying points in the cycle. Comparison with the ROSAT and Einstein "snapshots" of Hyades G stars strongly suggests that these more active "suns" have very long cycles, weak or no cycles, or cycles which are integral or sub-multiples of the solar cycle.

1. Introduction

A key question in cool star research is which, if any, solar-like stars have X-ray activity cycles like the Sun. The Mt. Wilson studies of Ca II (Baliunas et al. 1998) suggest that stars of moderate to low activity levels show solar-like cycles; however, in X-rays this evidence is marginal (Hempelmann et al. 1996). For high activity stars, such as RS CVn systems, the data are too sparse, while in the case of the Hyades F-K dwarfs, no evidence for cyclic activity exists (Stern 1998; Stern, Schmitt and Kahabka 1995). Finding comparable solar data over a complete cycle has also been problematic (see Stern 1998). Fortunately, the Soft X-ray Telescope (SXT) on Yohkoh (Tsuneta, et al. 1991) has now completed almost 10 years of continuous observations, providing a uniform, well-calibrated X-ray data base spanning a solar cycle. In this paper, we investigate the statistical properties of the SXT data and perform simulated "snapshot"-like observations of the Sun as a star in order to better understand the limited sample of long-term stellar X-ray variability.

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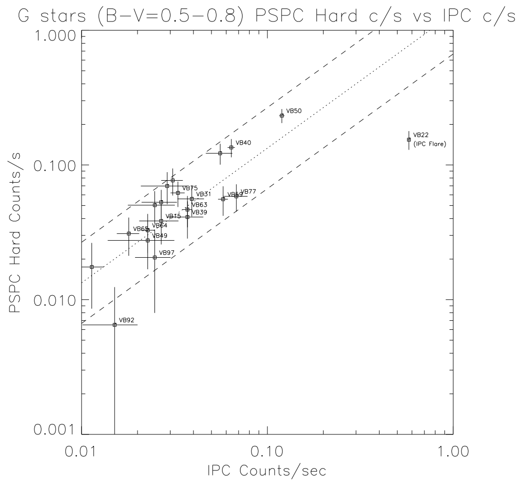

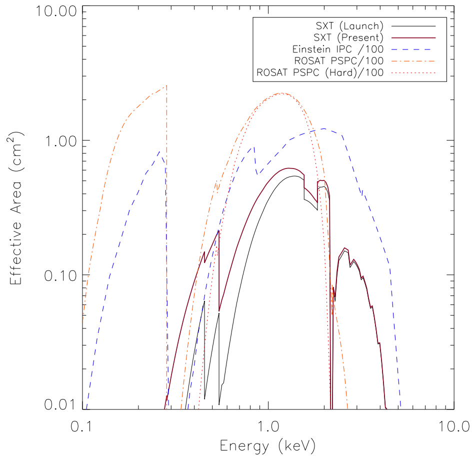

Figure 1. (left) Einstein IPC and ROSAT PSPC observations of Hyades G stars.

Figure 2. (right) Effective Areas for SXT Al.1 (at launch/present), PSPC (broad/hard bands), and IPC.

2. ROSAT and Einstein Observations

In Figure 1 we show the ROSAT PSPC (hard band only) and Einstein IPC count rates for a common set of 21 F8-G5 (B-V = 0.5-0.8) Hyades stars (cf. Figure 14 in Stern, Schmitt, and Kahabka 1995; Micela et al. 1988). The dotted line is an approximate conversion ratio between ROSAT (hard) and IPC counts, and the dashed lines represent factors of two higher or lower than this conversion factor. It can be seen from the figure that nearly all of these stars lie within the defined factor-of-two range. The notable exception, VB22, produced a flare during the Einstein observations and was reported as such in the Micela et al. (1988) paper. Thus this figure suggests that the $\sim$10 year difference in observing dates between the two missions reveals little, if any change in the stellar X-ray flux.

3. Yohkoh SXT Observations

Because of its similarity to the ROSAT PSPC hard band, we use the SXT thin Aluminum filter (denoted Al.1) in our analysis. (see Figure 2). We also point out that the SXT uses a CCD detector, which has a response weighted by photon energy, unlike the PSPC or IPC.

The sensitivity of SXT has increased throughout its 10 year lifetime, and its temperature response has evolved because of the progressive failure of its entrance filters. These changes have been corrected in our analysis by deriving a daily color temperature and emission measure from 2-filter observations and then normalizing the SXT Al.1 response to its first-year configuration. This procedure has been shown to be quite accurate by Acton, Weston, and Bruner (1999).

4. Characterizing The Yohkoh Cycle

Our observations consist of full-sun daily average irradiances in SXT instrumental units. The diurnal variability of the SXT data set is, with the exception of flares (which we specifically exclude), nearly identical to the daily average variability. In Figure 3(a) we show the daily average flux in units of DN/s (proportional to the number of electrons/s in each full-sun image) for the Al.1 filter data set. The cycle-long SXT data confirm that, from solar maximum to minimum, the X-ray flux in the Yohkoh passband changes by a factor of ~30.

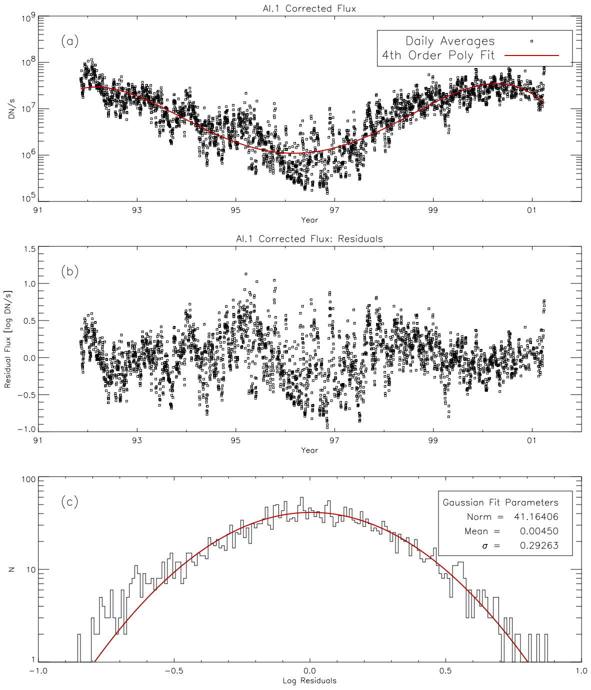

Figure 3. (a) Corrected Yohkoh Al.1 data with polynomial fit. (b) Fit residuals (log). (c) Gaussian fit to residuals (lognormal distribution)

As an example of how the SXT cycle-long database may be utilized, we fit a 4th order polynomial function to the logarithm of the SXT flux - shown as a solid red line in Figure 3(a). It is then instructive to plot the logarithm of the residuals to this fit, as shown in Figure 3(b). Finally, we show the histogram of these residuals, and a gaussian fit to them in Fig 3(c). This demonstrates that the solar cycle soft X-ray data is well-described by the combination of a smoothly varying polynomial (or possibly another continuous function which describes the log of the flux) and a lognormally distributed day-to-day variability. The lognormal (Aitchinson and Brown 1963) is a well known statistical distribution which arises in processes where successive observations are proportional to previously observed values. We will investigate the implications of this parameterization of the solar cycle in a later work; for now, we concentrate on the observed SXT fluxes themselves.

5. Solar Cycle Snapshots

Of particular interest is the question: *if we took random snapshots of the Sun at two different phases in its cycle, what is the probability that the two X-ray fluxes would be within some factor of each other?*, e.g. the factor of two or so that we see in the ROSAT/IPC comparison. As a first step, we can examine the correlation between a given SXT daily rate, and the same observation taken a known difference in cycle phase later. For the purposes of this investigation, we have taken the cycle length to be the span of the Yohkoh observations, or 3429 days ($\sim$ 9.4 years). When comparing two observations, we use modulo arithmetic to wrap this "cycle" back upon itself. The results of this analysis are shown in Figure 4 as flux-flux plots for 16 equally spaced points during the cycle. The solid and dashed lines in each figure represent a perfect correlation and factors of two on either side of this. It is clear that, as the phase difference increases beyond $\sim$0.1, the correlation rapidly disappears, and reappears as an anti-correlation at phase $\sim$0.5. This is all perfectly understandable: the question is, how can we best relate these results to the stellar observations? More specifically, what is the probability that a set of randomly observed solar X-ray snapshots would result in a distribution like that in Figure 1?

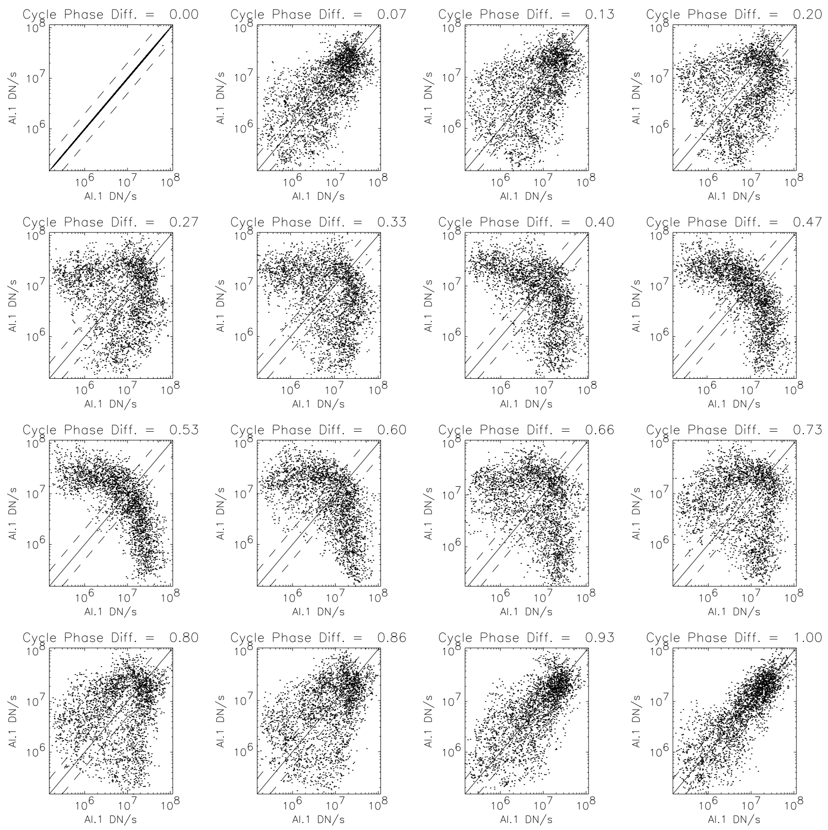

Figure 4. Flux-flux correlations in actual data at different cycle phases

6. Estimating The Probability

To determine the relevant probability distribution, we draw 100 flux-flux pairs with randomly selected phase differences from 0.0 to 1.0, and compute the fraction of these pairs which have values lying within a specified factor of one another. These fractions are plotted for factors of 2, 3, and 4 in Figure 5(a). Three features of the plots are readily apparent:

- At least 20% of the points lie within a factor of two of each other
- This percentage increases as the allowable range is increased
- For all cases considered, the probability that *all* randomly drawn points lie within a factor of two is quite small

To further quantify this, we compute the integral probability distributions for these cases as a function of the fraction of all points lying within a factor N of each other. This is shown in Figure 5(b). It is clear that, under the assumptions of this statistical "experiment", the probability that, say, >80% of the flux pairs would lie within a factor of two of each other is vanishingly small.

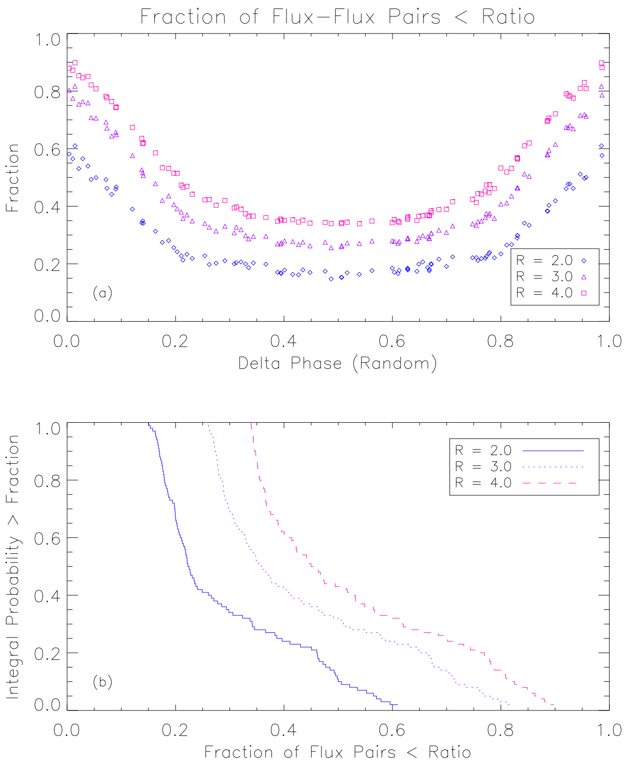

Figure 5. (a) Fraction of flux-flux pairs within ratio (2,3,4) at 100 random cycle phases. (b) Integral probability distribution of fraction having ratios < 2,3,4 for randomly chosen phase difference

7. Discussion

The Yohkoh SXT data provide a rich source of information regarding the Sun as a star. From a modeling viewpoint, the daily average Al.1 filter data are well described by a smoothly varying mean plus a lognormal distribution of day-to-day variability. SXT sees a cyclic variation of a factor of $\sim$30 in the 0.5–4 keV range, and a similar variation of at least a factor of 10 is seen in softer ($\sim$0.25–0.4 keV) SOLRAD data by Tobiska (1994). Although the IPC and PSPC data do not perfectly match these bands, they overlap both energy ranges, and should exhibit a cycle variation somewhere in this range, if they were observing the Sun. Examining "snapshot" solar X-ray data provides a basis to compute probability distributions for similarly obtained data from an ensemble of Suns. On the basis of a comparison with Hyades F-G stars, it appears that either:

- Hyades F-G dwarfs have either very long X-ray cycles, weak cycles or no cycle at all, or
- The sampling interval of 10 years between ROSAT and Einstein corresponds very closely to an integral or sub-multiple number of cycle lengths of the Hyades dwarfs

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