RECENT RESULTS ON THE STUDY OF THE SUN AS AN X-RAY STAR

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ABSTRACT. The Sun is an important test-bed for the physics of stellar coronae. However the context, the methods and the scope of solar studies are different from those of stellar ones and a direct comparison among the two is hard. In order to bridge the gap between solar and stellar coronal physics, we have developed and tested a method to compare directly X-ray data relevant to the solar and the stellar coronae; it is based on the wide band X ray data collected with Yohkoh/SXT. The intermediate results of this analysis (emission measure distributions vs. temperature, solar X-ray spectra, their evolution etc.) are important also in the context of solar physics. We discuss the solar X-ray characteristic in the stellar context, its variability during the cycle, solar X-ray flares, and how these results compare with those of stellar coronae.

1. Introduction

Coronal Physics is very important in the wider context of Astrophysics: it is a tracer of the presence of magnetic fields on stars, and of their generation and dissipation; it yields, therefore, evidence of a dynamo action. The presence of magnetic fields, in turn, is thought to be tied to the stars' loss of angular momentum: both the rotation speed and the coronal activity are tracers of the star's age. The importance of coronal physics is shown by its use in support of other areas of astrophysics; for instance X-ray observations are very effective to identify Star Forming Regions.

Studying late type (i.e. from F to M spectral types) stars' coronae can show how different stellar characteristics, such as mass, gravity, age, galactic environment, chemical composition etc., influence the features (temperature, luminosity, spectra, etc.) of the coronae. However stellar observations have several limitations, with respect to solar observations; for instance, they cannot resolve the stellar disk and have low flux at Earth, poor time coverage and resolution.

On the other hand observations of the Sun provide an enormous wealth of details, high angular resolution, good time coverage and time resolution, high spectral resolution (although over limited time and bands) as well as the capability to study in detail the magnetic structures origin of the X-ray emission; however they are "limited" to a 5 Gy old G0V star and, as such, not exceptionally active.

It is highly desirable to use jointly the information from both areas of coronal physics: the high level of details available for the Sun and the broad range of conditions present on stars. However, the methods and tasks of solar X-ray studies are typically different from those of stellar ones: for instance the solar X-ray observations are more and more dedicated to very high angular and spectral resolution, albeit over small sections of the solar disk or narrow spectral bands. At the same time very little or no attention is dedicated to the solar corona as a whole, and to answering questions typical of stellar observations such as "which is the solar X-ray luminosity (e.g. in the ROSAT, or Chandra, or XMM-Newton spectral bands)? and how does it evolve?" "which is the solar X-ray spectrum e.g. from 0.1 to 10 keV?". More in general, "which are the characteristics of the solar corona as a whole?", and "how to compare solar and stellar X-ray observations?"

In order to address these and further questions, we have developed and tested a method to translate Yohkoh/SXT data into stellar-like spectra. Yohkoh/SXT data have been taken several times each day, and with very high frequency during flares, from september '91 until now. These data have relatively high angular resolution - typically 5" and in some cases 2".5. In order to put this work in the proper reference frame, it is worth noting that NO X-ray solar spectroscopy over a wide spectral band, and vs. time is available at present time.

Our scope is to put solar and stellar data in a common context and we achieve such a task through a series of steps sketched as follows: starting from the Yohkoh/SXT data we "turn the Sun into an X-ray star", from that we synthesize the coronal spectrum and the observations with the X-ray stellar telescope of interest (e.g. ROSAT, ASCA, Chandra or XMM), we then apply the standard tools used to analyze stellar data. A direct comparison of the solar corona with the X-ray stellar observations can be accomplished with very little guess work, with our method, because we also put solar data in the same format and context as the stellar ones. With solar observations we have the additional advantage of resolving on the solar disk the sources of the X-ray emission; if required we can study only to some structures or a class of structures to ascertain their contribution to the whole emission and spectrum.

2. Deriving the solar X-ray spectrum

Comparing solar X-ray data to stellar data collected by world class X-ray observatories, such as XMM-Newton and Chandra, requires an instrument capable of spectral resolution ($E/\Delta E \approx 1000$) over the spectral band $0.1 < E < 10$ keV. Nowadays no instrument like this is available for solar X-ray observations.

Therefore we had to resort to a different approach: using Yohkoh/SXT data to infer the coronal emission measure and from that to derive the spectrum. The approach is fully described in Peres et al. (2000); see also Orlando et al. (2000) for a detailed description of some aspects of the method, of the solution of many instrumental and data analysis problems and of the wide set of simulations we made to evaluate the error sources in the whole process.

2.1. The emission measure vs. temperature of the corona

Using two images taken almost symultaneously through two different filters and using the standard Yohkoh/SXT data analysis we derive the temperature and emission measure in each pixel of the images: we obtain a map of temperature of the solar corona and a matching map of emission measure. A typical X-ray image is a square of 512×512 pixels each of 5" of side. We divide the range of temperature to which Yohkoh/SXT is sensitive, namely $5.5 < log\ T < 8$, into 29 equal (in log T) bins, adequate to the temperature resolution of the instrument. Summing the emission measure of all the pixels with temperature within a given temperature bin, we can generate an emission measure vs. temperature distribution (henceforth EM(T)) of the whole corona.

2.2. Synthesizing the X-ray spectrum of the corona

Using one of the available spectral synthesis code for optically thin astrophysical plasma, e.g. the MeKaL code (Mewe et al., 1986; Kaastra, 1992; Mewe et al. 1995), we derive the emitted spectrum for each temperature bin, taking into account the emission measure and temperature of that bin. Summing the spectral contribution from all the temperature bins we obtain the X-ray spectrum of the whole corona.

2.3. Deriving the focal plane spectra

Assuming a certain exposure time and a prescribed distance of the source (typically 1 pc for ease of comparison with other sources) we fold the synthesized solar spectrum through the instrumental response of the X-ray instrument of interest (including the combined effective area vs. photon energy of the mirrors, of the filters and of the detector and the matrix response of the detector) and divide by the photon energy, thus obtaining the number of photons collected in each energy bin. In our simulations beyond the several instrumental effects we take into account the Poisson fluctuations of the photon number.

Since the data are in the same format as those for stars we can apply the same tools used for the analysis and interpretation of stellar observation. Therefore we can compare with a high level of detail solar and stellar coronal data since we know the "parent" EM(T) and the detailed coditions of the "input" corona we can also check the role and effect on the final result of the tools used to interpret the data.

3. The characteristics of the corona during the solar cycle and during a large flare

In the following we discuss sample applications of our method.

Peres et al. (2000) have analyzed three different moments of the solar cycle: around the maximum of the cycle, around the minimum and during an intermediate phase; they also studied the solar corona during a large flare of intensity X-9 according to the GOES classification. The relevant results are shown in Fig. 1. It is immediately evident that the EM(T) around the maximum of the cycle steeply rises to a maximum at a temperature of 1.7×10^6 K, with a slope approximately $\propto T^{3/2}$, and then decreases with an even steeper slope. The slope $\propto T^{3/2}$ is consistent with a corona almost entirely made of hydrostatic loops and allows us to infer some features of the coronal loop population and of the coronal heating budget (Peres et al., 2000b).

Going from the maximum to the minimum of the cycle the maximum of the EM(T) moves to lower temperatures, i.e. slighly less than 10^6 K, and the entire EM(T) decreases by two orders of magnitude, and even more at temperatures above 10^6 K, essentially because no active region is present at the minimum of the cycle. The large flare generates a large hump in the emission measure distribution with a maximum around 2×10^7 K.

The next step is "transforming" the data got with Yohkoh/SXT into stellar-like spectra identical to those collected with stellar instruments for instance ROSAT/PSPC, the workhorse of recent stellar X-ray coronal physics or ASCA/SIS, and fitting the stellar spectra in terms of multiple isothermal components, as usually done for stars. For the maximum of the solar cycle the fitting requires two temperatures relatively low; both isothermal components have a modest emission measure with respect to what found for active stars, i.e. the results are adequate to a *moderately active* star. The same procedure applied to the solar corona during the minimum yields a focal plane spectrum fitted with just one, rather cool, isothermal component, of rather modest amplitude; its characteristics are similar to those of a *very low activity* star. Finally if we do the same for the corona during the large flare, we find two isothermal components whose temperatures and ratio of the emission measure values are typical of a very active star; however the overall emission measure is lower, by roughly two orders of magnitude, than that of a very active star.

Fig. 1 also shows the emission measure and temperature of the components found with the fittings discussed above and the results of the analogous study made for focal plane results of the ASCA/SIS observations. The fitting of ROSAT/PSPC data matches the maxima of the emission measure distribution as well as the total amount of the EM(T), i.e. the fitted temperature values closely correspond to the maxima of the distribution and the sum of the emission measure of the fitted components are very close to the integral of the "parent" EM(T) (Peres et al., 2000). Instead the fitting of ASCA/SIS spectra tends to bias the results toward the hotter part of the distribution (see also Orlando et al., 2000b); also the sum of the emission measure of the fitted components is significantly lower than the integral of the "parent" EM(T), showing another aspect of the intrinsic bias due to the ASCA/SIS spectral band, much harder than the ROSAT/PSPC one.

More recently Reale et al. (2000) used this technique to study eight very different solar flares, with the scope to explore the range of the several cases of flares possible. They study the evolution of the EM(T) and how it influences our findings on the stellar flares evolution in terms of star-averaged observables e.g. average temperature and emission measure evolution or average stellar surface X-ray flux and spectral hardness ratio.

As an example, Fig. 2 shows the evolution of the EM(T) during a rather large LDE flare, at several moments after the maximum. The EM(T) decreases as a whole and the hotter tail falls down even more rapidly; this flare had an unusually large amount of plasma at 10^8 K. It is worth noting that the hump due to the flare grows and decreases with small changes of the temperature of maximum EM(T), and the large changes of average temperature occur when the flare contribution is rather small. As a

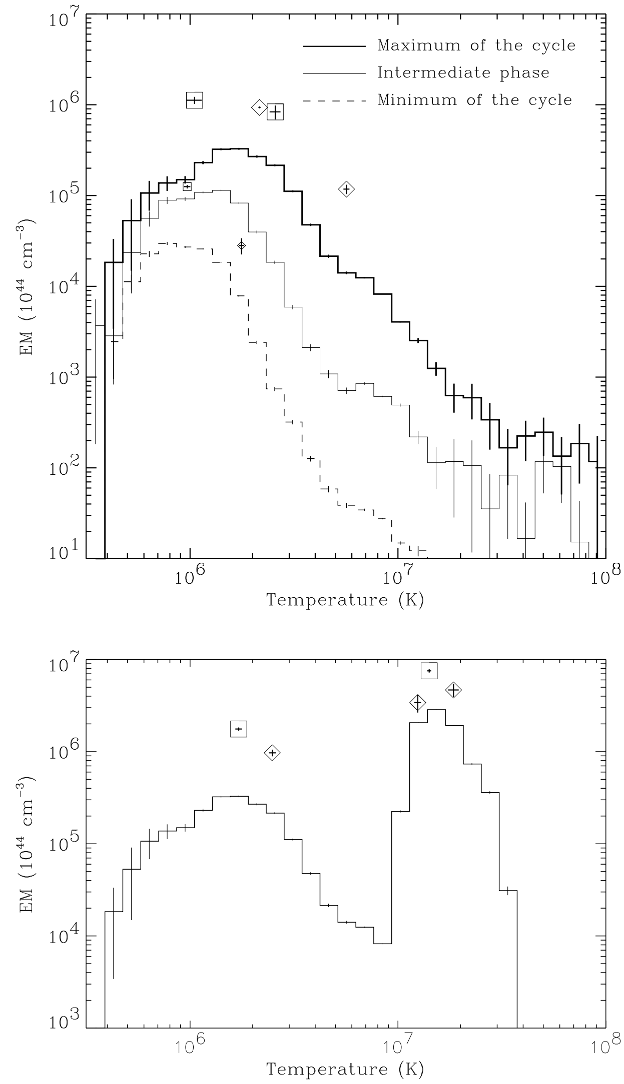

Fig. 1. Top panel: EM(T) for three phases of the solar cycle, and the results of the spectral fitting of synthesized spectra for ROSAT/PSPC (squares) and ASCA/SIS (diamonds), for the Sun at maximum (large symbols) and at minimum (small symbols) of the solar cycle. Bottom panel: EM(T) for the Sun during an X9 flare occurred on November 2, 1992. The fitting results are shown similarly to those on the top panel (from Peres et al., 2000).

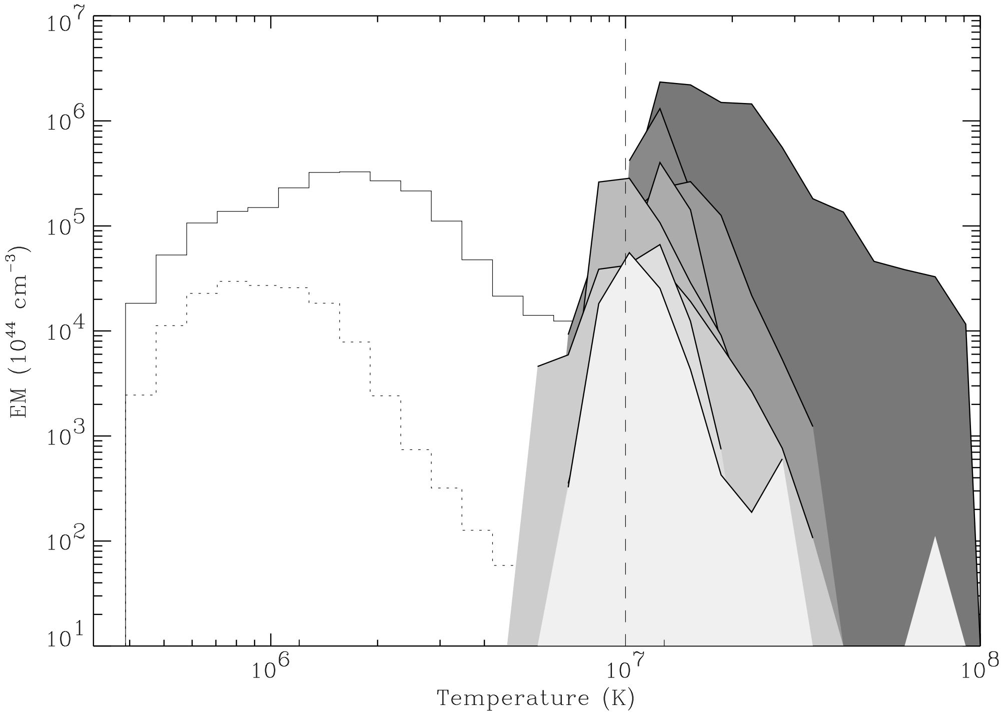

Fig. 2. Evolution of the EM(T) during the large X9 flare. Evolution goes from lighter to darkes shaded curves (from Reale et al., 2000).

consequence the EM(T), during the flare evolution, does not fill the gap between the two peaks at a few 10^6 K and at a few 10^7 K, respectively. This behaviour has a well known counterpart in the trajectory of flares in the average density, effective temperature (Reale et al. 2000; Serio et al., 1991; Jakimiec et al., 1992; Sylwester et al., 1993); such a characteristic has with the interpretation of the two coronal temperatures, routinely found with ROSAT/PSPC spectral fittings, as indicative of two well separated peaks of the emission measure distribution vs. temperature, the second probably due to a large number of uncorrelated flares, overlapping in time.

In a parallel study, Orlando et al. (2000b) are studying the contribution of the various classes of structures, present in the solar corona, to the EM(T) and spectrum. As in Drake et al. (2000) they have classified the regions of the solar disk as "active regions cores", "active regions" and "quiet background regions", according to their surface brightness in the band of the Al.1 filter, similarly to Hara et al. (1996), but the levels of brightness have been selected according to the distribution of nr. of pixels vs. surface brightness, obtained from a wide set of X-ray images at different phases of the cycle.

Fig. 3 shows the average-surface-flux vs. hardness-ratio graph ($F_X - -HR$) anal-

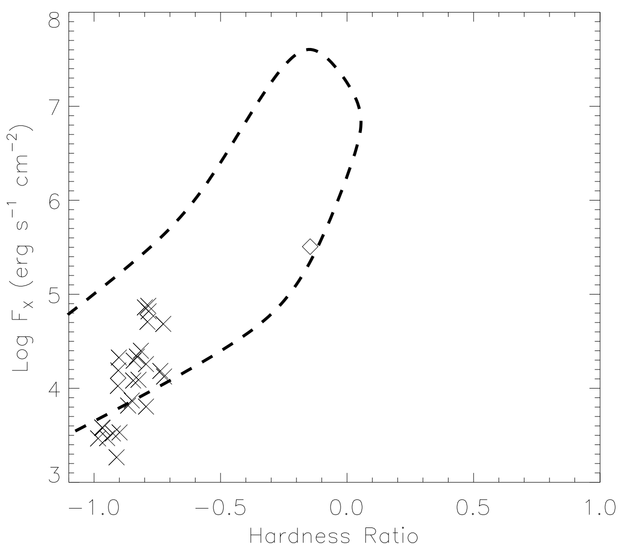

Fig. 3. X-ray surface flux in the ROSAT/PSPC band vs. spectral hardness ratio, for the solar corona at several times during the cycle (crosses). During the maximum the flux is high, during the minimum rather low. The diamond marks the whole solar corona during the large flare in Fig. 1 and 2 (adapted from Orlando et al. 2000b).

ogous to that of Schmitt (1997) who collected the ROSAT/PSPC observations of late type stars within 13 pc from the Sun. It is evident from the data points on the solar corona, sampled at several different moments of the solar cycle from the maximum to the minimum, that the Sun spans the part of low luminosity, low hardness ratio, of the stellar distribution. Furthermore the solar corona spans approximately 1.5 decade in average flux (or, equivalently, average luminosity); such a variation over the years is rather large and has few, if any, matches in the very active stars (Stern, 1998).

4. Conclusions

This project, aimed at comparing the solar corona with the stellar ones, has produced results important also within the context of solar physics per se: for instance it gives us a global view of the solar corona, the solar X-ray luminosity in selected spectral bands, the X-ray spectra of the solar corona and also of its component structures.

The EM(T) during the maximum of the solar cycle rises $\propto T^{3/2}$, peaks around 2×10^6 K and decreases with a rather steep power law of T. The distribution undergoes large changes during the cycle: at the minimum of the cycle the temperature of maximum EM(T) falls well below 10^6 K, the whole EM(T) decreases by orders of magnitude, and the X-ray luminosity in the ROSAT band varies by slightly more than one order of magnitude. It is well known that hardly active stars show analogous secular variability

(Stern, 1998).

Flares yield a large additional peak of EM(T) at a few 10^7 and large flares may have significant amount of emission measure at 10^8 K. Furthermore the flare's EM(T) evolves never filling the gap between the two maxima, at a few 10^6 K and at a few 10^7 K respectively.

The Sun during the cycle spans the lower part of the distribution of the late type stars in the $F_X - HR$ graph and remains in the low F_X -low HR part of this diagram, orders of magnitude below the most active stars.

The synthesis of stellar like spectra form the Sun is, at last, providing us with a set of templates useful for the physical interpretation of stellar coronae and, in particular, to constrain the magnetic processes at work in the stellar outer atmospheres.

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