THE SUN AS AN X-RAY STAR: OVERVIEW OF THE METHOD

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Abstract. We present a method to study the solar-stellar connection, i.e., the close similarity of the physical phenomena occurring on the Sun and on late-type active stars, by taking advantage of Yohkoh/SXT X-ray images. From such images, we first find the distributions of the whole disk differential emission measure, and from them we then synthesize spectra analogous to those collected by X-ray instruments aimed at stars other than the Sun. Here we illustrate the application of this method to ROSAT/PSPC and ASCA/SIS, and discuss test cases as well as future applications.

Key words: X-ray - Corona - Solar stellar connection

1. Introduction

Solar observations give us a unique opportunity to study in detail an example of a late type star and, in particular, to examine the spatial structure of the source regions of its X-ray emission. Such observations are not possible for the other late-type stars; it is therefore very important to be able to

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construct a variety of tests of the widely–accepted proposition (cf. papers in Linsky and Serio 1993; Noyes, 1985; Noyes, 1986; Wilson, 1994) that the Sun is in fact a reasonable prototype for coronal activity on such stars (cf. Vaiana et al. 1981). Quite aside from the fact that solar observations allow for spatial resolution (and the stellar observations do not), it is also the case that instruments used to observe the solar corona in general differ substantially from those used for stellar coronal observations; this results in the additional obstacle that measurements of coronal physical properties (e.g., temperature and density) for the solar corona are not easily compared with those of stellar coronae.

This paper addresses these problems by describing a method for exploring the coronal solar-stellar analogy, using the observations from the *Yohkoh* soft X-ray telescope (SXT), as well as providing initial illustrative results. More specifically, by using full disk images, we generate data that a non-solar X-ray instrument, such as *ROSAT/PSPC* or *ASCA/SIS* would collect when observing a star identical to the Sun, thus providing a general framework as well as a tool to compare directly solar and stellar data. The scope of the project includes to trace how the various kinds of structures, regions and phenomena resolved on the Sun's disk influence the stellar-like synthesized X-ray spectra, thus linking some stellar analogues of the phenomena we observe on the Sun with the stellar spectra. For instance, we could fit the derived solar spectra with the standard one- or two-temperature plasma model routinely applied to stellar X-ray spectra and then see how the fitting compares to the factual distribution of temperatures on the Sun's disk.

We present our method in Section 2, and the results in Section 3; our present findings are summarized, and future developments are discussed, in Section 4.

2. The Method

The Yohkoh/SXT data are X-ray wide-band photometric images with 2.5 arcsec angular resolution, at best (Tsuneta *et al.* 1991). These data are not directly comparable to the stellar spectra collected with ROSAT/PSPC ($\Delta E/E \approx 0.45$ at 1 keV) and ASCA/SIS ($\Delta E/E \approx 0.05$ at 1 keV): while these instruments do not resolve the star's disk, Yohkoh/SXT yields only broad-band spectral information.

Our approach is based on deriving the Differential Emission Measure vs. Temperature (DEMT) of the whole solar corona from Yohkoh/SXT images and on synthesizing the stellar-like spectra from the DEMT. From two practically simultaneous images taken with Yohkoh/SXT through two different filters, properly selected among the six available (Fig.1), the plasma temperature (T) and emission measure (EM) in each pixel of the field of view are derived from the ratio of flux measured in the bands determined by the two filters (Tsuneta *et al.* 1991), using the standard Yohkoh data processing. We then obtain an EM vs. T distribution on the Sun's disk by coupling the temperature and emission measure values in each pixel and then generating a histogram of all the emission measure values vs. the corresponding temperature. After dividing the range of temperature detectable by the instrument (nominally from around 10^6 K to a few 10^7 K) into several intervals (or bins) we sum all the EM values within each "bin" and finally divide by the temperature bin width to obtain a graph of differential emission measure (Fig. 1).

From the emission measure distribution, taking into account the plasma emissivity vs. temperature and the instrument spectral response, it is straightforward to synthesize spectra of the Sun as if it were a star observed by other instruments. More in detail, we synthesize the spectrum for each temperature bin of the DEMT, then sum the resulting spectra, taking into account the emission measure of each bin, into a single global spectrum that we finally filter through the instrument spectral response. The synthesis is accomplished with the Analysis System for Astrophysical Plasmas (Maggio *et al.* 1994), developed in IDL for presenting and interpreting the results of models of astrophysical plasmas.

3. Results

The distribution of emission measure, per se, provides interesting information, such as the relative role of plasma at different temperatures in determining the whole Sun X-ray emission and the relative contribution of the various regions on the disk. In this respect it is worth noting, for instance, how the emission measure distribution can be significantly different at different times, given the Sun's variability on various time scales. Fig. 2 shows the DEMT at two phases of solar activity: the very quiet Sun of the present solar minimum (1 June 94, 07:32) and the "active" Sun (27 February 1992, 21:14) with a few active regions. The latter are responsible for the hump in the DEMT around $5 - 7 \times 10^6$ K (cf. also Watanabe *et al.* 1995) as we have verified generating an analogous DEMT distribution after removing the active regions from the image.

Fig. 3 shows the corresponding X-ray spectra, folded through the ROSAT/PSPC spectral response, derived from the two DEMT distributions of Fig. 2. The simulation assumes that the star is located at a distance of 1 pc and the exposure time is 1000 s for the active-Sun-like conditions and 2000 s for the quiet-Sun-like conditions. We also take into account the number randomization due to the photon counting statistics. The number

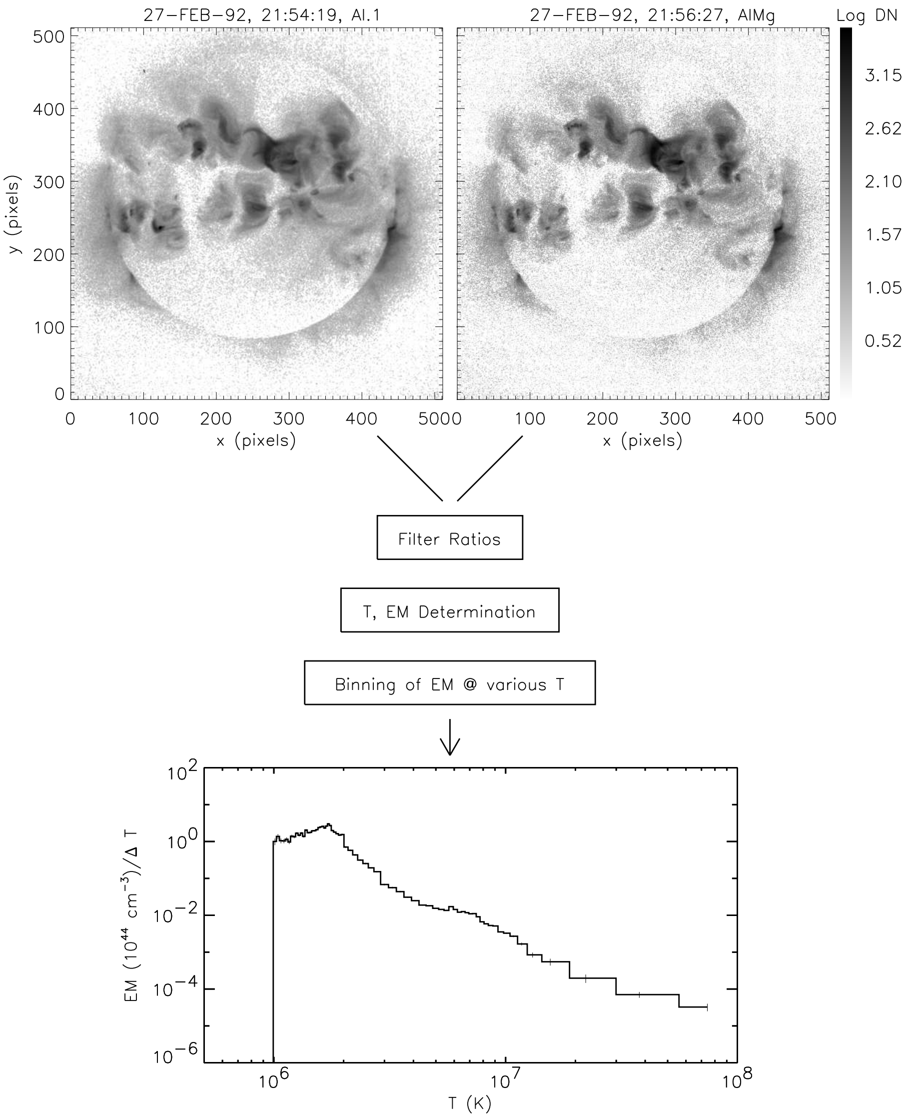

Figure 1. This figure outlines the method to obtain the whole-disk emission measure vs. temperature distribution. Two quasi simultaneous X-ray images obtained by Yohkoh/SXT through two different filters (Al 1265 A, upper left panel; Al 2930 A + Mg 2070 A + Mn 562 A, upper right panel), allow to derive the temperature and the emission measure in each pixel (middle box), on the basis of the calibration of filtered flux ratio. Coupling the T and EM values of each pixel and making an histogram of the emission measure vs. temperature values, we generate a differential emission measure distribution of the kind reported in the bottom panel.

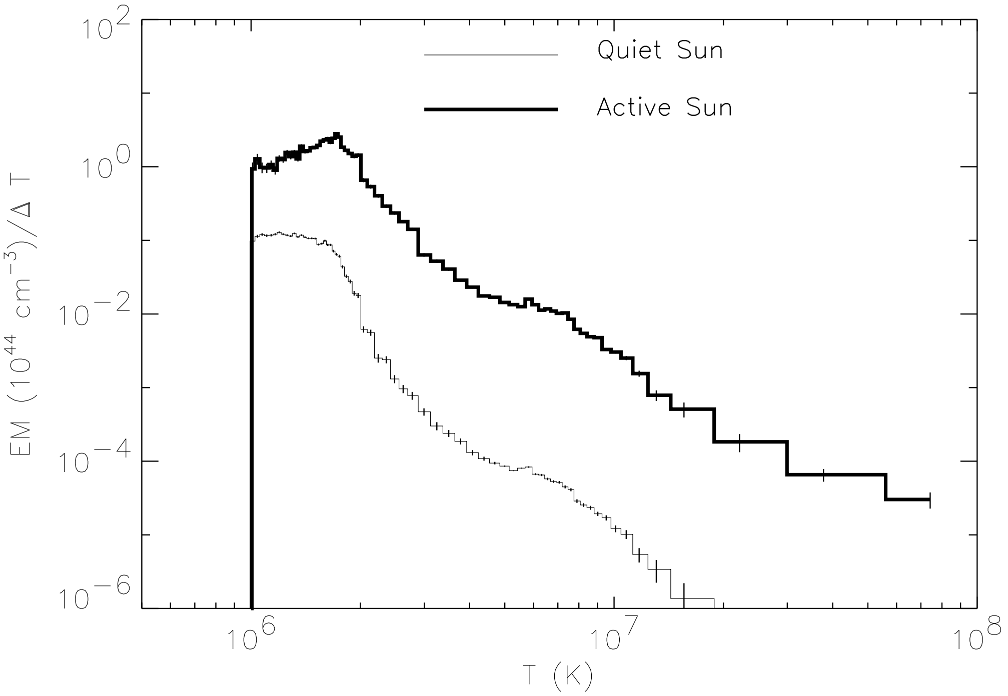

Figure 2. Two markedly different examples of differential emission measure pertaining to different times: a phase with significant activity (27 February 1992, 21:14 - solid line) and a phase without any sign of significant activity on the Sun (1 June 94, 07:32 - thin line).

of counts is amply sufficient to perform a statistically sound analysis on ROSAT spectra; the higher number of photons obtained for the active Sun is typical of a good stellar observation accomplished with ROSAT. These spectra have then been fitted with the one- and the two-component thermal models within the XSPEC environment for data analysis, a method routinely used for ROSAT/PSPC data interpretation. In the same figure the fitted temperature(s) in keV, the relevant fitted emission measure(s), the reduced χ^2 value of the best fitting model, and the number of degrees of freedom in the fitting. While the quiet Sun ROSAT spectrum can be well fitted with only one temperature, the active Sun cannot be fitted with a single temperature component but is well fitted with two thermal components. The first fitting is in good agreement with the findings typical of low activity stellar coronae, the other with moderately active coronae.

Fig. 4 shows the analogous X-ray spectra folded through the ASCA/SIS spectral response. The observed spectra would be obtained with 10^4 s of

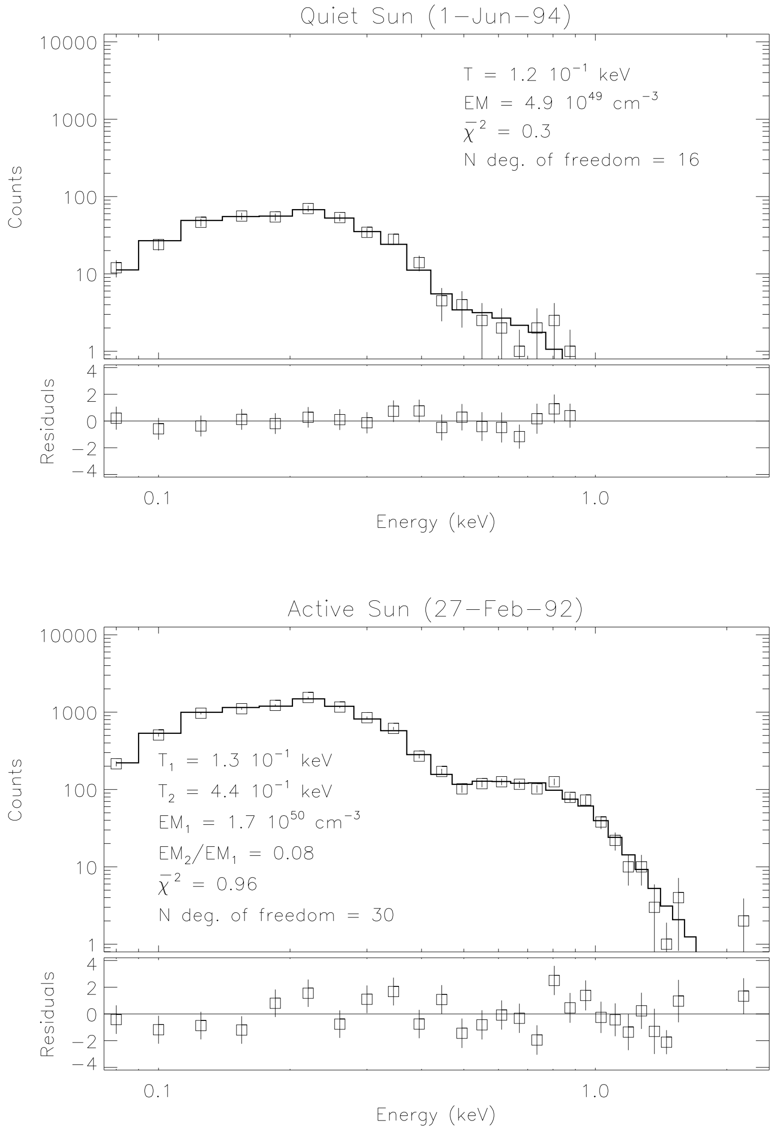

Figure 3. X-ray spectra of a star identical to the Sun observed with the ROSAT/PSPC, derived from the two DEMT's shown in Fig.2 and folded through the instrument spectral response. The star is located at a distance of 1 pc and the observing time is 2000 s for the quiet conditions and 1000 s for the active conditions. The quiet conditions are well fitted with one thermal component, the active conditions with two components. The relevant parameters, described in the text, are shown in the graph.

exposure, for the active Sun, obtaining 3364 photon counts, and 1.5×10^5 s for the quiet Sun obtaining 965 counts. The difference between the spectra of the two phases of the Sun's activity is now even more evident because of the larger sensitivity of ASCA/SIS to high energy photons. The synthesized spectra also show the ASCA/SIS spectral resolution capable to discriminate some lines or groups of lines.

4. Final considerations and future prospects

This method, already at its present level, allows us to characterize the distribution of plasma temperature on the Sun's disk and to identify the effect of active regions and other phenomena.

There is considerable room for refinements and we are presently working on expanding and improving our approach.

On one hand, the derivation of DEMT from Yohkoh images can be refined in several respects. It could be worthwhile to remove the influence of the radiation scattered by the telescope mirrors from the very bright regions of the image onto the very faint ones.

It is also worth exploring the effect of pixel summation, i.e. computing the DEMT after summing signal over "big pixels" made of 2×2 pixels, or 4×4 pixels, or bigger. This would help in reducing the noise which, along with the scattered light, may affect mainly the pixels with low signal and give rise to unrealistic flux ratios and, therefore, temperatures. Such a noise influence can, most likely, be present both in the high and in the low temperature tails of the distribution, respectively $\geq 2 \times 10^7$ K and $\leq 1 \times 10^6$ K, for the combination of filters chosen. In order to reduce the noise influence, the preliminary results here shown do not consider pixels with temperature below 1×10^6 K (on the other hand Yohkoh/SXT has virtually no sensitivity to plasma below such a temperature), or with less than 10 photons. The technique of pixel summation could also show how the DEMT distribution depends on the pixel size and on the unavoidable inclusion of plasma components at different temperatures in the same pixel.

We will take into account these improvements in an on-going work (Peres *et al.* 1997).

By the same token, we plan to include information from other instruments, most notably Yohkoh/BCS, and to fold the synthesized spectra through the spectral response of other non-solar instruments, so as to allow the comparison with a broader set of data. Future work will also include a more extensive analysis and possibly spectra of structures or regions imaged on the Sun's disk.

Yohkoh data, beyond giving highly detailed images and broadband photometry, provide the additional advantage of monitoring the Sun with good time coverage over several years with adequate time resolutions, thus showing many aspects of solar activity and different phases of the solar cy-

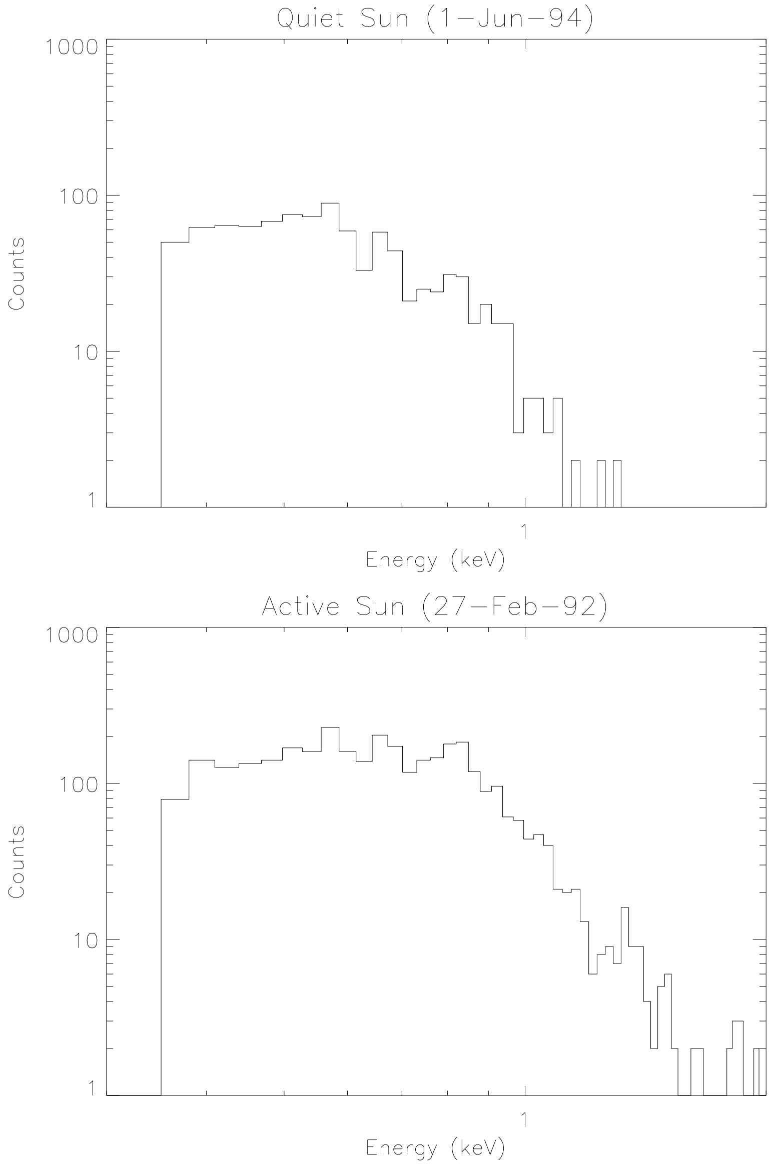

Figure 4. X-ray spectra of the Sun as would be observed with the ASCA/SIS, derived from the two DEMT's shown in Fig.2 and folded through the instrument spectral response. The 965 photon counts of the quiet-Sun-like star would be collected over 1.5×10^5 s. The 3364 photon counts of the active-Sun-like star would be collected in 10^4 s.

cle. It is worth comparing all these different views of the same star, the Sun, with the large diversity found on stars, each star, instead, being observed only occasionally and for short periods, and to evaluate the extent to which such a diversity, found even among very similar stars, may be ascribed to intrinsic variability of individual stars.

This project opens the possibility to use the wealth of the solar X-ray data to provide diagnostics as well as phenomenological models for many events and spectral features observed on stars. It is a direct way to bridge the gap between the solar and the stellar coronal physics and to understand better how the physical conditions on the stars influence the phenomena we see on the Sun, i.e. to investigate the solar-stellar connection.

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