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Large Scale Properties of Coronal Heating along the Solar Cycle

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Abstract. We discuss various studies of the global properties of coronal heating. Some of them find power laws tying the X-ray luminosity with the magnetic flux of individual structures, of the whole Sun, and of active solar-type stars. Others are based on methods to model the Sun as an X-ray star. We also briefly discuss solar-like active stars and how the Sun fits in the whole scenario. We use a new model, including all flares, of the Sun as an X-ray star to describe the evolution of the corona along the solar cycle and the implications on the heating of closed coronal structures. We point out that, as activity increases, more heating is released into the confined coronal plasma and such a heating has to be, on average, more intense in order to explain the widespread evidence of a temperature increase with activity. By the same token, nanoflare heating (if existent) has to increase and decrease along the cycle differently from flares.

1 Introduction

This work is dedicated to the global characteristics of the heating of the magnetically confined corona, and to its evolution along the cycle. The heating which brings the coronal plasma to, and maintains it at, a temperature of a million degrees is a distinctive feature of the corona; without this heating there would be no corona.

On the other hand, finding the main mechanism(s) causing the heating is a sort of an El Dorado for coronal physics; on one hand we mostly have only indirect markers of the heating like brightenings, temperature increases, plasma flows, and other evidence of dynamics; on the other hand several physical features of the plasma—e.g., very effective thermal conduction and plasma mobility along the magnetic field lines (i.e., very effective energy transport mechanisms)—all smear the effects of coronal heating in space, thus making it hard to tie the observed phenomena to the heating. So far we have understood many features of the coronal heating (see, for instance, Priest 1999; Ulmschneider & Musielak 2003), however still much has to be found.

In this perspective, several scientists have tried different methods to study the basic mechanisms; some (e.g., Gudiksen & Nordlund 2005; Peter et al. 2006) have tried to "forward model" the corona with models encompassing the basic mechanisms, simulating parts of the corona, synthesizing their emission, and trying to match the appearance of the dynamic solar corona. Others have tried

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to constrain the features of coronal heating by modeling some structures, or whole regions, of the solar corona using different kinds of heating and seeing which one matches the observed features (e.g., Priest et al. 2000; Reale et al. 2000; Demoulin et al. 2003).

The focus of this paper is on studies of the global features of the heating, a different aspect of the problem.

In this respect it worth noting that the emitting corona is entirely composed of closed magnetic structures (typically called "loops"). Models of the plasma magnetically confined inside these loops have shown that roughly half of the heat deposited in corona is radiated away, and the other half is conducted to the much cooler transition region (Vesecky et al. 1979). Therefore one can safely assume that the coronal emission is a tracer of the overall heating. This assumption is correct if one considers the entirety of the corona or even a whole loop; it however cannot be applied locally, i.e., to a specific point in the corona. For instance, the fact that a part of the corona is bright (or brightens) does not imply that heating is delivered there, because the coronal plasma is very effective in transporting energy. Energy may be delivered somewhere else and transported there, as it has been shown in a few cases (e.g., Reale et al. 2000). In this context within a factor of the order of two, global X-ray emission (or, better, coronal emission) can be a proxy of coronal heating.

This paper will touch a few points, among which: how the global coronal heating scales with the average intensity of the magnetic field and the length of the magnetic coronal structures, how the heating evolves with the solar cycle, and how the heating changes with activity level—both the overall amount and as specific intensity, i.e., heating per unit mass.

2 The Scaling with the Magnetic Field

Pevtsov et al. (2003) have shown that the X-ray luminosity $L_{\rm X}$ correlates well with the unsigned magnetic flux ϕ according to a power law $L_{\rm X} = \phi^{1.15}$. Their graph (Figure 1) includes various solar structures, the whole Sun, active stars, and T Tauri stars. The latter ones appear to depart from the power law but this is not surprising since a sizable amount of their X-ray emission is due to accretion phenomena, not to magnetic coronal activity (Calvet & Gullbring 1998). One has to be careful because the log–log graph over 15 × 12 factors of ten tends to smooth any detail or any departure from the law; however the very existence of this law shows that some general phenomenon is at work.

Schrijver et al. (2004) followed a different approach: they used a complex method to perform the synthesis of full-disk coronal images. They first extrapolated the field lines, then attached a loop model to each field line, and finally they used emission codes and visualization tools to generate, from the distribution of loops visible on the solar disk, a Yohkoh/SXT full-disk image. The magnetic field structure depended on a few parameters and their task was to find those parameters that best resembled observations, in order to match the coronal morphology and to identify the heating characteristics. Their heating had the functional form $F_{\rm H} = \epsilon B^{\alpha}/(f L^{\beta})$ (where $F_{\rm H}$ is the heating per unit area, B the magnetic field intensity, L the half loop length, and f a tapering function). The authors explored a grid of models for different values of the pa-

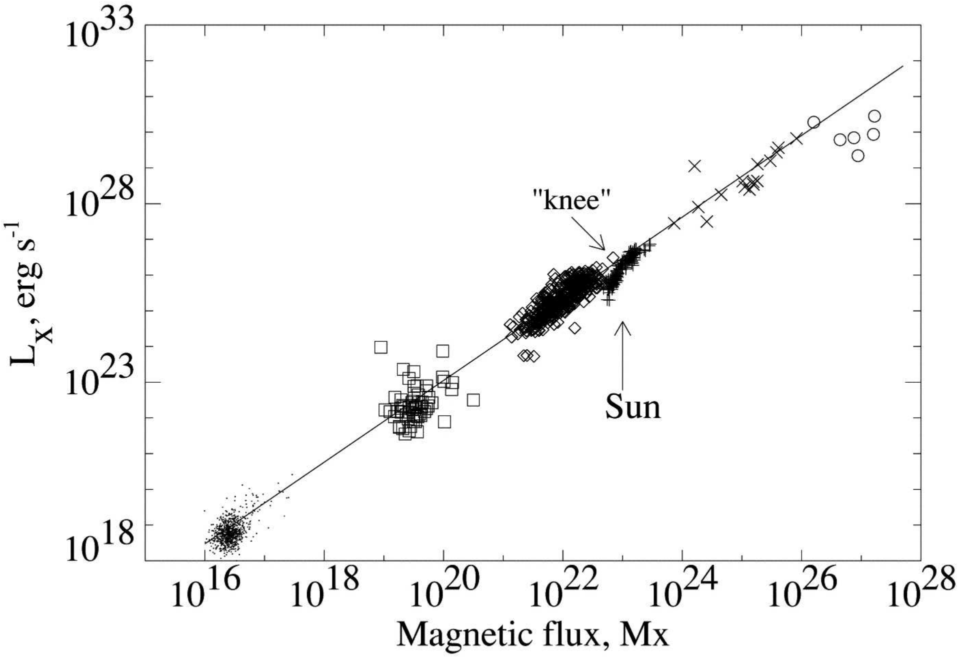

Figure 1. X-ray spectral radiance vs. total unsigned magnetic flux for solar structures, the Sun, and stars. Dots: quiet Sun. Squares: bright points. Diamonds: solar active regions. Pluses: solar-disk averages. Crosses: G, K, and M dwarfs. Circles: T Tauri stars. Straight line: power-law fitting discussed in the text. From Pevtsov et al. (2003) by the kind permission of the Astrophysical Journal.

rameters and found that the best agreement was for $\epsilon = 4 \times 10^{14}$, $\alpha = 1.0 \pm 0.3$, and $\beta = 1.0 \pm 0.5$ in cgs units. Such a finding is consistent with granulation-driven B-field braiding and apparently is not the same as that of Pevtsov et al. (2003).

However, Schrijver & Title (2005) compared the law mentioned above with that of Pevtsov et al. (2003). They found that the two laws agree, within errors, if L changes much less than B (or its changes are much less relevant). Since the same law seems to apply also to giant and subgiant stars (which have very different dimensions and much larger convection zones, implying much larger L), they had to find a better explanation. They supposed that the multiplicative factor, (i.e., 4×10^{14}) must scale with L which, in turn, should depend on the size of the convective zone. This is consistent with application of field-line braiding to convective zones of giants and subgiants (under the consideration that the convective velocity v_c in the convective zone changes much less than the pressure scale height).

3 The Coronal Heating for the Sun as a Star

In the process of studying the corona of the Sun as a star, our group found important aspects of the coronal heating and its evolution along the solar cycle and, more in general, with the level of activity. Our study aimed at putting into the same context solar and stellar coronal studies, taking good advantage of the possibility to study in detail the corona of the Sun (a representative late-type star) which allows us to study the structures generating the X-ray emission. There is a mutual advantage for solar and stellar science of putting coronal studies in the same context, overcoming the technical problems due to largely different observing methods, techniques and scopes. Solar studies provide a detailed scenario for the morphology and the physical phenomena at work, while the stellar studies provide a large variety of phenomena and physical conditions, and they show how several stellar parameters (e.g., age, abundance, and mass) influence the corona. We note that our approach, like many others, rests on the assumption of the solar-stellar analogy, i.e., that the same basic phenomena are at work in producing and maintaining the solar corona as those active in all the other solar-like stars.

3.1 The Method

Here we provide a very sketchy presentation of the method; a more detailed account of the method is provided by Orlando et al. (2000) and Peres et al. (2000). We transform Yohkoh/SXT or Hinode/XRT data into a format virtually identical to that of stellar X-ray observations, made with telescopes like ROSAT/PSPC, Chandra/ACIS, XMM-Newton/EPIC, etc. We can then apply standard methods of analysis used for stellar observations and compare directly our results with those of stellar X-ray studies. We can thus investigate the validity of the solar-stellar analogy and trace how different structures and phenomena resolved on the Sun are responsible for the observed characteristics in stellar X-ray spectra.

From two simultaneous solar X-ray images taken with different filters, we derive the temperature (T) and emission measure (EM) for each pixel in the corona, using the standard solar software data analysis tools. Then, from the two sets/images of T and EM values, we obtain the distribution of emission measure vs. temperature, $EM(T)$, first dividing the range of T detectable by the instrument (typically $5.5 < \log T\,[\mathrm{K}] < 8$) into bins adequate to the thermal and spectral resolution of the instrument, and then sorting all the pixels belonging to each temperature bin and summing up all the EM values of all the pixels within each temperature bin. In such a way we generate a histogram (extracted from the images) of EM vs. T, yielding the distribution of emission measure vs. temperature of the whole solar corona.

From this distribution, which is already important for solar studies, we can synthesize the emitted spectrum by computing the spectrum for each temperature bin and summing all the contributions properly weighted by the emission measure of each temperature bin. Then, folding through the instrument spectral response and through the response matrix, considering a typical distance in parsecs, and an exposure time accompanied by a statistical simulation of the photon counts, we generate a realistic focal plane spectrum of the Sun as a star, in the same format and context as stellar ones (i.e., as if it were observed with the stellar X-ray telescope of interest).

3.2 The Heating along the Solar Cycle

Peres et al. (2000) and Argiroffi et al. (2008) studied the corona of the Sun as a star in different phases of the solar cycle.

Peres et al. (2000) studied the corona at maximum, intermediate, and minimum phases of the solar cycle and found that the temperature of maximum emission measure, as well as the average coronal temperature, decrease slightly as the cycle wanes. More importantly, the overall emission measure decreases by more than one order of magnitude with the cycle and the high-temperature part of the distribution, which decreases with temperature, steepens considerably as the cycle wanes. Peres et al. (2001) developed a method to find the contribution of any set of static loops of given maximum temperature to the global emission measure of the Sun and the fraction of heating that goes into each of these classes of loops of given maximum temperature.

Coming from a stellar context, Peres et al. (2004) used the same approach as Schmitt (1997), who put coronal data of stars within 13 pc from the Sun in a graph of (averaged) X-ray surface flux vs. hardness ratio, the latter being a measure of the hardness of the spectrum, de facto a figure related to temperature. In the same graph, Peres et al. (2004) put the Sun at various phases of the cycle as well as various types of coronal structures—classified according to their X-ray surface brightness as quiet Sun, active regions, and cores of active regions (Orlando et al. 2001)—also flares have been put in the same graph (Reale et al. 2001). On one hand, from such a graph one sees that the Sun is a low-activity star, that stars of higher and higher surface flux (or activity) can be explained as having higher and higher fractions of their surface covered with active regions and cores of active regions. On the other hand, the most active stellar emission can be explained only with a significant fraction of flares or flare-like structures present at any time (Peres et al. 2004).

It is important to note that stars at various level of activity, the Sun along the cycle, and the various structures on the Sun all fall along the activity strip, implying that as activity increases (both along the solar cycle and going from less to more active stars), the corona not only gets more luminous—and therefore more heating has to be delivered into the corona—but also the heating has to be more intense in order to explain the higher temperature.

Indeed the emission measure vs. temperature of active or very active solar-like stars typically has a significant excess of emission measure at 10 MK or more, at variance with the Sun, an aspect we will discuss again at the end of this paper. Such a hot excess should be due to the presence of several flares at any time on the surface of stars. The superposition of the various flare light curves, plus our instruments' inability to detect possible small changes in the light curve, prevents us from isolating the possible flares.

We do not observe anything like this on the Sun. However, one has to consider that solar flare observations are typically concentrated on a specific flare, typically ignoring the remaining Sun, and, more in general, we do not know if the time-averaged Sun shows anything similar to stars. In order to explore this aspect, Argiroffi et al. (2008) studied the emission measure of the Sun time-averaged over a month (in order to consider the effect of many flares) and along the solar cycle. Since Yohkoh observes only some of the flares, they used the GOES observations which catch virtually all the flares. Also, they had

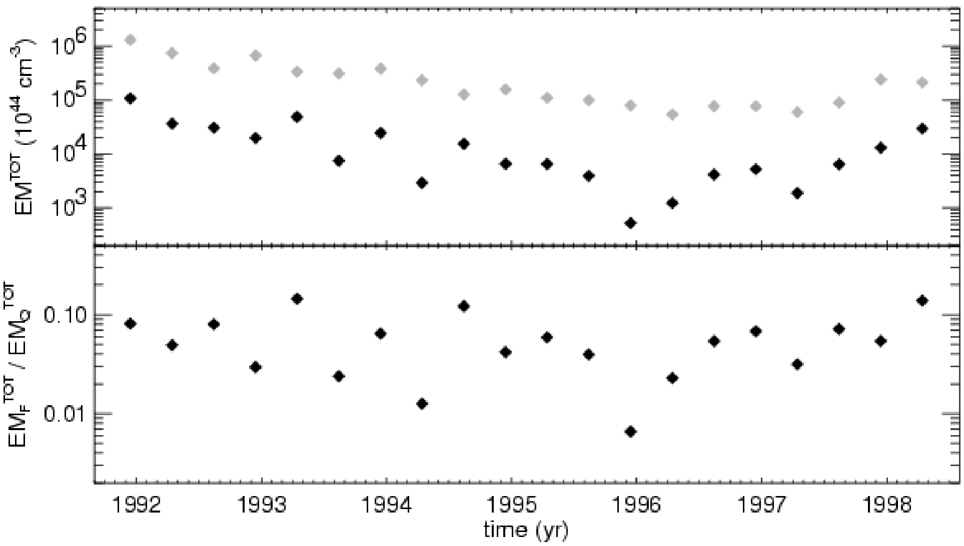

Figure 2. Upper Panel: total emission measure of the flares (black) and of the not-flaring (gray) coronal plasma vs. time. Lower panel: ratio of the two vs. time. From Argiroffi et al. (2008) by the kind permission of Astronomy and Astrophysics.

to cross-calibrate the two instruments in order to put the two sets of data in the same context. Having done all this, they considered the whole non-flaring Sun and all the flares, both time-averaged over a month, i.e., multiplying the emission measure by the time lapse over which it was taken, summing all these figures over a month, and finally dividing by the time lapse of a month.

Argiroffi et al. (2008) showed that the flare component is significantly in excess of the nonflaring Sun at higher temperatures, albeit not as much as occurs in active stars. If one follows the evolution of the non-flaring and flaring components over the cycle (Figure 2), as expected one finds they both wax and wane with the cycle, however not proportionally to each other. More specifically, the flaring component undergoes larger relative changes. The implication is that the heating of the non-flaring component behaves differently from that of the flaring component. Differently stated, if you believe in the existence of nanoflare coronal heating, nanoflares and flares have different global evolutions along the cycle. Also, they found that the emission measure above 3 MK for the non-flaring Sun, due mostly to plasma from active regions, evolves like the flares along the cycle.

On the other hand, if one compares the emission measure distribution of EK Dra, a very young Sun, with that of the Sun at maximum and at minimum of the solar cycle (Figure 3), one sees a similar effect: there is much less difference at low temperatures than there is at higher, flare-like temperatures. Again, going from low to high activity, the changes in heating have to be larger at higher temperatures, the implication being that not only higher activity implies more coronal heating, but also that this heating has to be more intense in order to produce higher temperatures.

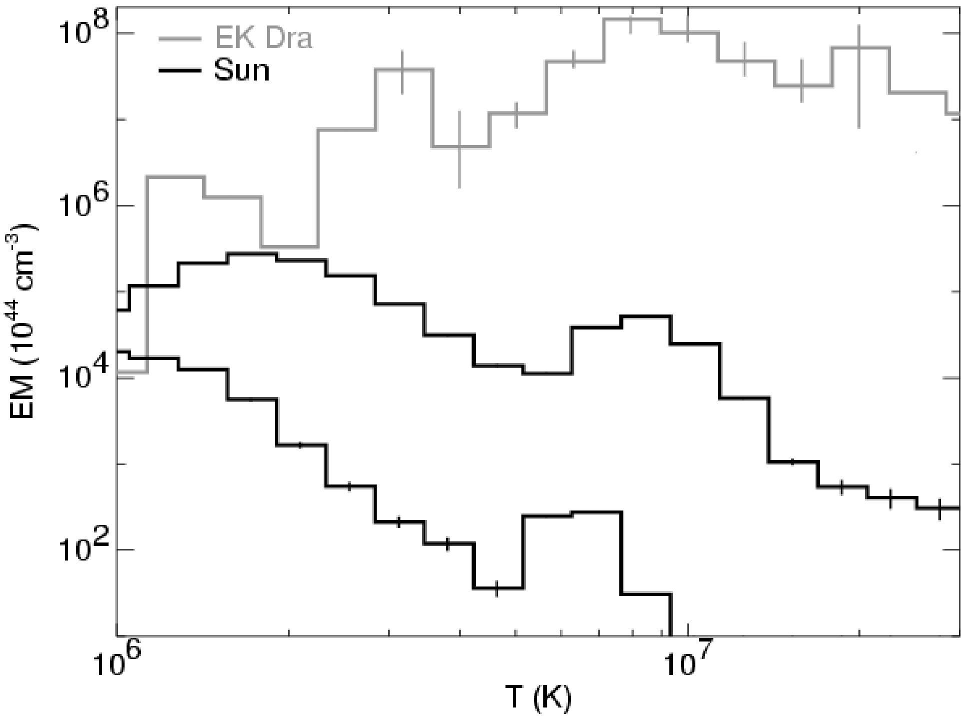

Figure 3. Solar emission distributions (including both flares and non-flaring plasma) near the minimum and at the maximum of the solar cycle (December 1991 and December 1995; both black) and the emission measure distribution of EK Dra (Scelsi et al. 2005; gray). From Argiroffi et al. (2008) by the kind permission of Astronomy and Astrophysics.

4 Conclusions

There is evidence of a global power law linking X-ray luminosity (and therefore global coronal heating) with magnetic flux and the size of coronal structures. This power law, found by Pevtsov et al. (2003) and discovered independently and differently by Schrijver et al. (2004) and by Schrijver & Title (2005), applies to various structures on the Sun, to the whole Sun, and to various active solar-type stars.

The total emission measure of the corona, and so approximately the coronal heating, varies by slightly more than one order of magnitude with the cycle, while the average temperature of the non-flaring corona varies by much less.

More activity implies more active regions on the Sun (as it proceeds across its cycle) and on the solar-like stars of different activity; but also one needs more flares (or flare-like structures) to be present on them. Thus, the more active Sun has more coronal emission measure but also a much hotter one; therefore more activity implies both more heating and a more intense heating, as testified by the higher temperatures.

On the Sun, the time-averaged global contribution of flares provides a contribution to the global emission measure at higher temperatures significantly in excess of that of the whole non-flaring Sun, a feature somewhat resembling active stars.

Global flare heating and global steady coronal heating evolve differently along the solar cycle, with flares showing larger relative changes, analogously to what one finds going from the Sun to a younger and more active Sun, EK Dra. Thus, if nanoflares are causing the heating of the non-flaring corona, global nanoflare heating has to increase and decrease along the cycle by a smaller amount than global flare heating.

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