Large scale properties of coronal heating along the solar cycle

G. Peres\textsuperscript{(1)}

Argiroffi\textsuperscript{(1)}, Orlando\textsuperscript{(2)}, Reale\textsuperscript{(1)}

\textsuperscript{(1)}Dip.S.F.A. – Univ. Palermo
\textsuperscript{(2)}INAF/OAPA
Focus of this talk on magnetically confined corona

No heating ⇔ no corona

No direct markers of heating (only indirect e.g. brightenings, plasma flows, rearrangements of morphology etc.) because thermal conduction, plasma dynamics, energy transfer along field lines etc. make it hard to identify the primary source and the mechanism(s) of coronal heating

Many features so far understood, much still to be found on heating

Sept. 2009 G. Peres – SOHO 23
1) Large effort to find the basic mechanisms

2) Attempts to “forward model” parts of corona and heating mechanisms (e.g. Gudiksen 2005, Peter 2006): basic modeling and match aspect of dynamic corona

3) Constrain the features of coronal heating modeling observed structures or regions (e.g. Priest et al. 2000, Reale et al. 2000, Demoulin et al. 2003)

We will concentrate on the global features of heating and therefore on a global approach
Scaling of heating with $B$ and $L$

Contribution of various parts of corona and its changes along the cycle

How does the heating change with [stellar and solar] activity level and along the cycle

Stellar coronal cycle(s?)
Corona entirely composed of closed coronal structures (loops)

Approximately half of the heat deposited in corona is radiated away, the other half conducted to TR (Vesecky, Antiochos and Underwood 1979)

So global coronal emission is a tracer of global coronal heating

The link heating - emission is OK on a **global** scale

but not on a **local** one

e.g. if a brightening appears somewhere in a loop does not mean heating occurred there (Reale et al 2000) instead for the overall budget it is ok.
Pevtsov et al. (2003)

X-ray luminosity vs. Unsigned magnetic flux
For various solar structures and late-type stars plus T-Tauri stars

Evidence of global power law \( L_x = \Phi^{1.15} \)

Careful with the log scale over many decades!
Schrijver et al. (2004) Full disk EUV and X-ray simulations and visualizations to identify the heating characteristics

Grid of values: best (visual) agreement for $F_H = \epsilon B^\alpha / (f \ L^\beta)$

$\epsilon = 4 \times 10^{14} ; \ A = 1.0 \pm 0.3 ; \ \beta = 1.0 \pm 0.5$ cgs units

(F$H$ heating per unit area, B mag field, L half loop length, f tapering function)

Consistent with granulation-driven B field braiding
Schrijver et al. (2005) compared their $F_H = 4 \times 10^{14} B^{1.0 \pm 0.3} / (f L^{1.0 \pm 0.5})$
with Pevtsov et al $L_x = \Phi^{1.15}$

The two laws agree (within errors) if $L$ changes much less (or its changes much less relevant) than $B$

Application also to giants and subgiants (which have very different dimensions and much different convection zones, implying much larger $L$)

Factor $(4 \times 10^{14})$ must scale with $L$. This is consistent with application of field line braiding to convective zone of giants and subgiants ($v_c$ changes much less than $H_p$).
Need to put solar observations into stellar context and To understand the contribution of various structures to X-ray emission

**Sun:** detailed physical scenario

**Stars:** large variety of phenomena and physical conditions

**Key point:**

The stellar observations “trade” the advantages of spatial resolution for the ability to constrain physical parameters which the Sun does not allow us to change (rotation rate, effective gravity, photospheric T, etc)

Ex.: relationship between rotation rate and stellar activity

(Pallavicini et al. 1981)
The solar-stellar analogy

How far does the solar model apply to other stars?

How do the underlying processes differ?

How realistic is this assumption?
Our Approach

Based on Direct Experimental Measurements

- Transform Yohkoh/SXT data into a format virtually identical to that of stellar X-ray observations
  - Ex.: made with ROSAT/PSPC, Chandra/ACIS, XMM-Newton/EPIC
- Apply standard methods of analysis used for stellar obs.
- Compare results with those of stellar X-ray studies

Objectives of our Project

- Investigate the validity of the solar-stellar analogy
- Trace how different structures and phenomena resolved on the Sun are responsible for the observed characteristics in X-ray stellar spectra
The Corona of the Sun as a star

Analysis of the Yohkoh/SXT data

(Orlando et al., 2000; Peres et al., 2000):

- From two simultaneous SXT images taken with different filters, derive the temperature and emission measure for each pixel in corona.

- From the two sets of T and EM values, sort all the EM belonging to each T bin, rearrange and obtain the distribution of emission measure vs. temperature, $EM(T)$: we divide the range of T detectable by the instrument ($5.5 < \log T \ [K] < 8 \ K$) into bins and sum up all the EM values within each "temperature bin".
From the EM(T) Distr. to the Coronal Spectrum
... to the X-ray Spectrum of the Sun as a Star

6-Jan-92

\[ C_j = \frac{t_{\text{exp}}}{4\pi D^2} \sum_k \int_{E_j}^{E_{j+1}} A(E)M(j, E) \frac{P(T_k, E)EM(T_k)}{E} dE \]

D = 1 pc
t_exp = 5 \times 10^4 sec

Folding the synthetic spectrum through the instrument response

Chandra/ACIS
Evolution of the X-ray Sun during the cycle

(Orlando et al. 2001)

Yohkoh - SXT integrated disk counts
3-70 Å band (Al.1 filter)
[100-fold change in Yohkoh SXT band Acton et al. 1996]

+ all cases our group studied (see the following)
Arrows= in the following we show their Differ. Emission Measure vs. T.
Whole-Disk EM(T) Distributions

(Peres et al. 2000)
EM and T of the solar corona during the cycle

Emission measure vs. T at three times (red arrows) (Peres et al. 2000)

Total emission measure (dots) and emission-measure-weighted temperature (squares) along the cycle (from Orlando et al. 2004) (see also Acton, 1996)
X-ray Flux and Hardness Ratio

- The Sun during the solar cycle 22 (Orlando et al. 2001)

F, G, K, M stars within 13 pc from the Sun (Schmitt 1997)

Temperature changes a little
Emission measure, $L_x$, $F_x$ a lot
Selecting Different Coronal Regions

(Orlando et al. 2001)
Contribution of Different Coronal Regions to the X-ray Flux and hardness ratio

F, G, K, M stars within 13 pc from the Sun
(Schmitt 1997)

- Cores of Active Regions
- Active regions
- Background corona

(Orlando et al. 2001)
Contribution of Different Coronal Regions to the X-ray Flux and hardness ratio

F, G, K, M stars within 13 pc from the Sun
(Schmitt 1997)

- Sun along the cycle
- Cores of Active Regions
- Active regions
- Background corona
  (Orlando et al. 2001)

- Flares
  (Reale et al. 2001)
Peres et al. (2004)

Increase of stellar activity not just an increase of area covered by ARs but also increase of fraction of surface covered with hotter and hotter plasma (time-UNresolved flares ?)

analogously for the solar cycle

NOT JUST MORE HEATING BUT ALSO MORE CONCENTRATED CORONAL HEATING (In order to obtain hotter plasma)
Since emitting plasma is confined in magnetic loops

\[ F_x = K F_H = K E_H L \]  
\[ E_H \text{ is the heating per unit volume, } L \text{ the loop semilength}; \quad K \sim 0.5 \text{ (Vesecky, Antiochos and Underwood, 1979 [VAU 79])} \]

The hardness ratio is easily converted to \( T \) (temperature)

Applying loops scaling laws (Rosner, Tucker and Vaiana, 1978; VAU 79)

\[ E_H = 10^5 \, p^{7/6} \, L^{-5/6} \]

\[ T = 1.4 \times 10^3 \, (pL)^{1/3} \]

We can rearrange the previous graph and fit the data as follows
Scaling laws of whole Sun, individual structures, active stars (Peres et al 2004)

\[ p = 1.2 \times 10^{-3} T_6^{5.2} \]

\[ n = 4.3 \times 10^6 T_6^{4.2} \]

\[ L = 3.0 \times 10^{11} T_6^{-2.2} \]

\[ E_H = 1.7 \times 10^{33} L^{-3.6} \]
Active late type stars have large amounts of Emiss Measure at high $T (> 10^7$ K) at any time. Unresolved flares or steady hot plasma? The Sun does not have anything like that... maybe.

What if we take the time-average of all the flares? Need GOES to catch all the flares, Yohkoh just observed some of them. Use GOES data, cross-calibrate them with Yohkoh/SXT. Put the two data sets together $\langle EM(T) \rangle$ every 4 mo: solid flare/GOES, shaded steady/Yohkoh.
EM(T) averaged over a month, every 4 months
blue steady corona (Yohkoh)
red flaring corona (GOES)

If nanoflares heat the steady corona they behave differently from flares along the cycle

Same as above but for $T > 3 \times 10^6$ K

The EM of hotter quiescent and flaring plasma manage to remain very similar, if not proportional, during the cycle
Argiroffi et al. (2008)

EM(T) for EK Dra (Young and active Sun)
Sun at Max with time average of flares
Same at Min

Need of larger increase of EM at high T to match EK Dra

Increase of activity means more heating and more concentrated

If nanoflares heat the corona they scale differently from flares with activity
X-ray cycles in stars

Which cycles? (Stern, 1998)
Hard to detect: need to follow periodically over many years possibly cyclic stars
Limited availability of adequate (and highly on demand) X-ray telescopes

Several stars more active (i.e. stronger X-ray emitters) than the Sun
X-ray from magnetic activity → Magnetic activity from dynamo →
Dynamo tied to cycle

Therefore strong X-ray emitters should have a cyclic evolution (???)
(Uhm????)
X-ray activity cycle in HD81809 (Favata et al 2008)

clear 8.2 yrs CaII cycle; enough flux and observations for XMM monitoring a 8.3 Yrs X-ray cycle; evidence of a flare; small total Temperature change, larger EM change (like the Sun)

Strong evidence also for 61 Cygni A and B, Hempelman et al (2006) a Cen A and B (Robrade et al 2005) (see also Ayres et al., 2008)
Conclusions I

- **Global power laws** linking X-ray luminosity with magnetic flux, dimensions etc. (Pevtsov et al. 2003; Schrijver et al. 2004, 2005) ⇒ **dissipation of braided B field**

along the cycle

- **Total EM** of coronal (heated to > 10^6 K) plasma varies by more than one order of magnitude
- **<T>** of corona changes much less

- More activity (BOTH along the solar cycle AND from the Sun to more active stars)
  - imply more active regions AND more flares (only flares can explain most active stars)
  - (i.e. more and more heating but also more intense heating)
Conclusions II

• Excess in EM due to flares also on the Sun (albeit time-averaged) ...

• Flares and steady coronal heating (nanoflares ?) behave differently along the solar cycle: flares change more

• Similarly hotter part of coronal EM increases more with stellar activity

• $T > 3 \times 10^6$ coronal plasma matches the evolution of time-averaged flares

• Firm evidence of solar-like X-ray cycle only for one star (maybe a couple more show a hint of a cycle in X-rays)
However...

Despite
• the conceptual problems
• the limitations of present day instruments
• their limited availability

Some studies are accumulating evidence of long term evolution of stellar coronae, in addition to what reviewed by Stern (1998) ...