Solar–Stellar Connection: Relevance of Yohkoh Data

S. Orlando, G. Peres and F. Reale

Istituto ed Osservatorio Astronomico,
Piazza del Parlamento 1, 90134 Palermo, Italy

R. Rosner

Dept. of Astronomy and Astrophysics, University of Chicago;
Enrico Fermi Institute, Chicago, Illinois, USA

H. Hudson

Solar Physics Research Corp. Tucson, Arizona, USA

Abstract. The similarity of late–type stars to the Sun is often assumed when studying the physical conditions in their coronae. In order to explore better such a "solar–stellar" connection we use the Yohkoh/SXT X–ray images to generate the distribution of the emission measure vs. temperature of the Sun and, from that, the expected emission, as it would be observed by non–solar X–ray telescopes such as ROSAT/PSPC and ASCA/SIS. We discuss the role of the various solar structures in determining the total distribution of the emission measure vs. temperature and in determining the stellar–like synthesized X–ray spectra.

1. Introduction

The driving idea of this project is to explore the solar–stellar analogy, i.e. the presumption that the coronae of solar–like stars behave in a way similar to that of our Sun.

We consider solar observations as the opportunity to study in detail a late type star and, in particular, to examine the spatial structure of its X–ray emission. However, the instruments used to observe the solar corona differ substantially from those used for stellar coronal observations; therefore measurements of physical properties of the solar corona are not easily compared with those of stellar coronae.

Using the Yohkoh Soft X–ray Telescope (SXT) data we find how the X–ray Sun would look if observed as a star with a non–solar instrument, such as ROSAT/PSPC or ASCA/SIS, thus allowing the homogeneous comparison of solar and stellar observations and the study of the solar–stellar connection in a straightforward way.

Our approach is based on first deriving the Differential Emission Measure vs. Temperature [DEM(T)] of the whole solar corona from Yohkoh/SXT images and on synthesizing the stellar–like spectra from the DEM(T).

As an example, in this paper we use such a method to trace how the various kinds of structures resolved on the Sun influence the X–ray spectra, with the scope to link the phenomena we observe on the Sun with features of stellar spectra.

The paper is structured as follow: in section 2 we briefly outline the method; in section 3 we present the results; and, finally, in section 4 we present the summary and conclusions.

2. The method

In a previous paper (Peres et al. 1997a[1]; in the following paper I), we outlined the method for exploring the coronal solar–stellar analogy, using the observations from the Yohkoh/SXT. In this section, we give only a brief summary of the method, referring the reader to paper I and also to Peres et al. (1997b) and Orlando et al. (1997) for more details.

From two nearly simultaneous images taken with Yohkoh/SXT through two different filters, and using the known ratios of filtered signal vs. plasma temperature (Tsuneta et al. 1991), we derive temperature and emission measure for each pixel in the field of view, i.e. an image of coronal temperature and a matching image of coronal plasma emission measure.

From the temperature and emission measure images, we obtain a distribution of emission measure vs. temperature, by dividing the range of temperatures detectable by the instrument (nominally from a 5×10^5 K to a few 10^7 K) into narrow bins and summing up all the emission measure values within each "bin" of temperature.

Then, we take advantage of the information contained in the DEM(T) distribution to synthesize the spectrum of various part of the Sun, as if it were a nearby star observed with a non–solar X–ray telescope, such as ROSAT/PSPC or ASCA/SIS. The method proceeds as follows: 1) synthesize the relevant emitted spectrum from the DEM(T); 2) fold it through the telescope and detector spectral response; 3) put the Sun at a typical distance (in this work we have chosen 1 pc) and assume to observe it for a time long enough to obtain enough photons for a reasonable analysis. The number of photons in the j–th detector channel are:

$$C_j \;=\; \frac{t}{4\pi\ D^2} \;\times\; \int dE\ A(E)\ M(j,E)\,\frac{1}{E}\ \int dT\ \ P(T,E)\ EM(T) \qquad (1)$$

where t is the exposure time, D is the distance at which we put the Sun, E is the photon energy, $A(E)$ is the global instrumental effective area, $M(E,j)$ is the detector response matrix, T is the plasma temperature, $P(T,E)$ is the spectral emission model and $EM(T)$ is the emission measure derived from Yohkoh data.

The rightmost integral yields the global solar spectrum, the other one folds it through the instrument response. The whole synthesis is easily performed

[1] http://www.astropa.unipa.it/Library/preprint_oapa.html/yohkoh_birth.ps.gz

within the Analysis System for Astrophysical Plasmas (ASAP) developed by Maggio et al. (1994).

We then apply the standard data analysis of the selected instrument to the synthesized spectrum.

3. Results

In paper I, we applied the method discussed above to analyze how the emission measure distribution can be significantly different at different phases of the solar cycle, and, as a consequence, how the corresponding star–like X–ray spectra change. The comparison of all the different views of the same star, the Sun, with the large diversity found on stars can be very helpful to evaluate the extent to which this diversity may be ascribed to intrinsic variability of each individual star.

In this paper we investigate the relative contribution of the various regions on the disk in determining the whole Sun X–ray emission.

As an example, to show the contribution of various parts of the Sun in determining the total spectrum, we considered the Yohkoh observations listed in Table 1 during the solar maximum activity. In Figure 1, we show the low exposure time X–ray image 2 (upper panel) listed in Table 1. From the low exposure time images 1 and 2 (see Table 1), we have selected the active region cores, saturated in the longer exposure images, (selected as those pixels yielding $> 100/78$ phot ms^{-1} pixel^{-1}) in both the Al.1 and AlMg bands, and, from the long exposure time images 3 and 4 (see Table 1), we have selected the regions of intermediate brightness between active regions and very quiet regions, typically of too low signal in the shorter exposure images, (selected as those yielding a number n of photons $100/2668 < n < 1000/2668$ phot ms^{-1} pixel^{-1}) in the same bands. The lower panel in Figure 1 shows the active region cores in black, and the regions of intermediate brightness in gray.

Table 1. X–ray Yohkoh/SXT observations selected to analyze the role of the various solar structures in determining the whole disk DEM(T) distribution.

N.	Date	Time	Filter	Exp. time (ms)
1	27–Feb–92	21:13:47	AlMg	78.0
2	27–Feb–92	21:35:07	Al.1	78.0
3	27–Feb–92	21:54:19	Al.1	2668.0
4	27–Feb–92	21:56:27	AlMg	2668.0

We computed the DEM(T) distributions for the two kind of regions selected above. The DEM(T) of the active region cores has an excess around $5 - 7 \times 10^6$ K which is completely absent in the DEM(T) correspondent to regions of intermediate brightness. This feature is characteristic of active regions as discussed in paper I (see also Watanabe et al. 1995).

Figure 2 shows the X–ray spectra, folded through the ROSAT/PSPC spectral response for the intermediate brightness regions and for the active region

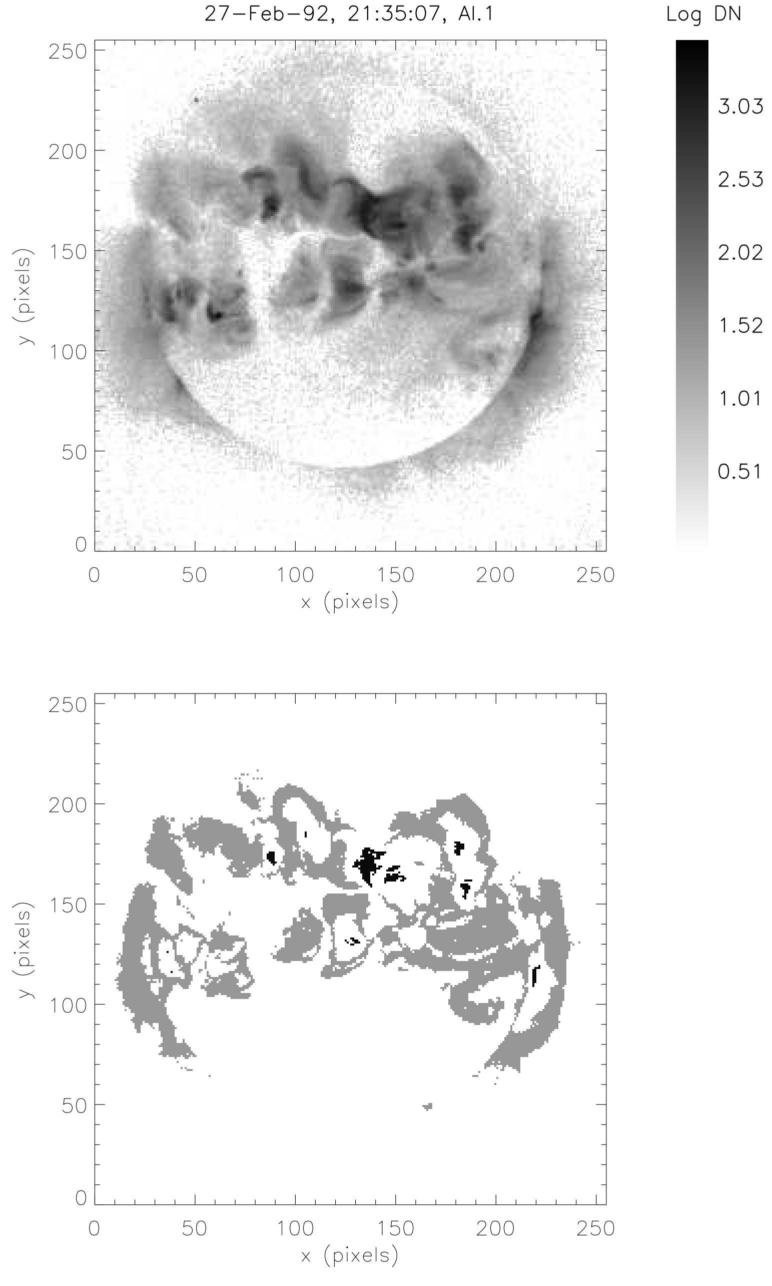


Figure 1. Upper panel: The active Sun of February 27, 1992. This Yohkoh/SXT X–ray image was obtained with a 78 ms exposure time through the filter Al 1265 Å. Lower panel: The active region cores (black) and the regions of intermediate brightness (gray) selected on the disk (see text).

cores, derived from the two DEM(T) distributions. These spectra simulate the X–ray spectra that one would obtain observing only a part of the Sun from a distance of 1 pc. We assumed an exposure time of 3000 s, and we simulated the number randomization due to the photon counting statistics. In both cases the number of counts is sufficiently high to perform good statistically analysis on ROSAT spectra. We analyzed the simulated spectra within the XSPEC environment for data analysis, fitting them with the one–component and the two–component isothermal model spectra usually adopted for the analysis of X–ray observations. In Figure 2, we report the best–fit models (solid curves) and the results of the model fitting (shown in the inset): the fitted temperatures in units of keV and emission measures in units of cm^{-3}, the reduced χ^2 value of the best fitting model, the number of degrees of freedom in the fitting, and the total number of counts.

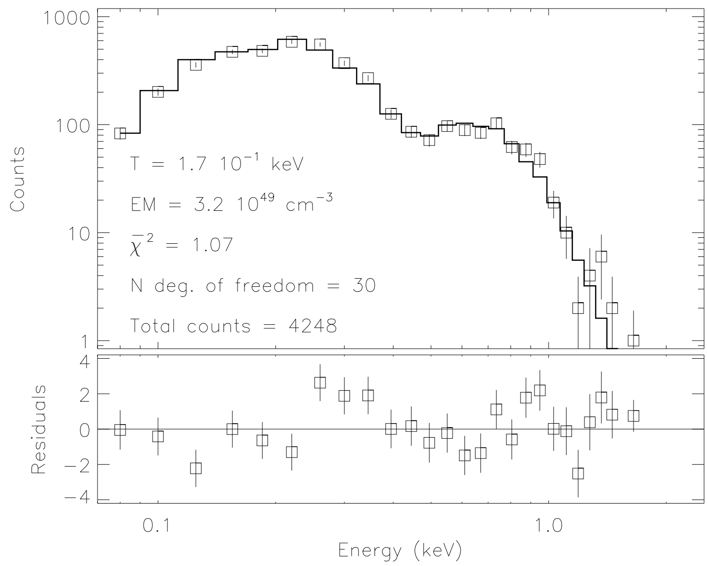
Note that the spectrum corresponding to the parts of the Sun of intermediate brightness can be well fitted with only one isothermal component with temperature $T = 1.7 \cdot 10^{-1}$ keV. Instead, a single thermal component is not sufficient to fit the spectrum corresponding to the active region cores which is well fitted with a two–component isothermal model with $T_1 = 1.4 \cdot 10^{-1}$ keV and $T_2 = 4.5 \cdot 10^{-1}$ keV. It is worth noting that the hump in the DEM(T) of the active region cores around $5 - 7 \times 10^6$ K ($4.3 - 6.0 \cdot 10^{-1}$ keV) is responsible for the second isothermal component in the ROSAT/PSPC spectrum.

In Figure 3, we report the analogous X–ray spectra folded through the ASCA/SIS spectral response. These spectra correspond to what one would obtain observing only a apart of the Sun from a distance of 1 pc, over an exposure time of 3×10^5 s. The results of the model fitting show that the temperatures of the isothermal components are systematically larger than the analogous temperature in the ROSAT/PSPC cases. This effect is due to the larger sensitivity of ASCA/SIS to high energy photons. Note also the capability of ASCA/SIS to discriminate some lines or groups of lines, thanks to its higher spectral resolution.

4. Summary and conclusions

We used a method to study the solar–stellar connection which takes advantage of Yohkoh/SXT solar X–ray observations (see paper I), to analyze the role of various solar structures in determining the total distribution of the emission measure vs. temperature, DEM(T), and to trace how these structures resolved on the Sun's disk have a role in the stellar–like synthesized X–ray spectra. As an example, in this paper we derived the DEM(T) distributions for parts of the Sun of intermediate brightness and for active region cores. From these DEM(T), we synthesized the corresponding X–ray spectra that one would observe with non–solar X–ray instruments, such as ROSAT/PSPC and ASCA/SIS, and, finally, we analyzed such spectra with the standard method routinely used for non–solar data interpretation, namely one– or two– temperature plasma model fitting. Such a method allowed us to see how the fitting compares to the effective distribution of temperature on the Sun's disk.

Our analysis showed the role of active region cores in determining the stellar like solar spectrum.



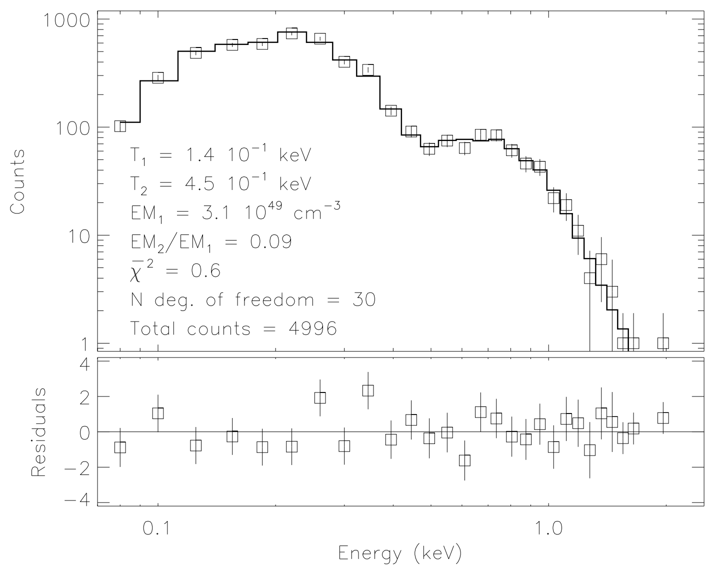


Figure 2. ROSAT/PSPC simulated spectra that one would obtain observing only the parts of the Sun of intermediate brightness (upper panel) and the active region cores (lower panel) from a distance of 1 pc, over an exposure time of 3000 s. The solid lines are the best–fit models and the inset shows the results of the temperature fit to the spectrum. We also show the residuals, namely, the differences between models and data divided by the errors.

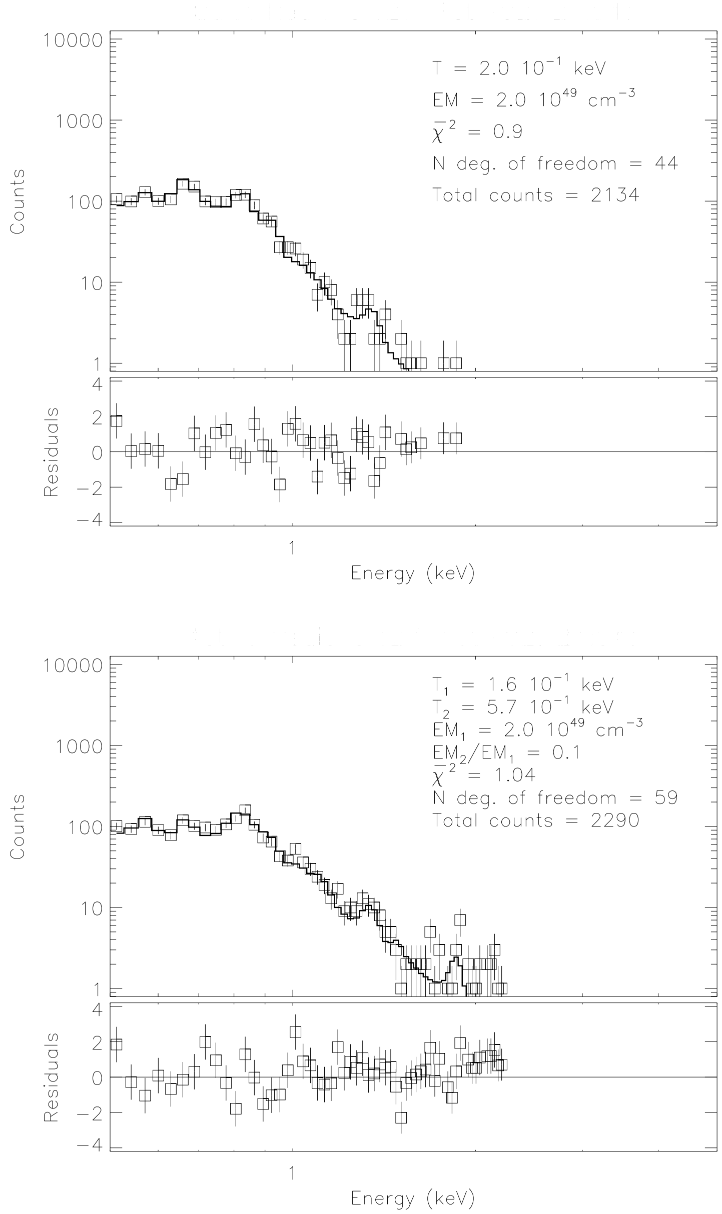


Figure 3. The analogous results as in Figure 2 for ASCA/SIS, for an exposure time of 3×10^5 s.

Acknowledgments. We acknowledge partial support from the Agenzia Spaziale Italiana and from the Italian Ministero dell'Università e della Ricerca Scientifica e Tecnologica.

References

Maggio, A., Reale, F., Peres, G., & Ciaravella, A. 1994, Comp. Phys. Comm., 81, 105

Orlando, S., Peres, G., Reale, F., Rosner, R., & Hudson, H. 1997, in preparation

Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. 1997a, "Observational Plasma Astrophysics: Five Years of Yohkoh and beyond", Proc. of the Yohkoh 5th Anniversary Symp., in press (paper I)

Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. 1997b, in preparation

Tsuneta, et al. 1991, Solar Phys., 136, 37

Watanabe, et al. 1995, Solar Phys., 157, 69