VIEWING THE SUN AS AN X-RAY STAR

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ABSTRACT

The Sun is the late-type star we can study with the highest level of detail. In the interpretation of stellar data, therefore, it is often assumed that the physical processes of the coronae of late-type stars are similar to those of the solar corona, i.e. the "solar-stellar analogy". In order to investigate the validity of this assumption, we have started a program to study systematically the Sun as an X-ray star. Our program aims to explore how far the solar model can be applied to other stars. In this paper we review the results obtained from these studies and, in particular, we discuss the variability of a star identical to the Sun during its cycle, the contribution of different coronal regions to the whole corona X-ray spectrum, and the role of flares. We find that the non-flaring Sun during its cycle fits well in the stellar scenario as a low-activity star. Our results suggest that the coronae of stars from low to intermediate activity may be explained as the effect of structures similar to those present on the Sun, changing the relative weight of the different kinds of non-flaring coronal regions; the coronae of very active stars may be explained if a continuous flaring activity characterizes these stars. Possible implications in stellar data interpretation are discussed.

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. They provide us a very detailed physical scenario of the phenomena occurring in corona. It is not surprising, therefore, the strong interest in comparing such a detailed physical scenario with that obtained from stellar observations, less detailed but address a larger variety of phenomena and physical conditions.

Although without the advantages of spatial resolution, the stellar observations have the ability to constrain physical parameters which the Sun does not allow us to change such as the rotation rate, the effective gravity, the photospheric temperatures, etc. The stellar observations, therefore, allow us to explore the parameter space necessary to uncover fundamental features of coronal activity as, for instance, the by now classical relationship between the rotation rate of a star and its level of activity (Pallavicini et al. 1981).

Many stellar data are interpreted in the light of the so-called "solar-stellar analogy" (e.g. Noyes, 1985; Noyes, 1986), i.e. the assumption that the coronae of late-type stars are the result of physical processes similar to those leading to the solar corona (e.g. Vaiana et al. 1981). Given the impact of this assumption on stellar physics, it is important to ask: how far does the solar model apply to other stars? how do the underlying processes differ? or, in other words, how realistic is this assumption?

In this context, we have developed a method which allows us to compare solar and stellar data (Orlando et al. 2000; Peres et al. 2000; hereafter Papers I and II). Our approach is based on direct experimental measurements made with the Soft X-ray Telescope (SXT) on board Yohkoh. The essence of our method is to translate the Yohkoh/SXT data into a format virtually identical to that of stellar observations made with an X-ray instrument (e.g. Rosat/PSPC or Chandra/ACIS, or XMM-Newton/EPIC), apply to them the standard methods of analysis used for stellar observations and, finally, compare the results with those of stellar X-ray studies. The objectives of our project include: to investigate to what extent the solar-stellar analogy can be considered valid and to trace how different structures and phenomena resolved on the Sun may be responsible of the characteristics observed in X-ray stellar spectra.

In this paper, we review the main results obtained in our systematic study of the Sun as an X-ray star. In particular, we have analyzed how the Sun changes during its cycle (Orlando et al. 2001, hereafter Paper IV), how different coronal regions resolved on the Sun contribute to its X-ray spectrum (Paper IV), and how flares may change the stellar-like spectrum of the Sun (Reale et al. 2001, hereafter Paper III). We have also studied the X-ray variability induced by different phenomena occurring in the solar corona (Orlando et al. 2003, hereafter Paper V). Finally, we briefly mention how various regions compare with stellar emission (Peres et al. 2001; Peres et al. 2003, hereafter Paper VI).

The paper is structured as follows: we describe our method and the sample of Yohkoh/SXT observing sequences analyzed; we discuss the results of our analysis; and finally we draw our conclusions and we discuss the implications for stellar data interpretation.

THE METHOD

In this section we summarize the main steps of our method to “translate” the solar data collected with Yohkoh/SXT into the format of stellar X-ray observations (for a more detailed description of the method see Papers I and II).

The first step is to derive the maps of temperature and emission measure of the corona from two nearly simultaneous (within 3 minutes) X-ray images taken with Yohkoh/SXT through two different filters. These maps allow us to obtain a distribution of emission measure vs. temperature, EM(T), of the whole visible solar corona (or of regions selected on the solar disk) in the range of temperature to which Yohkoh/SXT is sensitive ($5.5 \leq \log T(\mathrm{K}) \leq 8$).

This intermediate result is already important by itself for solar and stellar studies; for instance, the EM(T) distributions show the contribution of the coronal plasma at different temperatures in determining the X-ray emission and they can be compared with those derived from the analysis of stellar observations (see, for example, Drake et al. 2000).

In the second step of our analysis, we synthesize the global X-ray spectrum of the solar corona using the EM(T) distribution derived and the MEKAL spectral code (Kaastra, 1992; Mewe et al. 1995). Finally we obtain the focal-plane, stellar-like spectra folding the synthesized spectrum through the spectral response of a non-solar instrument.

The final result of the application of our method is a stellar-like spectrum of a star identical to our Sun in the format of a real stellar observation (e.g. collected with the X-ray instruments on board Rosat, Chandra and XMM-Newton). We are able, therefore, to apply the standard methods of analysis commonly used in stellar physics to such simulated data.

YOHKOH/SXT DATA

The method outlined in the previous section has been applied to observing sequences collected with Yohkoh/SXT through different filters and with different exposure times. In particular, a sample of full-disk observations collected between December 1991 and April 1996 outside flares has been analyzed in order to cover virtually the whole range of solar activity (see Paper IV), namely from the maximum to the minimum of solar cycle 22. This is illustrated in Figure 1 where we show the total coronal light curve in the thin aluminum filter passband obtained from the SXT Log database: the data that we have specifically analyzed are marked with a cross and are representative of different moments of the corona during the solar cycle. Each selected observing sequence includes images of different exposure times in the thin aluminum (Al 1265 Å) and the Al/Mg sandwich (comprising Al 2930 Å, Mg 2070 Å, Mn 562 Å, and C 190 Å) filter passbands. This set of filters has allowed us to derive maps of temperature and emission measure of the whole corona or of regions selected on the disk (Tsuneta et al. 1991; Papers I and II).

A sample of partial-frame observations of flares well-observed for most of their duration and covering a wide range of flare intensities and physical conditions has been used to study the contribution of flares to the EM(T) distribution and the global X-ray spectrum of the solar corona (see Paper III). Each observing sequence was taken in flare mode in the two filter passbands specific for flare mode observations, i.e. Be 119 μm and Al 11.4 μm.

All the data of our samples were first processed according to the standard Yohkoh analysis software: standard corrections (data decompression, dark current subtraction, pin-hole visible stray light subtraction), image alignment, removal of the cosmic rays spikes, and vignetting correction.

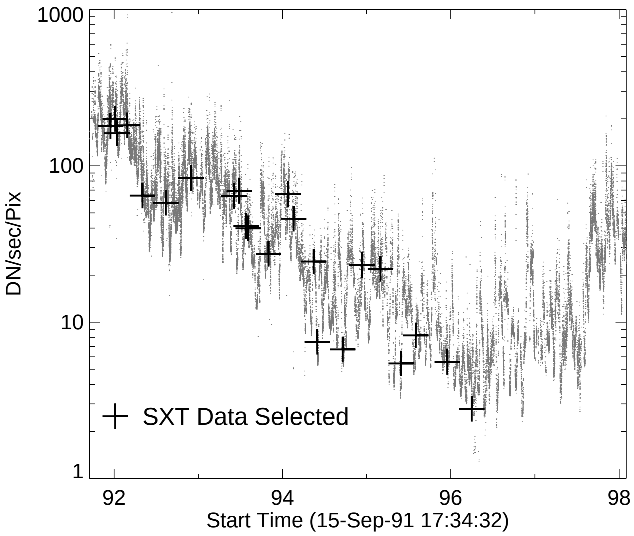

Fig. 1. Light curve of the total solar coronal flux at Earth, obtained from the full-disk SXT images through the thin aluminum filter (adapted from Orlando et al. 2001). The crosses mark the data we have selected for detailed analysis.

RESULTS

From the sample of data in Figure 1, we have derived the EM(T) distributions of the whole solar corona and also the contribution of different coronal regions resolved on the disk to the EM(T) in different phases of the solar activity, and the corresponding stellar-like synthesized X-ray spectra. Flare observations have been used to derive the contribution of flaring regions to the EM(T) and X-ray spectrum of the whole solar corona.

In this paper we focus on the analysis of Rosat/PSPC simulated spectra and on the comparison of our results with those derived from the analysis of real stellar observations (e.g. Micela et al. 1997; Schmitt et al. 1995; Schmitt, 1997; Marino et al. 2002).

The X-ray Sun During the Solar Cycle

Our method has been used to analyze how the Sun observed as an X-ray star changes during its cycle (see Papers II and IV). A first result of our analysis was the study of the evolution of the EM(T) distribution in the non-flaring corona during the solar cycle. In Figure 2 we show the EM(T) at three different moments of the cycle, namely close to the maximum (January 6, 1992), in an intermediate phase (July 27, 1993), and close to the minimum (June 1, 1994). Qualitatively, the EM(T) distribution shows the same general shape throughout the solar cycle: it monotonically increases up to $\sim 10^6$ K, reaches a maximum between 1 and 2 $\times 10^6$ K, and decreases monotonically toward higher temperatures. On the other hand, the EM(T) distribution shows large quantitative variations. In particular, from the maximum to the minimum of solar activity: a) the temperature of maximum EM shifts from $\sim 2 \times 10^6$ K to $\sim 10^6$ K; b) the EM decreases by a few orders of magnitude at all temperatures; and c) the slope of the descending branch of the EM(T) distribution gets steeper. These decreasing trends are the direct consequence of the gradual decrease of the number of active regions (characterized by hot plasma) on the disk.

The PSPC focal plane spectra derived from the EM(T) discussed above have been fitted with multiple isothermal MEKAL spectra, a standard method of stellar physics. Our analysis has shown that the focal-plane spectra are well fitted with one or two different isothermal components, as it is the case, typically, with late-type stars spectra (Schmitt et al. 1990).

Many authors have studied the level of activity and the variability of late-type stars deriving the X-ray surface flux in the PSPC band, $\log F_X$, vs. the PSPC spectral hardness ratio defined as (e.g. Schmitt, 1997; Micela et al. 1997)

$$\mathrm{HR} = \frac{H - S}{H + S} \tag{1}$$

where S are the total counts in the band $0.13 - 0.40$ keV and H are the total counts in the band $0.55 - 1.95$ keV. In Figure 3, we compare the diagram $\log F_X$ vs. HR of the whole solar corona outside flares along the solar cycle (see

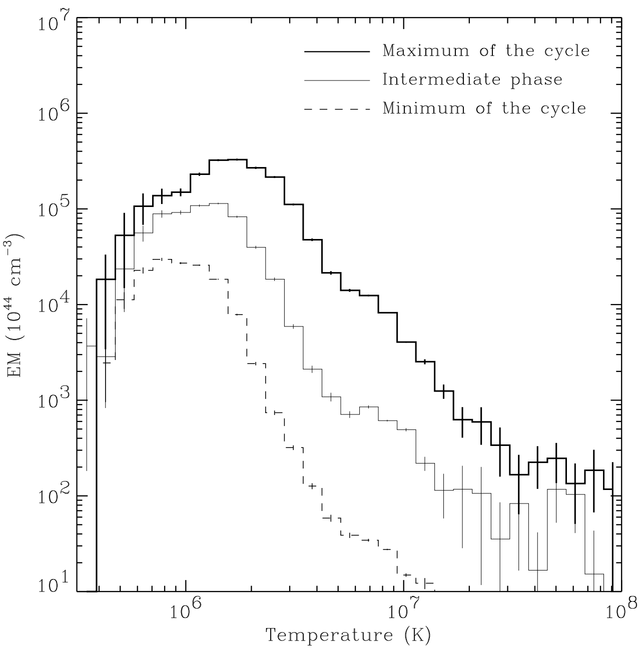

Fig. 2. Emission measure distributions vs. temperature derived for three different phases of the solar cycle (adapted from Peres et al. 2000): close to the solar maximum (January 6, 1992 - thick solid curve), in an intermediate phase (July 27, 1993 - thin solid), and close to the minimum (June 1, 1994 - dashed).

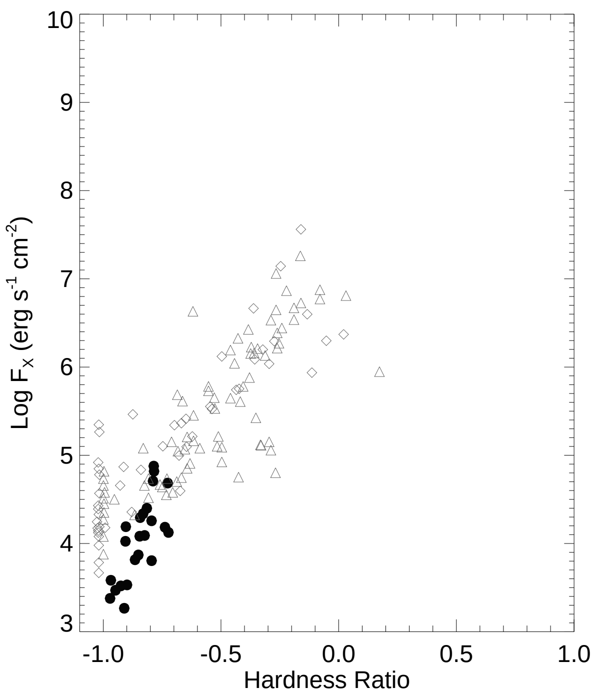

Fig. 3. X-ray surface flux (erg s^{-1} cm^{-2}) in the PSPC band vs. the hardness ratio between soft and hard PSPC counts for the Sun during the solar cycle (filled circles; adapted from Orlando et al. 2001) and for F, G, K, and M stars within 13 pc from the Sun (empty grey triangles and diamonds; from Schmitt, 1997).

Paper IV) with the analogous one of a sample of F, G, K, and M stars within 13 pc from the Sun found by Schmitt (1997).

We have found that the non-flaring Sun across the cycle covers the low-HR low-F_X part of the diagram fitting well in the scenario of low activity late-type stars (see Figure 3), implying that the Sun is a typical low activity late-type star.

In addition, we note that the range spanned by solar X-ray surface flux is large (more than one order of magnitude) and that a correlation HR-F_X is evident. It is worth noting also that the non-flaring Sun even close to the maximum of its activity cannot reproduce the high values of HR and F_X observed in more active stars. Since the "solar-stellar analogy" assumes that also the coronae of these stars are the result of physical processes similar to those at work on the Sun, the obvious question is if and how the phenomena and structures observed on the Sun can explain these high values of HR and F_X.

To answer this question, we have investigated the contribution of single different classes of coronal regions, including flaring ones, resolved on the Sun to the EM(T) and the X-ray spectrum of the whole solar corona. This analysis has been the subject of Papers III and IV, and we summarize the main results in the next two sections.

Contribution of Different Non-flaring Coronal Regions to the Whole Corona X-ray Spectrum

In Paper IV we have analyzed the contribution to the EM(T) and the X-ray spectrum of the whole corona by non-flaring coronal regions. To select the different classes of regions on the disk, we have adopted a criterion based on the SXT pixel intensity (see Paper IV); we have considered the background corona (BKC), the medium brightness portion of active regions (ARs), and cores of active regions (COs). For all the full-disk observations outside flaring of our sample, we have derived the EM(T) distributions of the three kinds of regions and we have synthesized the corresponding parent spectra and the PSPC focal-plane spectra.

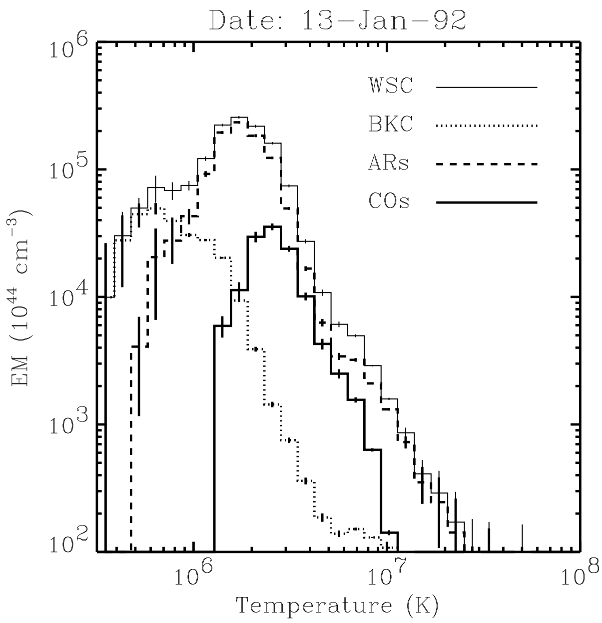

Fig. 4. Emission measure distributions vs. temperature derived for the whole solar corona (marked with a thin solid line) observed on January 13, 1992 (during the maximum of the solar cycle) and for the classes of coronal regions selected on the disk (adapted from Orlando et al. 2001): background corona (BKC, dotted line), the medium brightness portion of active regions (ARs, dashed), and cores of active regions (COs, thick solid).

Figure 4 shows, as an example, the EM(T) distributions derived for the whole solar corona (WSC) and the composing regions observed on 13 January 1992 (during the maximum of the solar cycle). It is worth noting that different coronal regions can have very different EM(T): the one of COs is characterized by a sharp peak at $T \sim 3 \times 10^6$ K, whereas that of the BKC has a peak at $T \sim 1.5 \times 10^6$ K; the EM(T) of the ARs peaks at an intermediate temperature and it is the dominant contribution to the EM(T) of the WSC during the maximum of the solar activity[1].

From the PSPC focal-plane spectra of the classes of regions selected, we have derived the X-ray surface flux[2]

[1]In Paper IV we have shown that during the minimum of the solar activity, the dominant contribution to the EM(T) of the whole solar corona comes from the BKC.

[2]Note that when considering the F_X of the coronal regions one may equivalently assume that the hypothetic star is totally covered by the regions under analysis.

(F_X) vs. the hardness ratio (HR) and we have compared our results with the one derived by Schmitt (1997); such a comparison is illustrated in the left panel of Figure 5. Note that each class of regions selected does not show a clear correlation HR-F_X along the solar cycle similar to that found for the whole solar corona (see Figure 3). On the other hand, the data of each class are clustered in a different part of the diagram and both the values of HR and F_X increase going from the BKC to the ARs, to the COs.

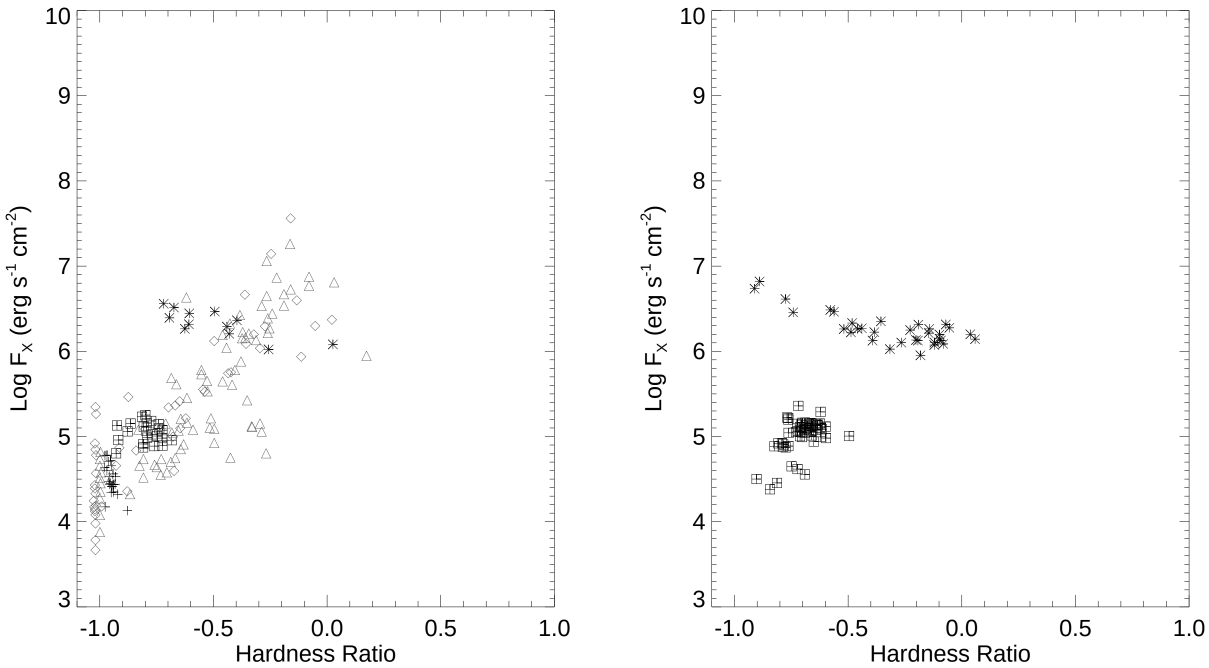

Fig. 5. As in Figure 2 for different coronal regions selected on the solar disk, namely background corona (crosses), active regions (squares), and cores of active regions (stars). The left panel shows the result obtained in different phases of the solar cycle (adapted from Orlando et al. 2001). The grey triangles and diamonds are for F, G, K, and M stars from Schmitt (1997). The right panel shows the result obtained during the minimum of solar cycle 22 (July-December 1996), when the X-ray solar activity was dominated for several months by only one active region (adapted from Orlando et al. 2003). The different data points correspond to different phases of the active region evolution.

The BKC covers a very narrow range of HR in the part of the diagram populated by very low activity stars typically detected only in the soft PSPC band (Schmitt 1997). The ARs show values of F_X and HR higher than those of BKC, but still too low to explain the values observed in intermediate-to-high activity stars. On the other hand, the F_X and HR values characterizing intermediate activity stars could be explained if a significant fraction of the stellar surface were covered by COs.

In Paper V (still in preparation), we are studying the long term evolution of a solar active region from its emergence to the decay phase (July-December 1996), analyzing the contribution of both the medium brightness portion of the active region (AR) and its core (CO). The right panel in Figure 5 shows the values of HR and F_X for the AR and the CO along the active region evolution derived from the PSPC spectra. The two panels of Figure 5 show that the components of one active region during its evolution (i.e. AR and CO) span the HR-F_X values of all classes of regions; in practice, it is shown in stellar-like format that an active region evolves from the condition of active stars to those in quieter stars.

In conclusion, the analysis of the contribution of different non-flaring coronal regions to the whole X-ray spectrum of the Sun supports the hypothesis that the X-ray emission of late-type stars up to intermediate activity ones are dominated by ARs and COs similar to those observed on the Sun and that the different levels of emission of these stars are simply due to a different surface coverage with solar-like ARs and COs (see also Paper VI). On the other hand, our analysis shows also that even covering entirely the stellar surface with COs one cannot explain the very high values of F_X observed in very active stars.

It is worth emphasizing that the flaring regions have been excluded from this analysis and they easily contribute to increase the surface X-ray flux and the emission measure weighted temperature. The analysis of the role of flares in characterizing the X-ray spectrum of the Sun observed as a star has been the subject of Paper III whose results are summarized in the next section.

The Role of Coronal Flares

For all the partial-frame observations of our Yohkoh/SXT sample, we have derived the evolution of the EM(T) distributions of the flares selected and we have synthesized the focal-plane spectra that PSPC would collect. Then we have investigated the contribution of flaring regions to the EM(T) and to the X-ray spectrum of the whole solar corona.

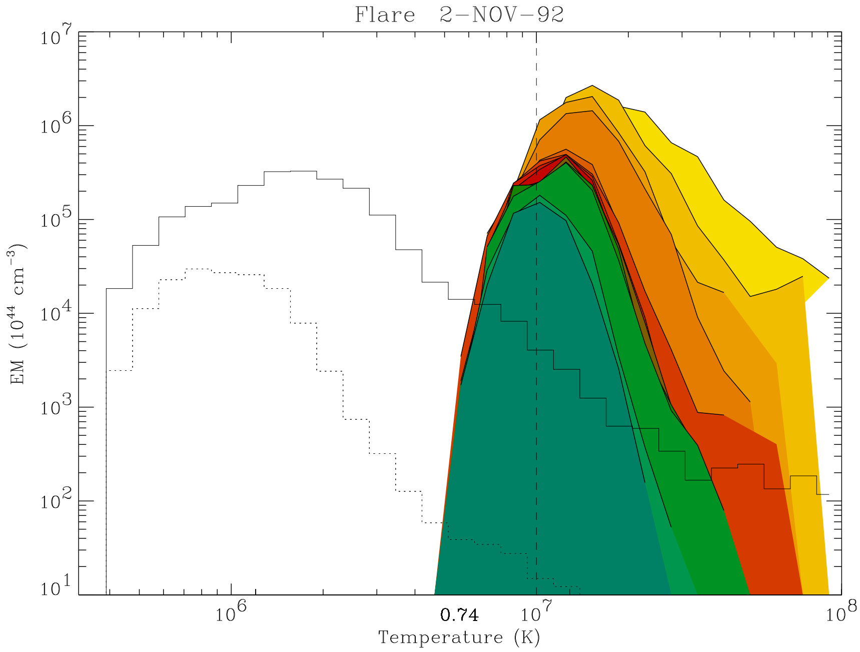

Fig. 6. Evolution of the EM(T) distribution during a large flare observed in November 2, 1992 (adapted from Reale et al. 2001). The emission measure distributions are sampled every ~ 2 min since the beginning of the valid data. The time sequence goes from lighter to darker grey shaded profiles. For reference the EM(T) distributions for the Sun close to the maximum (January 6, 1992) and close to the minimum (June 1, 1994) of the cycle are shown.

In Figure 6 we show, as an example, the evolution of the EM(T) during a large X-class flare observed in November 2, 1992; in the same figure, we show for reference the EM(T) distributions for the Sun close to the maximum (January 6, 1992) and close to the minimum (June 1, 1994) of the cycle. The figure shows that at any flare phase the EM(T) of the flaring region is quite narrow and concentrated at high temperature, covering a temperature decade around $\sim 10^7$ K. The presence of a flare, therefore, changes significantly the whole corona's EM(T), introducing a second well separated and transient peak in the distribution at high temperatures (typically around 10^7 K). The amount of hot plasma depends on the flare intensity and, in the example considered, the EM(T) reaches maximum values $> 10^{50}$ cm^{-3}. In Paper III, we have found that, in general, the EM(T) evolution of a flare is practically independent of the flaring region morphology and that hot plasma at temperatures above 3×10^7 K is present in flares more intense than M class.

From the EM(T) distributions of the flaring regions, we have synthesized the PSPC spectra integrated on time intervals of hundreds of seconds to increase the overall statistics of the fitting process (see Paper III for more details). The F_X vs. HR values for each time bin in which a spectrum has been collected, and for all flares of our sample are shown in Figure 5 (left panel). All data points appear to lie in a relatively thin vertical strip around HR ~ 0.3 and with F_X ranging from 10^6 to 10^9 erg cm^{-2} s^{-1}. The almost constant HR is mostly due to the fact that the flare average temperature, of which the hardness ratio is a proxy, does not change much from $T \sim 10^7$ K, during the flare evolution[3] (see Figure 6). The comparison with the results derived by Schmitt (1997) shows that the flaring regions observed on the Sun, in any phase of the flare evolution, are harder than typical stellar coronal emission and they span a large range of high surface flux comparable if not higher than those observed in very active stars: solar-like flares appear, therefore, to correspond to upper limit conditions both for X-ray flux and hardness ratio of solar-like stellar coronae.

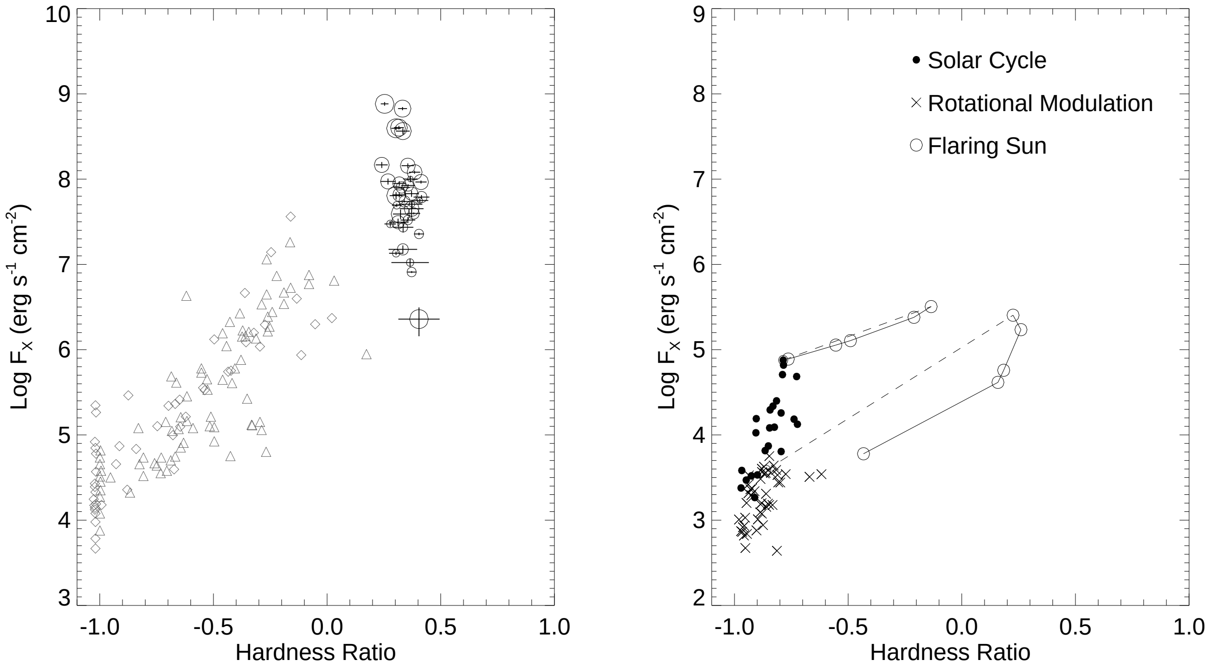

Fig. 7. Left panel: as in Figure 2 for flaring regions selected on the solar disk (adapted from Reale et al. 2001). The grey triangles and diamonds in the left panel are for F, G, K, and M stars from Schmitt (1997). Right panel: as in Figure 2 for the flaring Sun (empty circles; Orlando et al. 2003), the non-flaring Sun during its cycle (filled circles; Orlando et al. 2001), and the non-flaring Sun during six consecutive solar rotations (crosses; Orlando et al. 2003). The rise phase of the flares is marked with a dashed line and the decay phase with a solid line.

Variability in the X-ray Band

Our analysis has allowed us to investigate the X-ray variability induced by rotational modulation and by different phenomena occurring in the solar corona, such as solar cycle and flares (Orlando et al. 2002). In particular, we have characterized the X-ray variability in the PSPC band using the diagram F_X vs. HR, as shown in Figure 7 (right panel). In a previous section, we have already discussed the X-ray variability of the non-flaring Sun induced by its cycle of activity (see Paper II and IV) and we have pointed out the correlation between F_X and HR (see also Figure 3).

In Paper V, we are studying the X-ray variability due to rotational modulation analyzing the non-flaring solar corona during six consecutive rotations when only one active region was present on the disk[4] (see Figure 7). Also in this case, we find a correlation between F_X and HR with the same slope derived for the non-flaring Sun during its cycle. Note that the non-flaring Sun shows a variability in F_X up to 2 orders of magnitude (right panel in Figure 7).

In Paper V, we are also studying the variability due to solar flares, considering the flaring Sun in two extreme cases: when it was close to the maximum and close to the minimum of its cycle (see right panel in Figure 7). We find that the contribution of a flare at the peak of its intensity makes the PSPC spectrum very hard in comparison with the non-flaring Sun; the X-ray variability induced by a flare leads again to a correlation between F_X and HR but, at variance with the previous cases, with strong variations of both F_X and HR.

[3]In addition, the hardness ratio, as defined by Schmitt (1997), is weakly sensitive to temperature variations around $T \sim 10^7$ K.

[4]Note that this particular case, with only one active region in corona, leads to a significant variability due to rotational modulation.

The main conclusion of our analysis is that the rotational modulation and the solar cycle lead to an X-ray variability (in the PSPC band) characterized by the same slope in the HR-F_X diagram. The X-ray variability induced by flares instead is characterized by a slope in the HR-F_X diagram flatter than that found in the other cases. In Paper V, we compare our results with those derived by Marino et al. (2002) from the analysis of a sample of G stars observed with Rosat/PSPC; we find that the variability observed in intermediate activity stars is compatible with the variability due to the evolution of a flare rather than due to rotational modulation or activity cycles.

SUMMARY AND CONCLUSIONS

In this review, we have summarized the main results obtained in a program dedicated to study systematically the Sun as an X-ray star. We have tuned up a new method which uses spatially resolved X-ray images of the Sun to a) derive the EM(T) distributions of the whole solar corona and of different coronal regions selected on the disk in different phases of the solar activity, and b) to synthesize the stellar-like spectra of the Sun. Our method provides a template for stellar data interpretation using real data (those collected with Yohkoh/SXT) and making very few model assumptions (those included in the spectral codes used).

Our method allows us to compare solar and stellar activity. The results of our analysis, therefore, are important to look for counterparts of solar phenomena and structures on stars, and to identify several aspects of stellar coronal phenomena with their solar counterparts. Thanks to this comparison, we are able to use the complementary information coming from solar and stellar observations to investigate the physical phenomena governing the coronae of late-type stars.

In this paper we have discussed part of the results obtained analyzing the non-flaring Sun during the solar cycle, investigating the contribution of different coronal regions to the whole corona EM(T) and X-ray spectrum, and studying the role of flares. These results suggest that one may explain the coronae of stars from low to intermediate activity by changing the relative weight of the different kinds of non-flaring coronal regions, but these regions cannot reproduce in any way the high values of X-ray surface flux observed on very active stars (see Paper VI for a more complete discussion). On the other hand, the analysis of flares supports the idea that these high values of F_X can be explained if a continuous flaring activity characterizes these stars (Güdel, 1997, Drake et al. 2000, Paper VI). In this scenario the stellar surface is covered by active regions, flares are very frequent and their light curves overlap, canceling out any variability due to the single events. Our analysis has shown that the F_X of flaring regions is an upper limit for the F_X values observed in very active stars and, therefore, increasing enough the rate of production of flares can lead to F_X values reproducing those observed in very active stars. An additional support to this scenario comes from the evidence that the emission measure distribution of very active stellar coronae, obtained from spectrally resolved XUV observations, is double-peaked; the first peak is at a few 10^6 K, and the second peak above 10^7 K (e.g. Griffiths and Jordan, 1998). In Paper III, we have found that a continuous, moderate, flaring activity may produce a second peak in the EM(T) distribution as shown in Figure 6 where a double-peaked EM(T) is obtained combining the EM(T) of the whole corona to the envelope of the EM(T)'s during flares (see also paper VI).

At present, we are studying the X-ray variability that we should observe on a star identical to the Sun. In particular, we are analyzing the effect of the rotational modulation caused by an active region to the stellar-like spectra and we are studying the global evolution of the X-ray flux and spectrum of this region observed from its emergence to its decay phase (Orlando et al. 2002; Paper V). The comparison of the characteristics of X-ray variability due to different coronal phenomena (rotational modulation, solar cycle, flares, etc.) can give some hints for the interpretation of the X-ray stellar variability. In particular, we have already found that the variability induced by rotational modulation and by the solar cycle are both characterized by a similar correlation between F_X and HR with a steep slope due to the small variation of HR. On the other hand, the variability due to the evolution of a flare has completely different characteristics in F_X-HR diagram: the correlation between F_X and HR has a flatter slope than in the cases discussed above and, in general, the hardness ratio reaches high values when the flare is close to the peak.

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