Lecture 12

Flare Lightcurves

March 1, 2017

Questions regarding flare heating

- **When** is flare plasma heated: only at the very start or throughout the flare evolution? Impulsively or more gradually?
- **Where** is flare plasma heated: is the primary energy deposition in the corona or in the lower atmosphere or both?
- **What** is the mechanism of flare heating: by shocks? Non-thermal particles? Conduction? Or else?
- **How much** is the energy used to heat flare plasma?

Time dependent imaging and spectroscopic flare observations in multiple wavelengths have the enormous advantage.

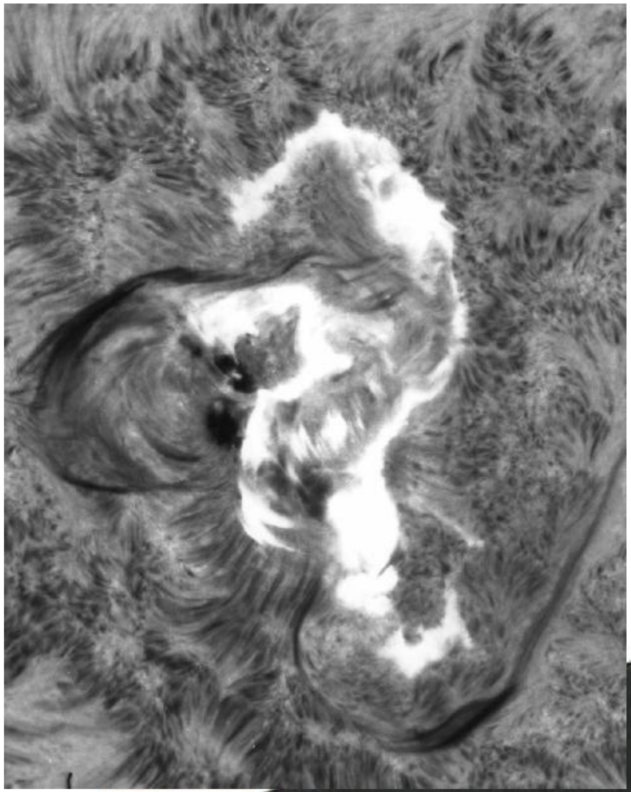
Questions regarding flare heating

$$\rho c_v\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial s}\right)=-\frac{p}{A}\frac{\partial}{\partial s}(Au)+\tfrac{4}{3}\mu\left|\frac{\partial u}{\partial s}\right|^2+\frac{1}{A}\frac{\partial}{\partial s}\left[A\kappa\frac{\partial T}{\partial s}\right]-n_e^2\Lambda(T)+h$$

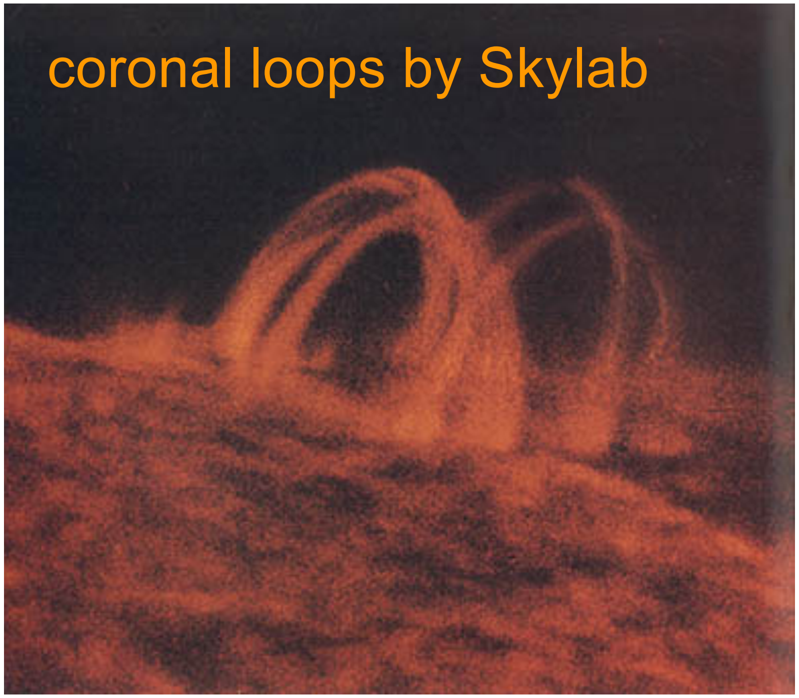
$$\frac{dE_{tot}}{dt}\approx -\underbrace{\int_{s_{tr}}^{L/2} n_e^2\Lambda(T)A\,ds}_{\text{radiative loss}}+\tfrac{1}{2}u^3A\Big|_{tr}+\underbrace{\tfrac{5}{2}puA\Big|_{tr}}_{\text{enthalpy flux}}\underbrace{-\kappa\frac{\partial T}{\partial s}A\Big|_{tr}}_{\text{conductive flux}}+\overbrace{\int_{s_{tr}}^{L/2} h\,A\,ds}^{\text{heating}}$$

$$C_\lambda(t)=\int R_\lambda(T)n^2(T)\frac{dl}{dT}dT\,,$$ counts/s/pxl

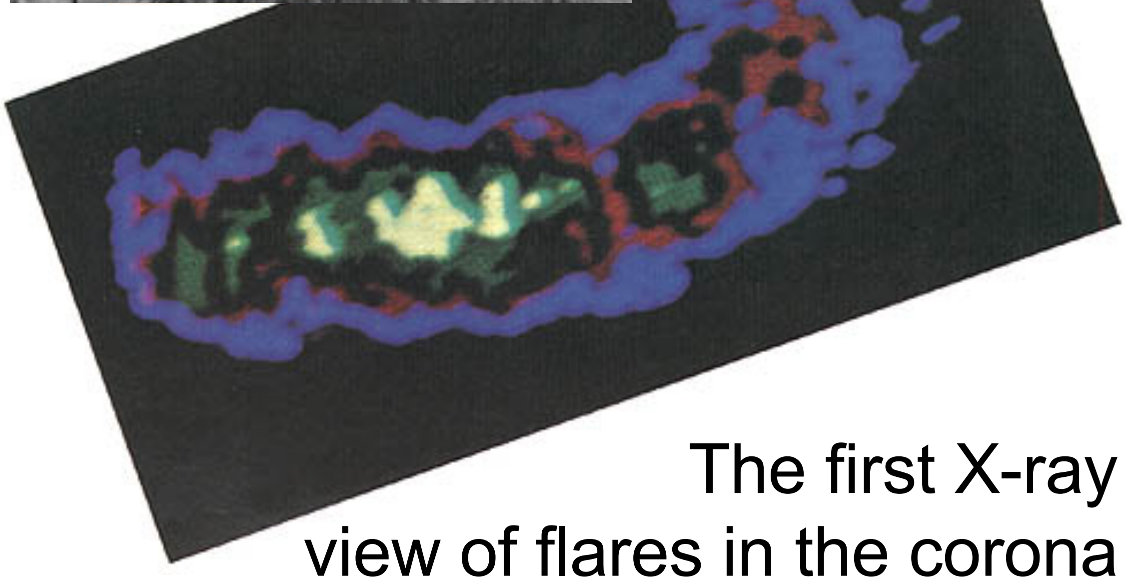
Two approaches of doing this, forward or backward.



The great "seahorse" Hα flare by BBSO



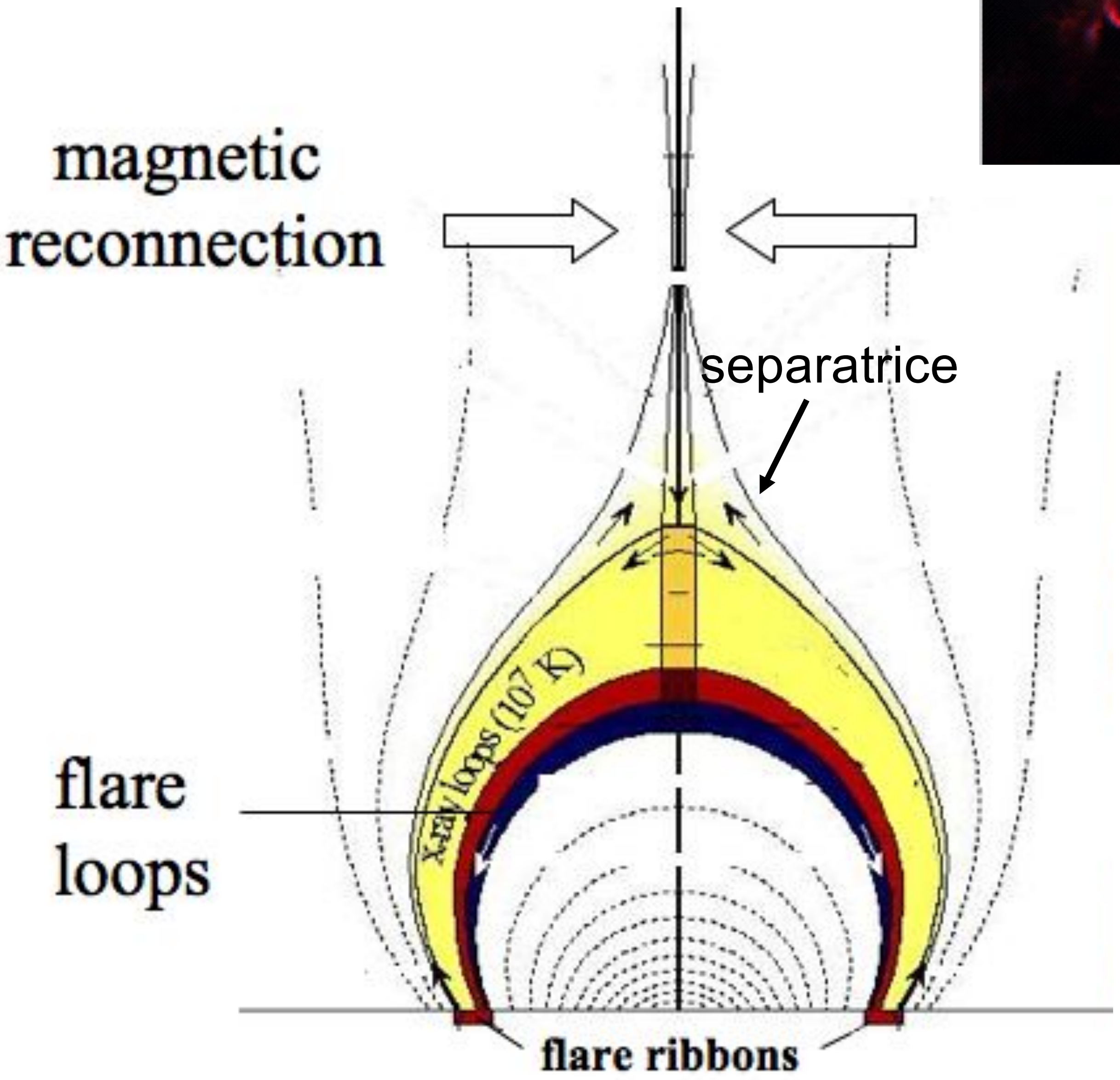
coronal loops by Skylab



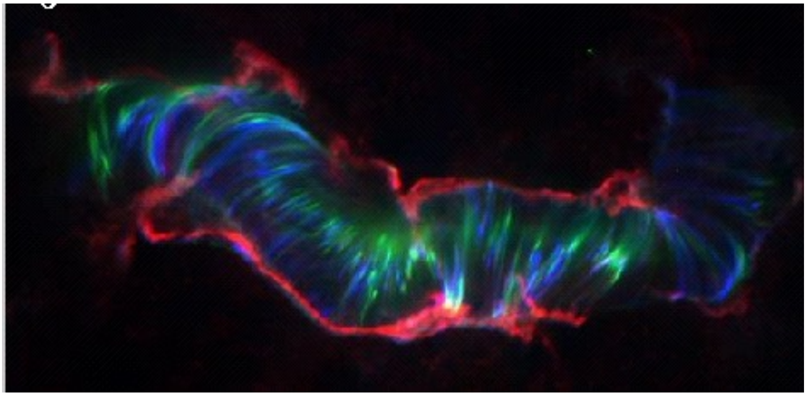
The first X-ray view of flares in the corona

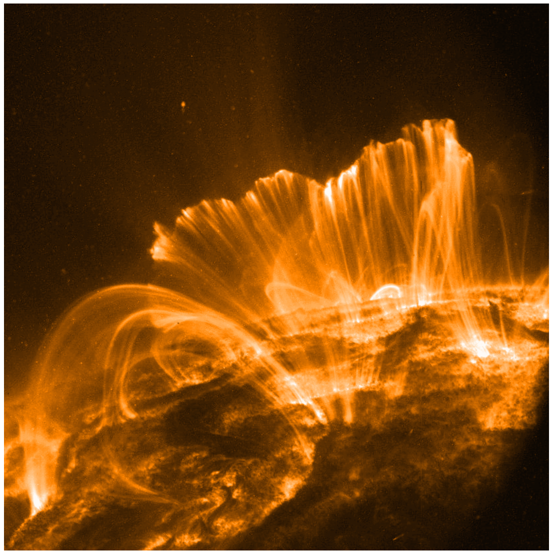
Telescopes on the ground and in space have captured the signature morphology of solar flares: ribbons and loop arcades.

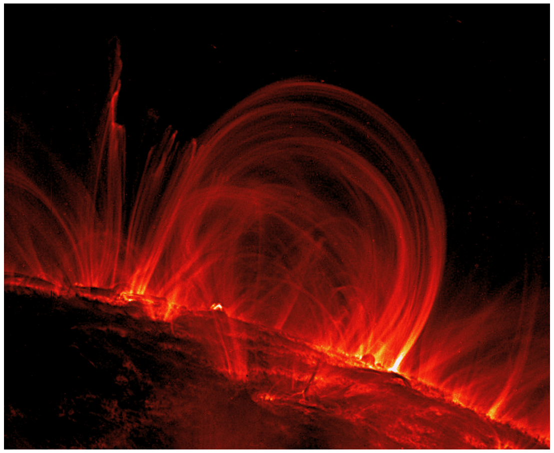
The standard flare configuration



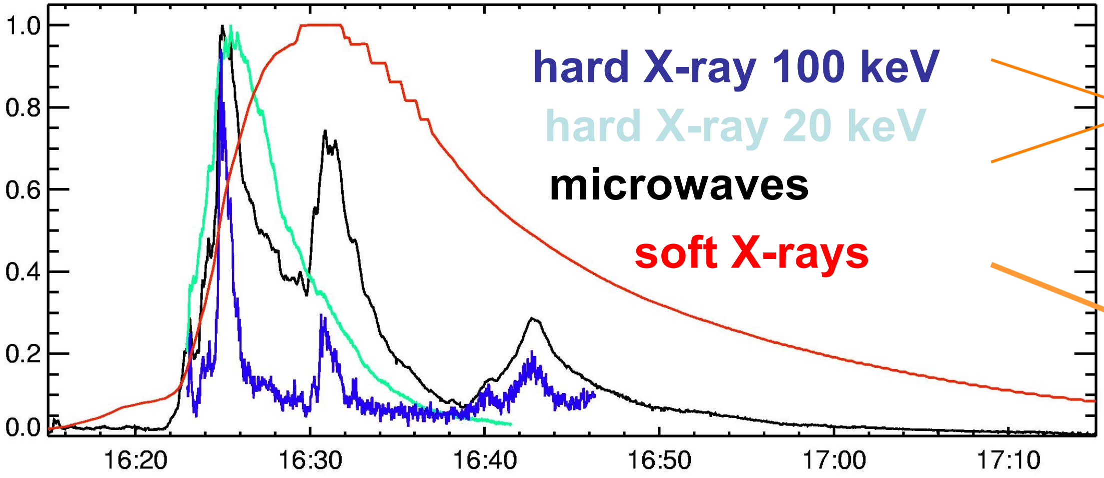
(adapted from Forbes & Acton, 1996)







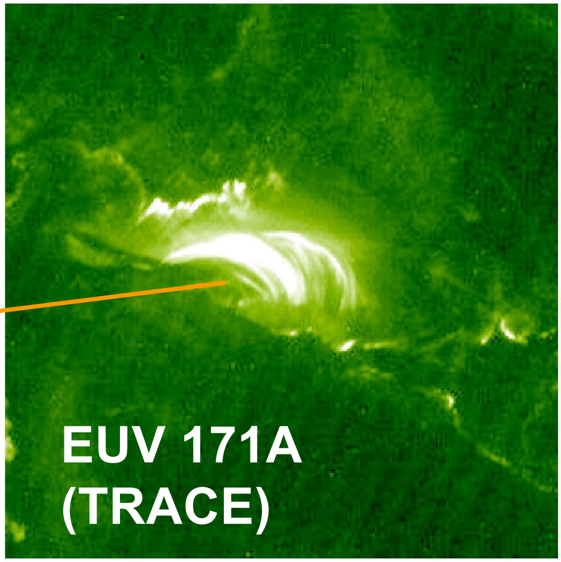
Flare emission across the electromagnetic spectrum

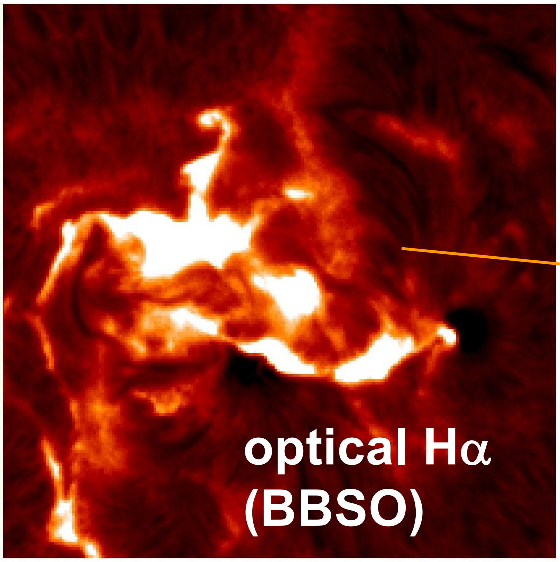


Bremsstrahlung & gyro-synchrontron emissions by non-thermal electrons.

thermal emission by 10^{6-7} K plasmas

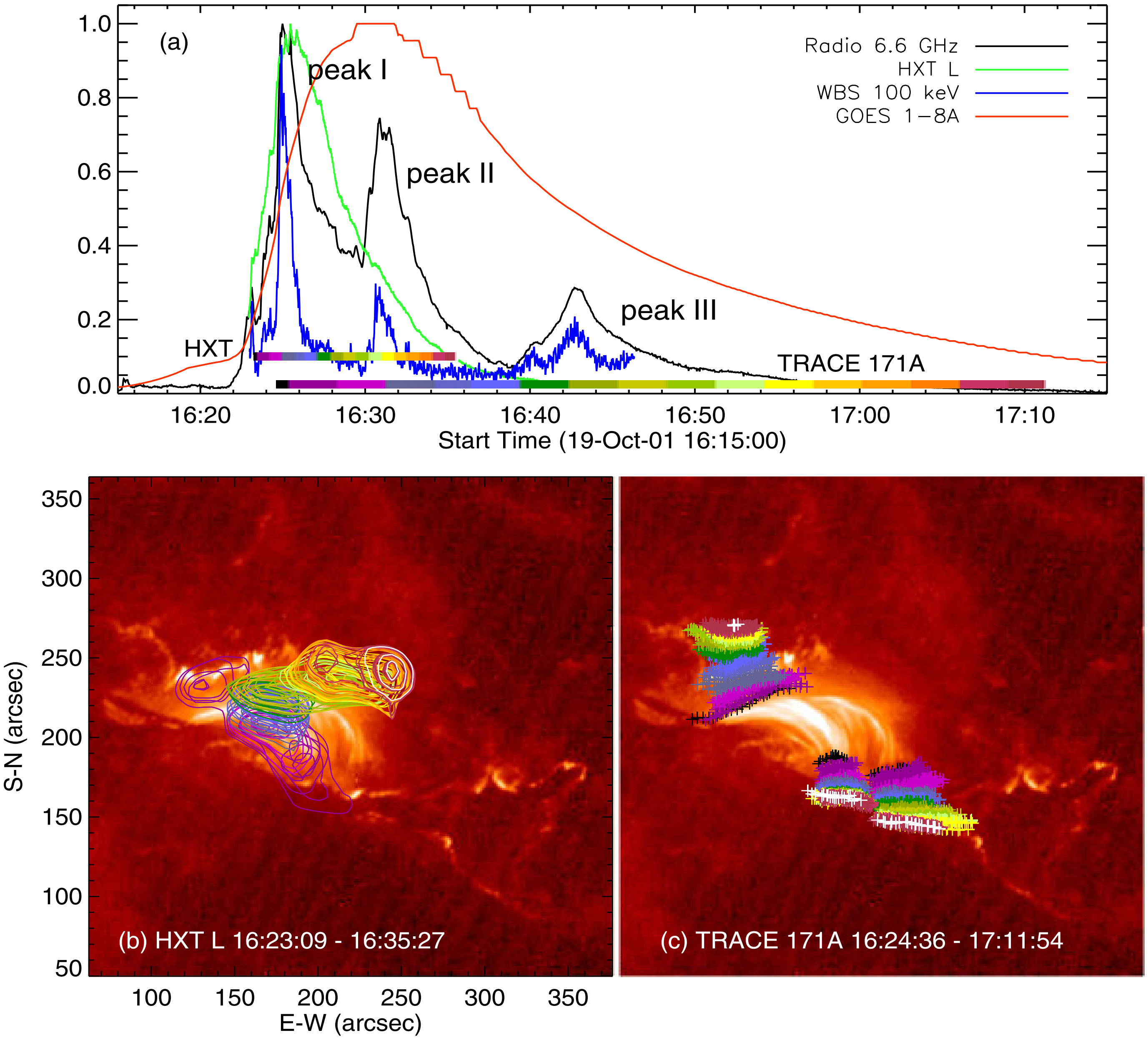
flare loops (10^6 K) in the corona



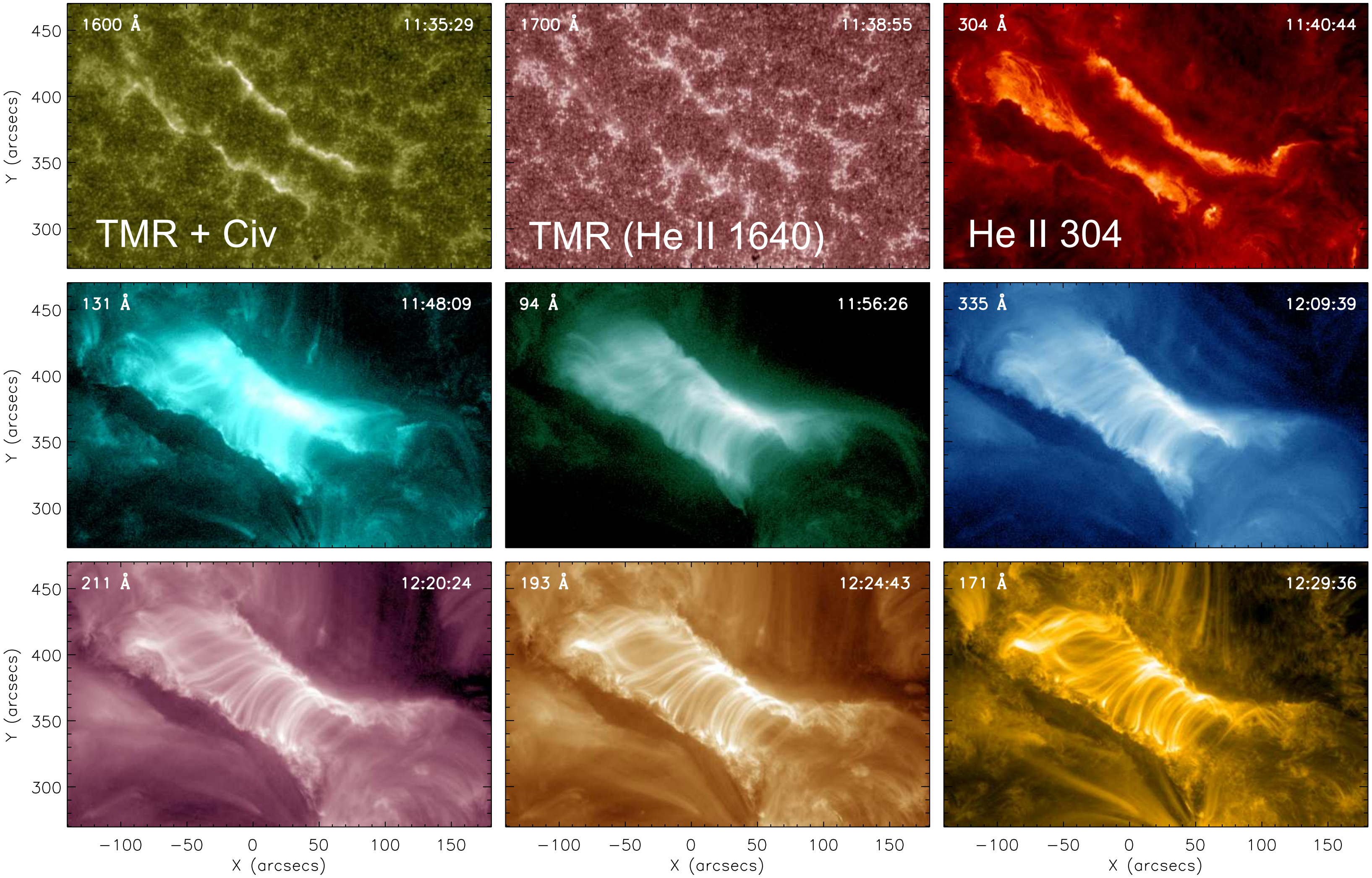


flare ribbons (10^{4-5} K) in the chromosphere

Flare emission across the electromagnetic spectrum

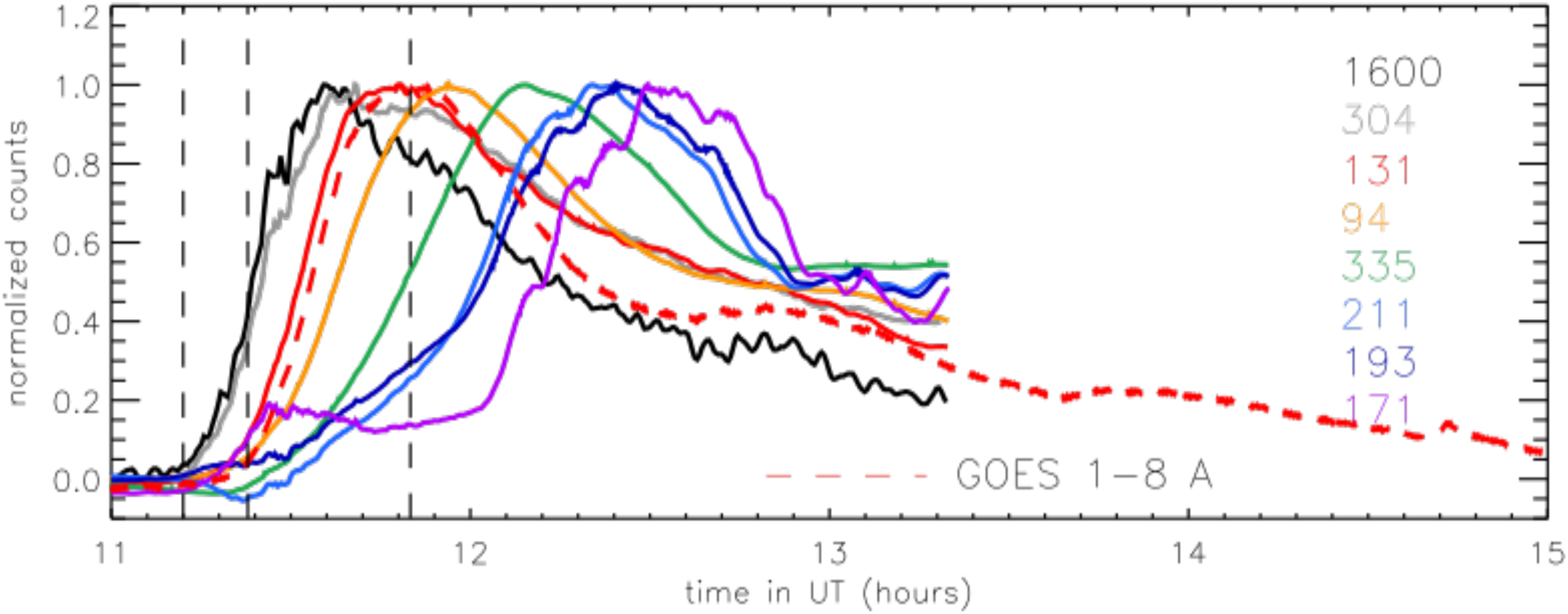


The view from the chromosphere to the corona



3500 K – 10 MK, 1″ – 2″, full-disk, 12 – 24s, 24/7, by AIA

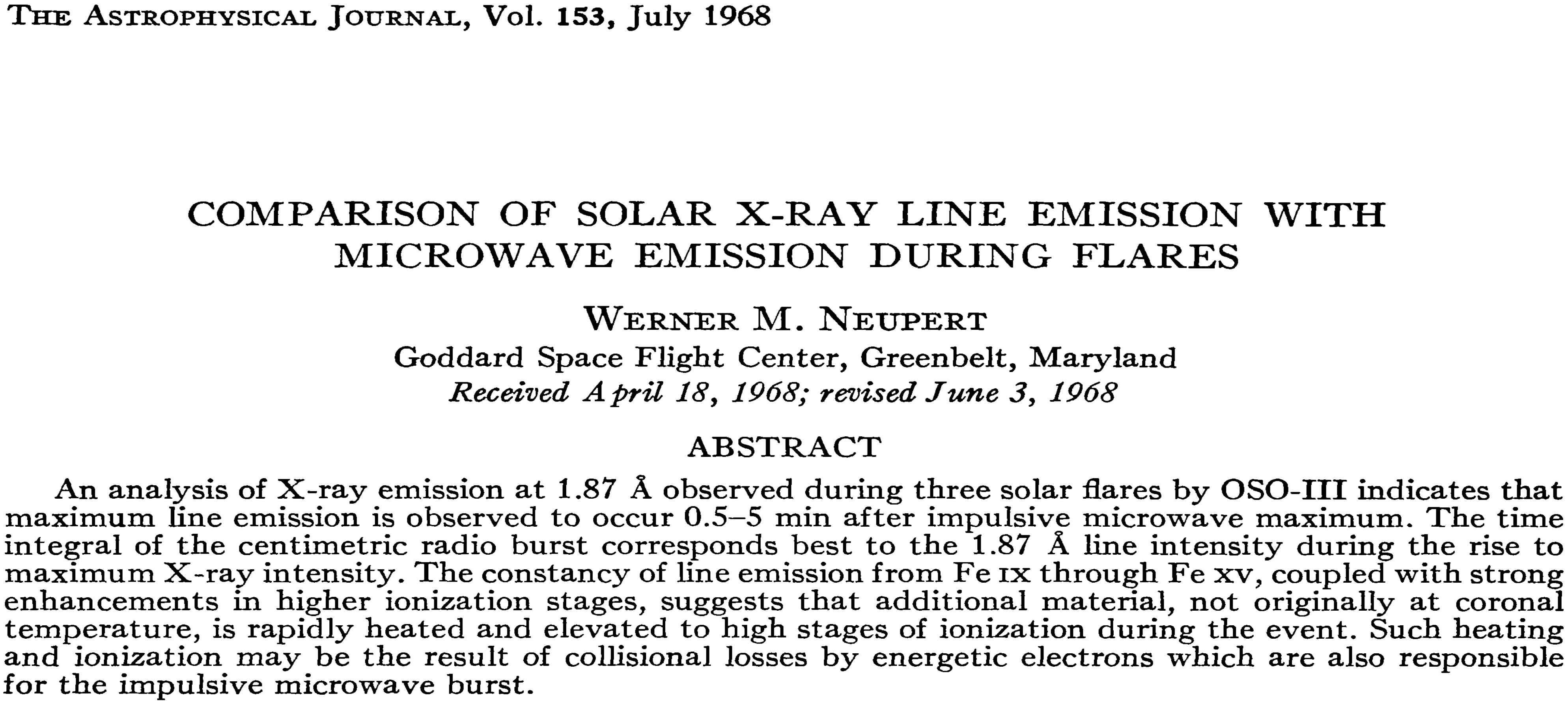
Heating (?) and cooling sequence



The order of peak emission: chromosphere 0.1 MK – corona 10 – 6 – 3 - 2 – 1 MK, with time lags of 10, 10, 15, 15, 10 min.

The Neupert Effect: when is the heating?

Neupert (1968), "Comparison of Soft X-ray Line Emission with Microwave Emission During Solar Flares", states that the time integral of microwave burst corresponds best to X-ray line emission from rise to maximum.



THE ASTROPHYSICAL JOURNAL, Vol. 153, July 1968

COMPARISON OF SOLAR X-RAY LINE EMISSION WITH MICROWAVE EMISSION DURING FLARES

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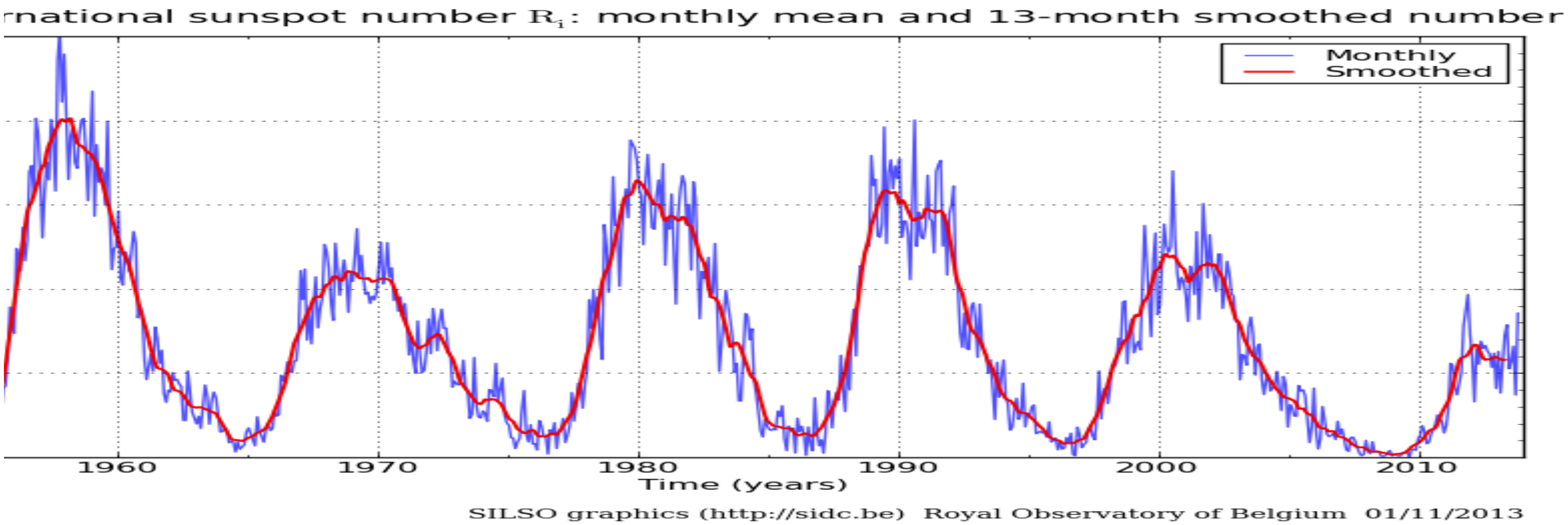
Received April 18, 1968; revised June 3, 1968

ABSTRACT

An analysis of X-ray emission at 1.87 Å observed during three solar flares by OSO-III indicates that maximum line emission is observed to occur 0.5–5 min after impulsive microwave maximum. The time integral of the centimetric radio burst corresponds best to the 1.87 Å line intensity during the rise to maximum X-ray intensity. The constancy of line emission from Fe IX through Fe XV, coupled with strong enhancements in higher ionization stages, suggests that additional material, not originally at coronal temperature, is rapidly heated and elevated to high stages of ionization during the event. Such heating and ionization may be the result of collisional losses by energetic electrons which are also responsible for the impulsive microwave burst.

The Neupert Effect: when is the heat?



SILSO graphics (http://sidc.be) Royal Observatory of Belgium 01/11/2013

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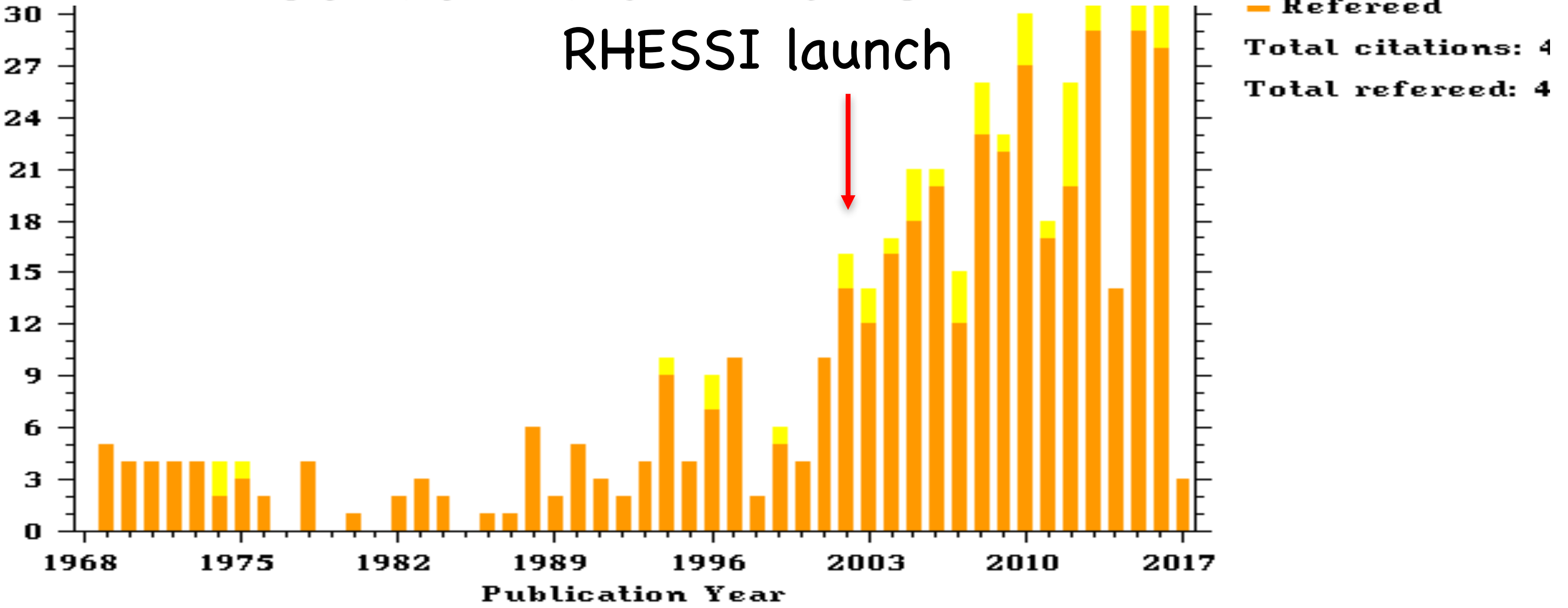
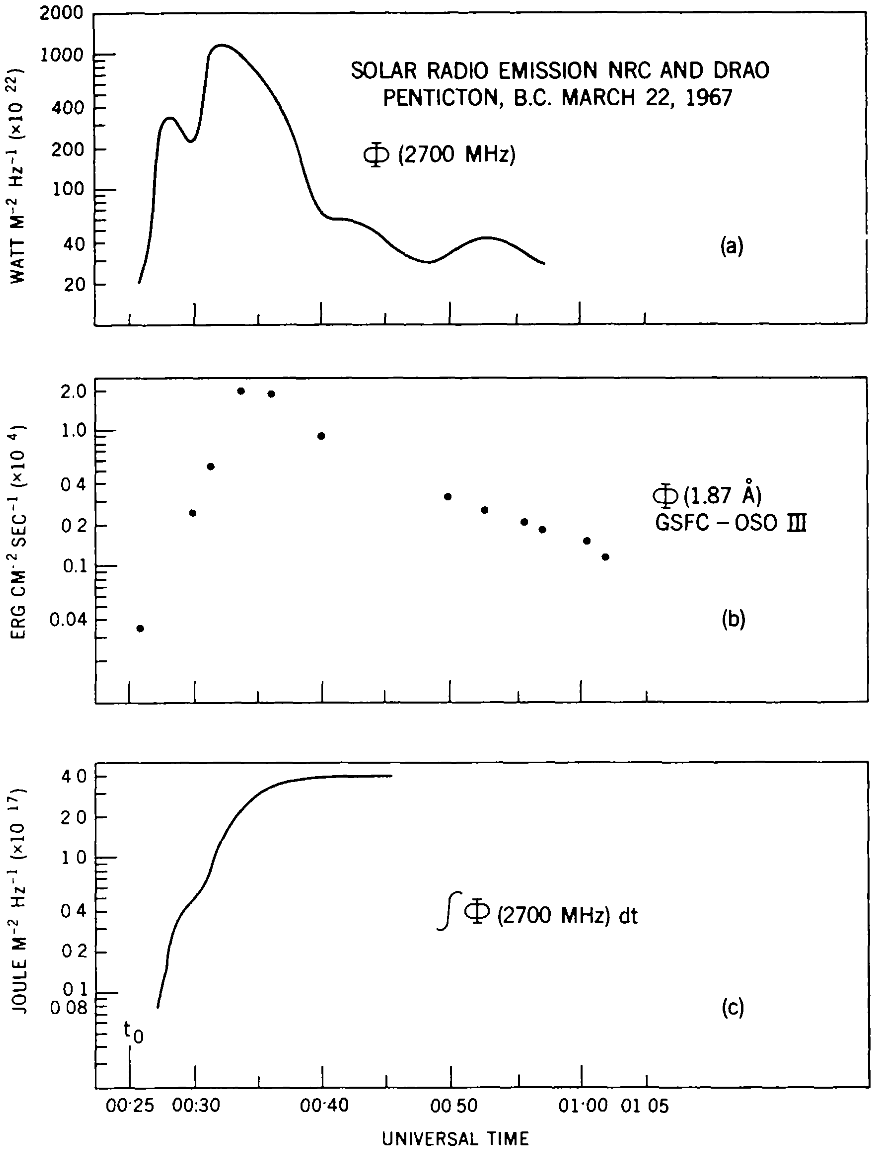
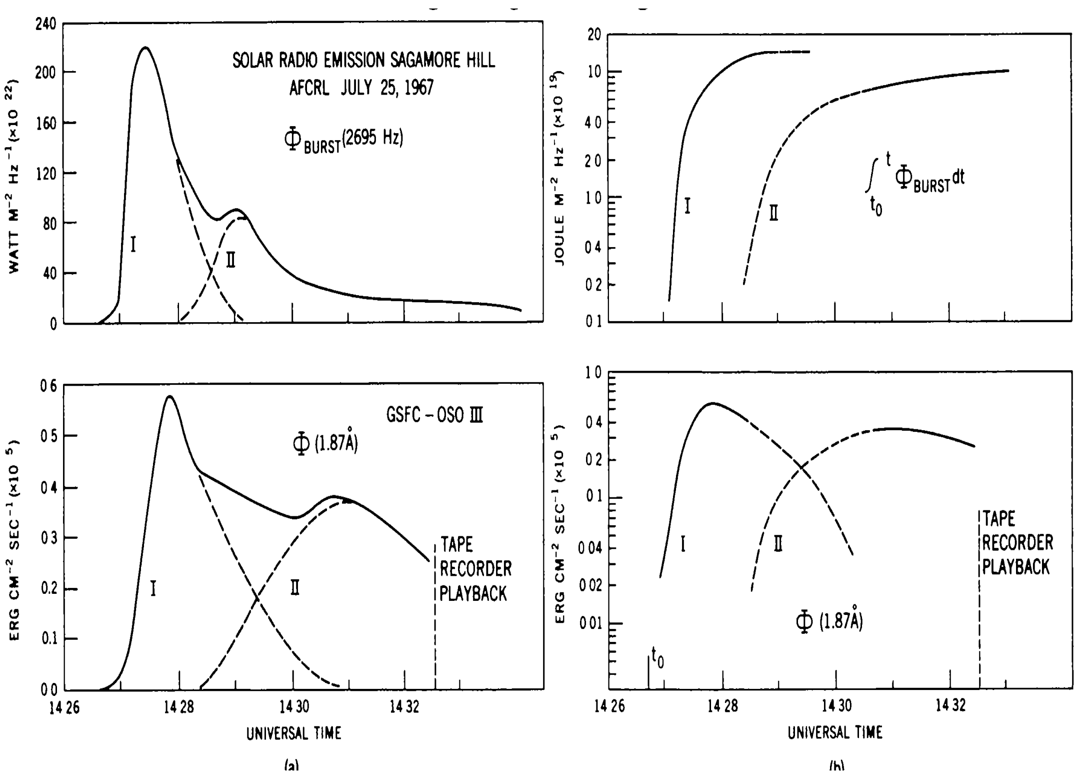


RHESSI launch

The Neupert Effect: SXR vs. Microwave Integral





Neupert (1968)

The Neupert Effect: SXR derivative vs. HXR

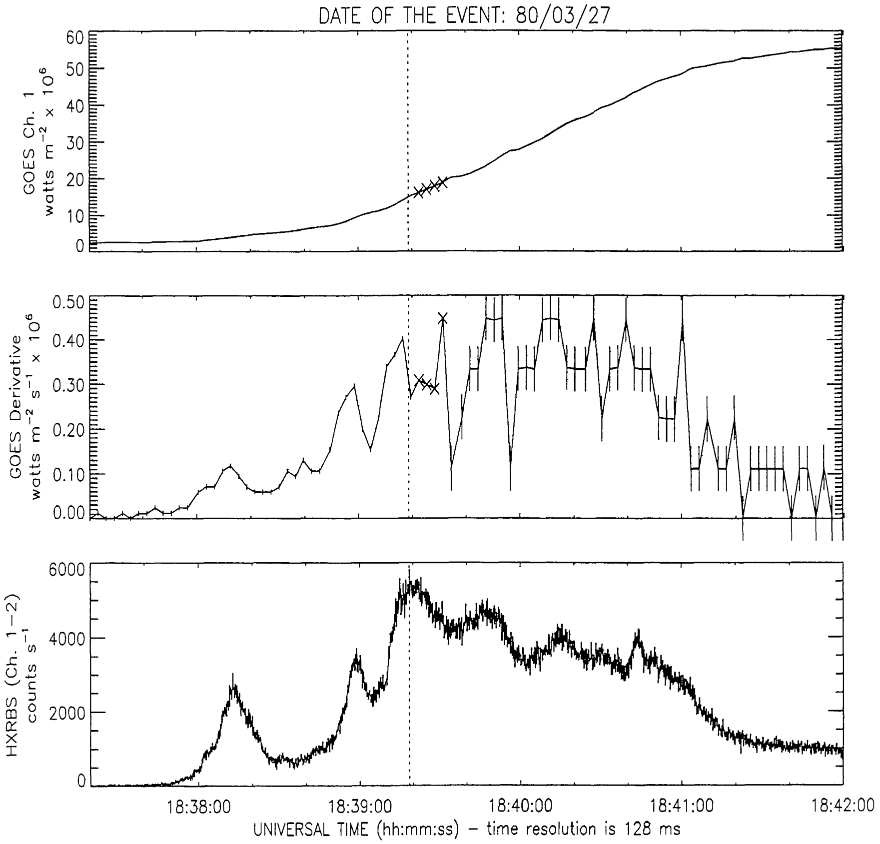


Fig. 1. *Top*: GOES 1–8 Å soft X-ray time profile plotted with a time resolution of 3 s for a flare on 1980 March 27. Note that the points marked with an × in the top and middle plots indicate the location of the GOES gain-change spike that has been removed and replaced with interpolated values. *Middle*: Time derivative of the top plot obtained by taking first differences and dividing by the 3-s interval duration. The error bars represent estimates of the equivalent $\pm1\sigma$ uncertainties resulting from the digitization of the GOES data. Note the increase in the length of these error bars after 18:39:30 UT because of the larger digitization step size in the lower gain state. *Bottom*: HXRBS 26–51 keV (Channels 1 and 2) hard X-ray time profile plotted on the same time scale but with the time resolution indicated at the bottom of the plot (see Dennis *et al.*, 1991; for the HXRBS energy calibration as a function of time during the mission for other events). The vertical broken line through all the plots indicates the time of the highest HXR peak for comparison with the SXR plots.

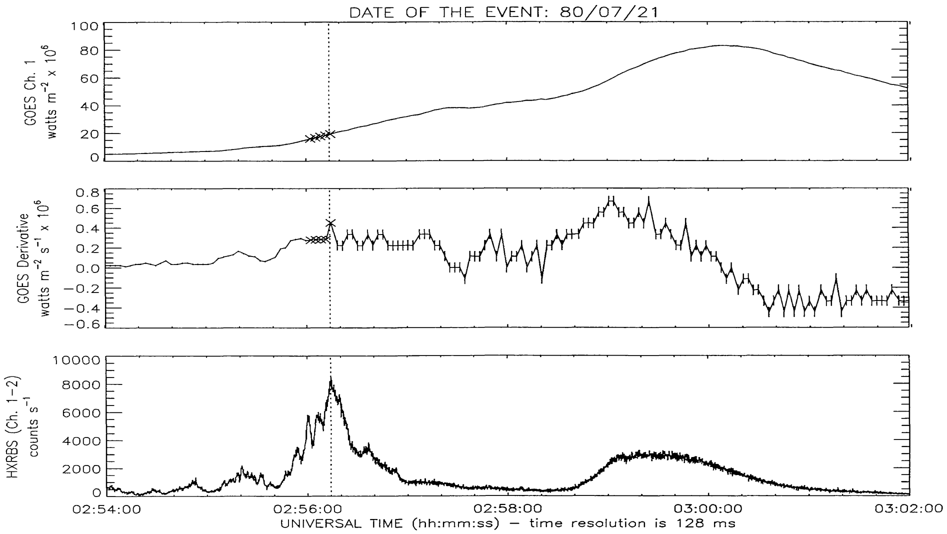


Fig. 3. Similar plots to those shown in Figure 1 for a flare on 1980 July 21.

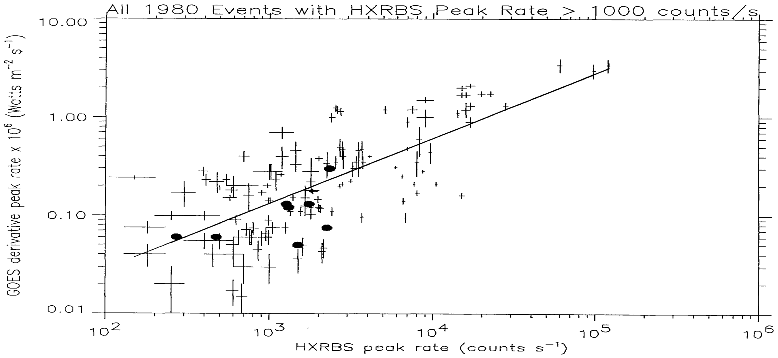


Fig. 5. Scatter diagram showing the amplitude of the SXR time derivative peak corresponding to all HXR peaks in the 66 Class 1 events with HXRBS peak rates >1000 counts s^{-1} detected in 1980. The vertical error bars represent estimates of the equivalent $\pm1\sigma$ uncertainties on the GOES time derivative resulting from digitization; horizontal bars represent the uncertainty in reading the HXRBS rate from the plots. Filled circles are plotted to show the SXR derivative value at the time of those HXR peaks that do not show any corresponding peak in the SXR time derivative plot.

Dennis & Zarro 1993: 80% (of 66 large events SMM/HXRBS) show good correlation

The Neupert Effect: the Larger Story

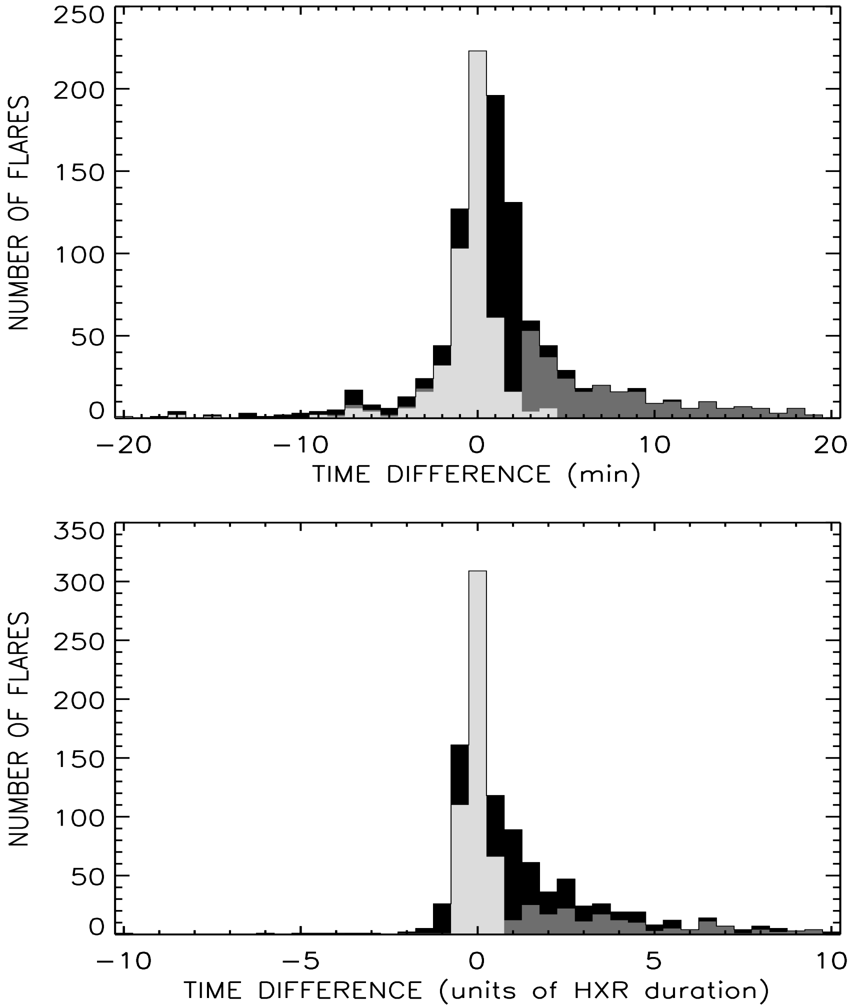
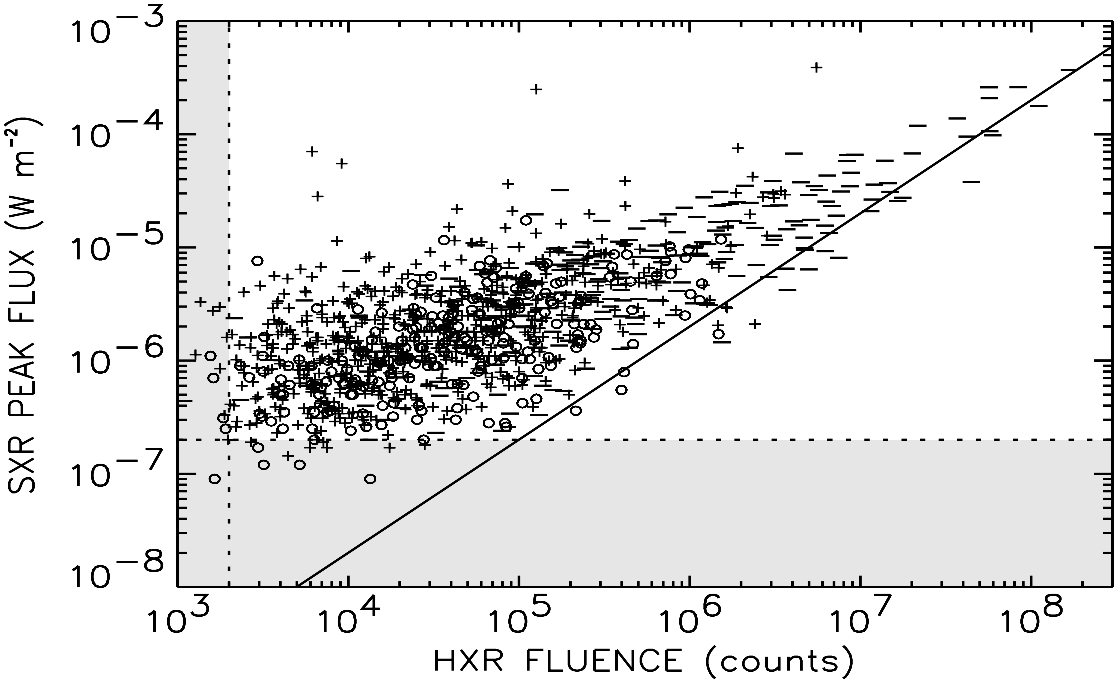
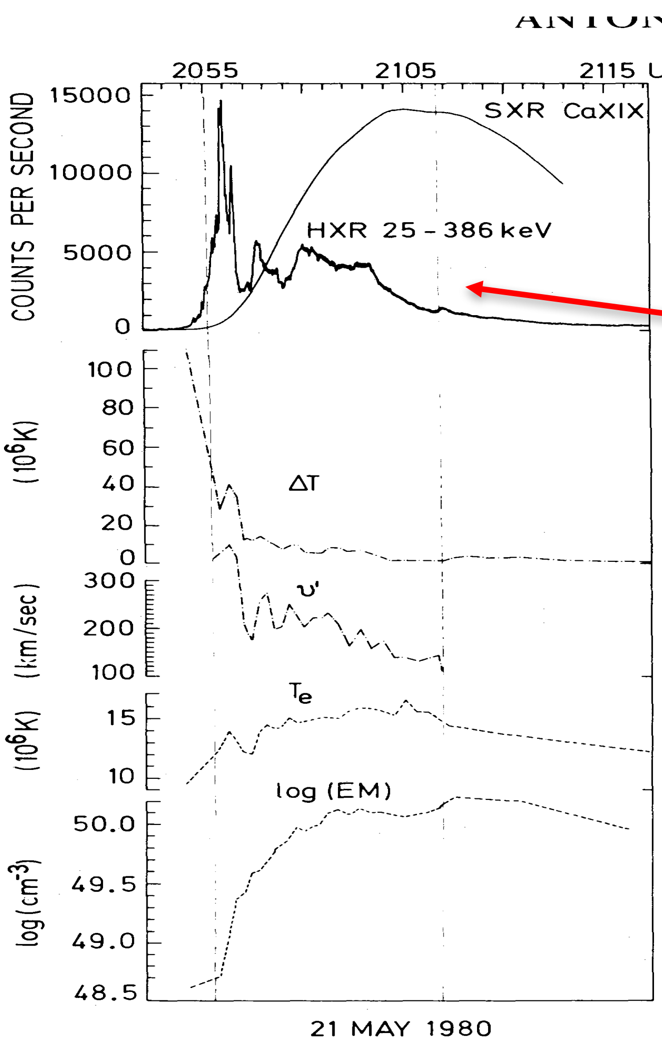


Fig. 1. Histogram of the difference of the SXR maximum and HXR end time, given in absolute values (top panel) and normalized to the HXR event duration (bottom panel). Positive values indicate that the maximum of the SXR emission occurs after the end of the HXR emission, negative values vice versa. The shading refers to different samples of events, which are compatible with the timing expectations of



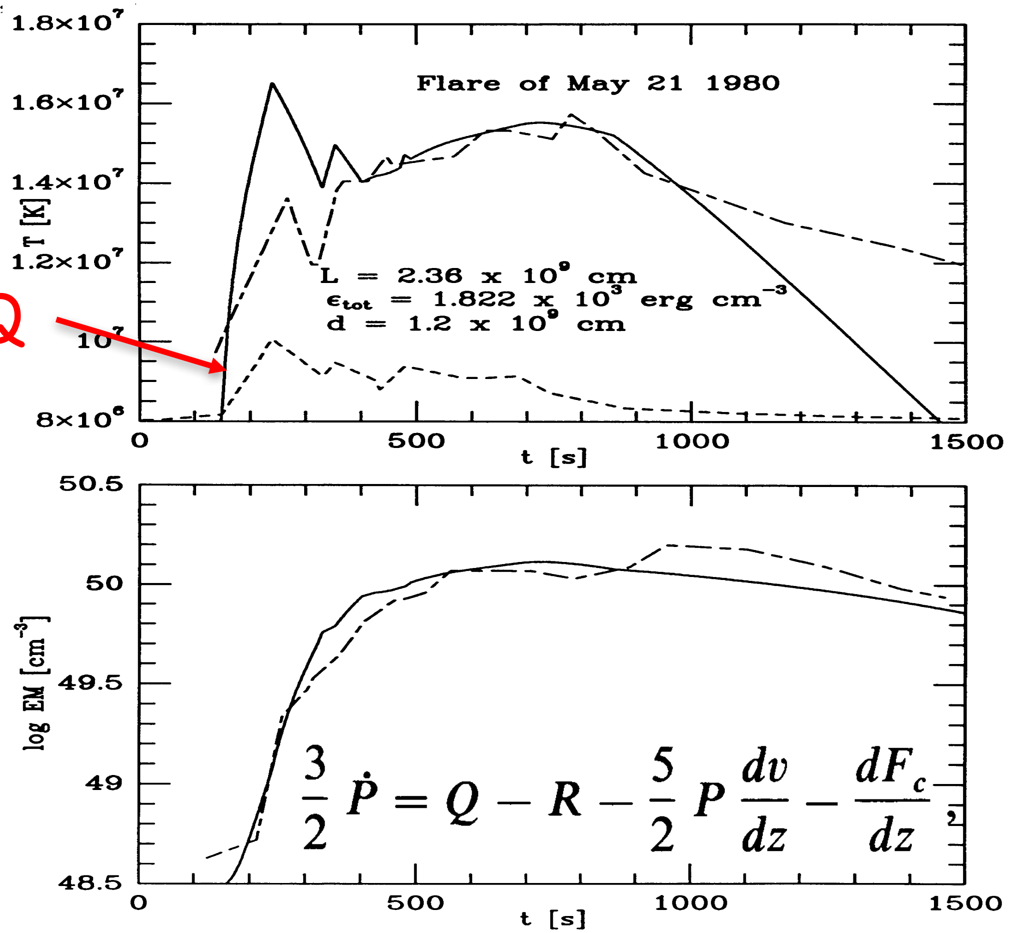
Veronig et al. 2002: Neupert effect in >1000 SXR/HXR events by GOES and *Burst and Transient Source Experiment* on *Compton Gamma-Ray Observatory* (BATSE/CGRO; 25–50, 50–100, 100–300 and >300 keV, 1~s, 1997-2000, 2738 HXR events.)

Heating during the HXR burst



Antonucci, Gabriel, Dennis 1984, ApJ

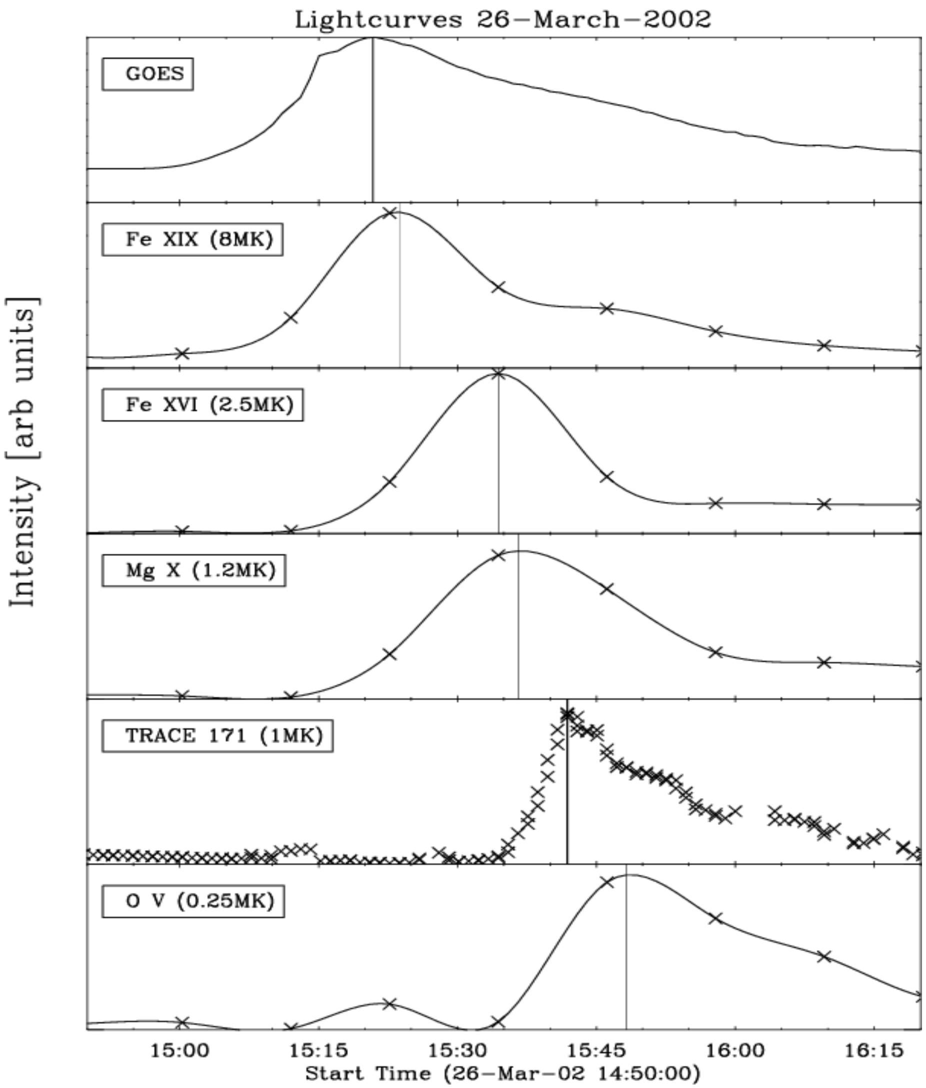
Q



$$\frac{3}{2}\dot{P} = Q - R - \frac{5}{2}P\frac{dv}{dz} - \frac{dF_c}{dz},$$

Fisher & Hawley 1990 (also Mariska/Emslie/Li, 1990s)

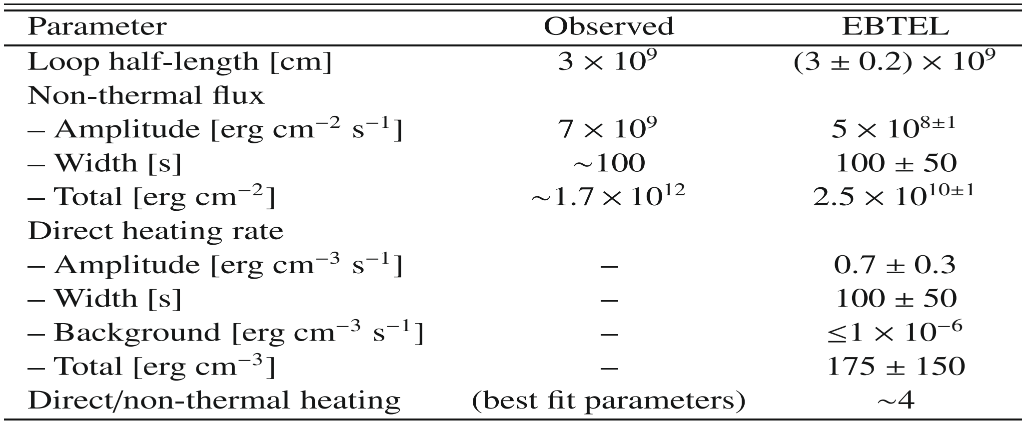
Heating during the HXR burst



$$\frac{d\overline{P}_i}{dt} \approx \frac{2}{3}\left[Q_i + \frac{\Gamma_i}{L_i} - \frac{1}{L_i}\left(R_c + R_{tr}\right)_i\right],$$

$$\frac{d\overline{n}_i}{dt} = \frac{c_2}{5c_3 k L_i \overline{T}_i}\left(\left(-F_0\right) - R_{tr} + \Gamma\right)_i$$

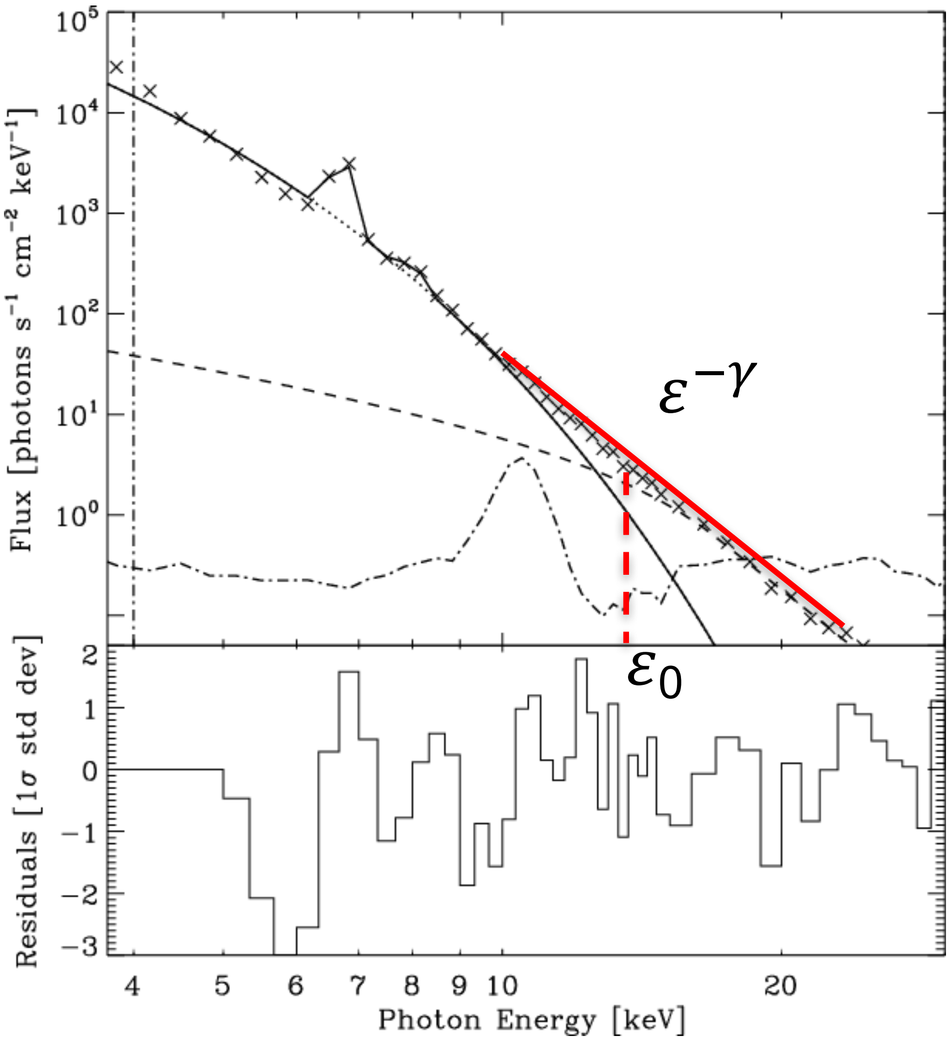
EBTEL; Klimchuk et al. 2008

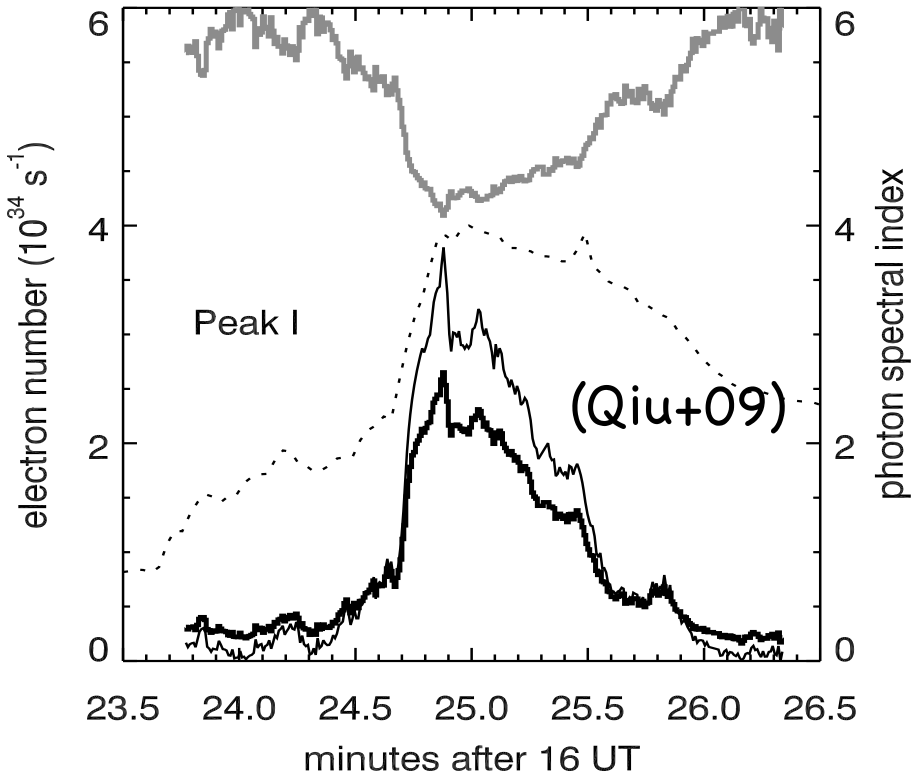


Parameter	Observed	EBTEL
Loop half-length [cm]	3×10^9	$(3 \pm 0.2) \times 10^9$
Non-thermal flux		
– Amplitude [erg cm^{-2} s^{-1}]	7×10^9	$5 \times 10^{8\pm1}$
– Width [s]	~100	100 ± 50
– Total [erg cm^{-2}]	$\sim1.7 \times 10^{12}$	$2.5 \times 10^{10\pm1}$
Direct heating rate		
– Amplitude [erg cm^{-3} s^{-1}]	–	0.7 ± 0.3
– Width [s]	–	100 ± 50
– Background [erg cm^{-3} s^{-1}]	–	$\leq1 \times 10^{-6}$
– Total [erg cm^{-3}]	–	175 ± 150
Direct/non-thermal heating	(best fit parameters)	~4

Raftery et al. 2009

Fitting the XR spectrum to find energy, and else

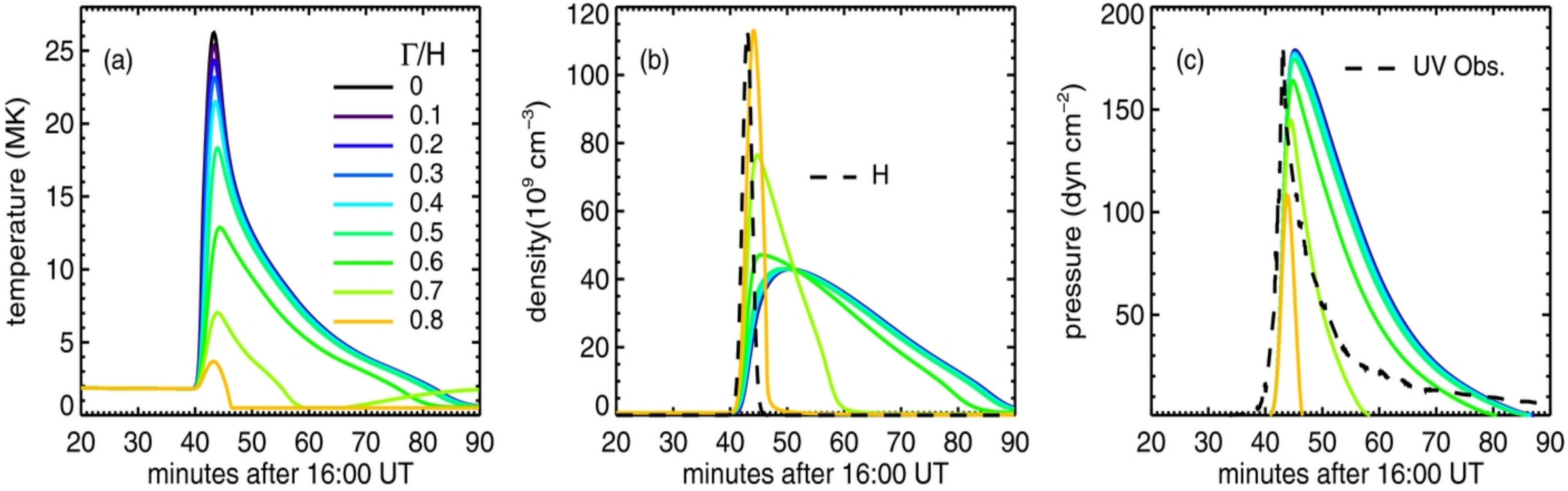




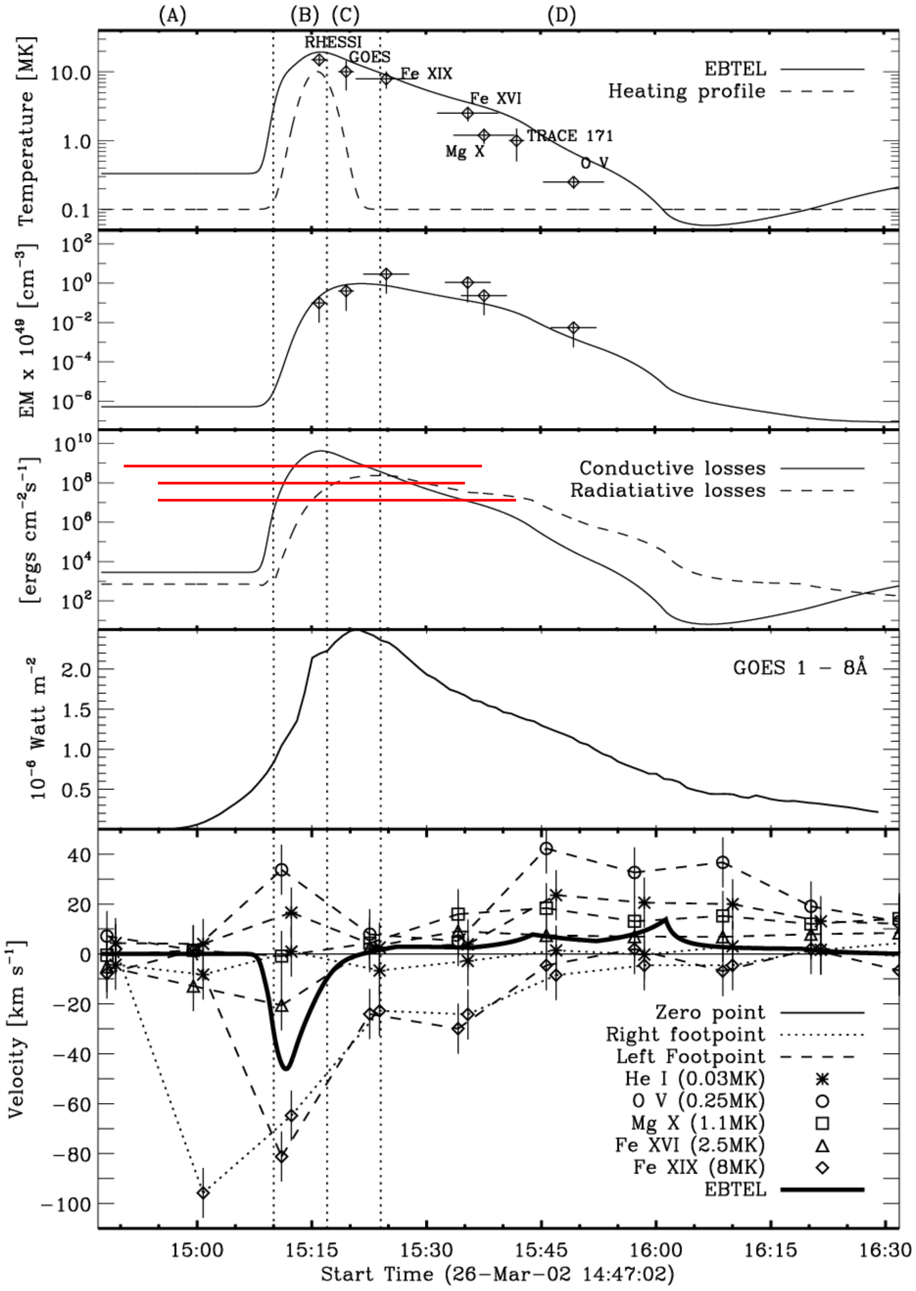
Typical flare non-thermal flux:
$\Gamma \sim 10^{9-12}$ erg/s/cm^2

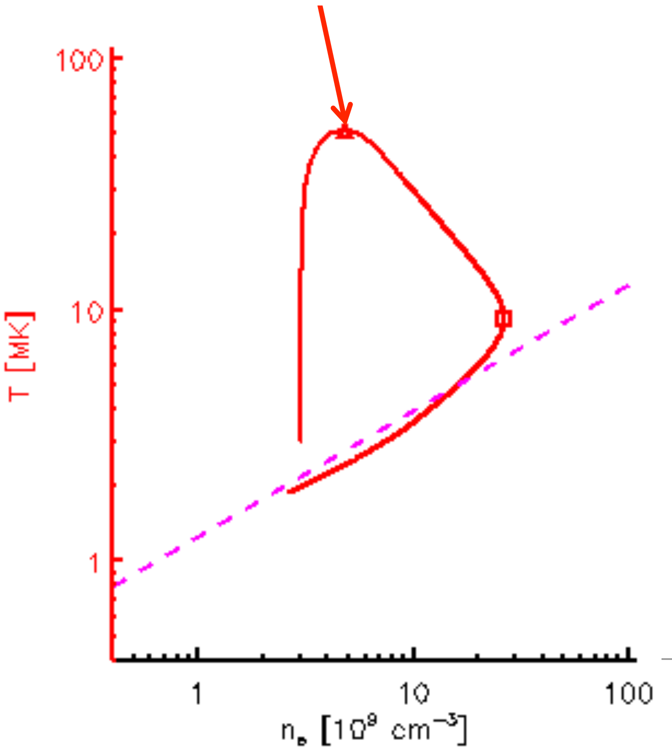
$I(\varepsilon) = a\varepsilon^{-\gamma}$ (photons/s/cm^2/keV), $F(E) = AE^{-\delta}$ (electrons/s/keV)

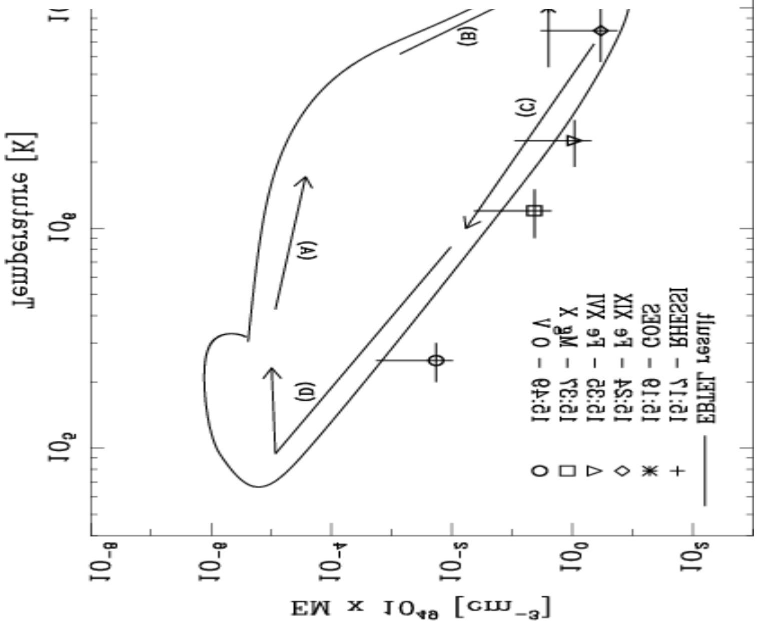
$N_{tot} = \int_{E_0}^{\propto} F(E)dE$ (electrons/s), $E_{tot} = \int_{E_0}^{\propto} E\,F(E)dE$ (ergs/s)



Different amount of "non-thermal heating" produces different coronal signatures (Winter et al. 2011, Liu et al. 2013)







Raftery et al. 2009

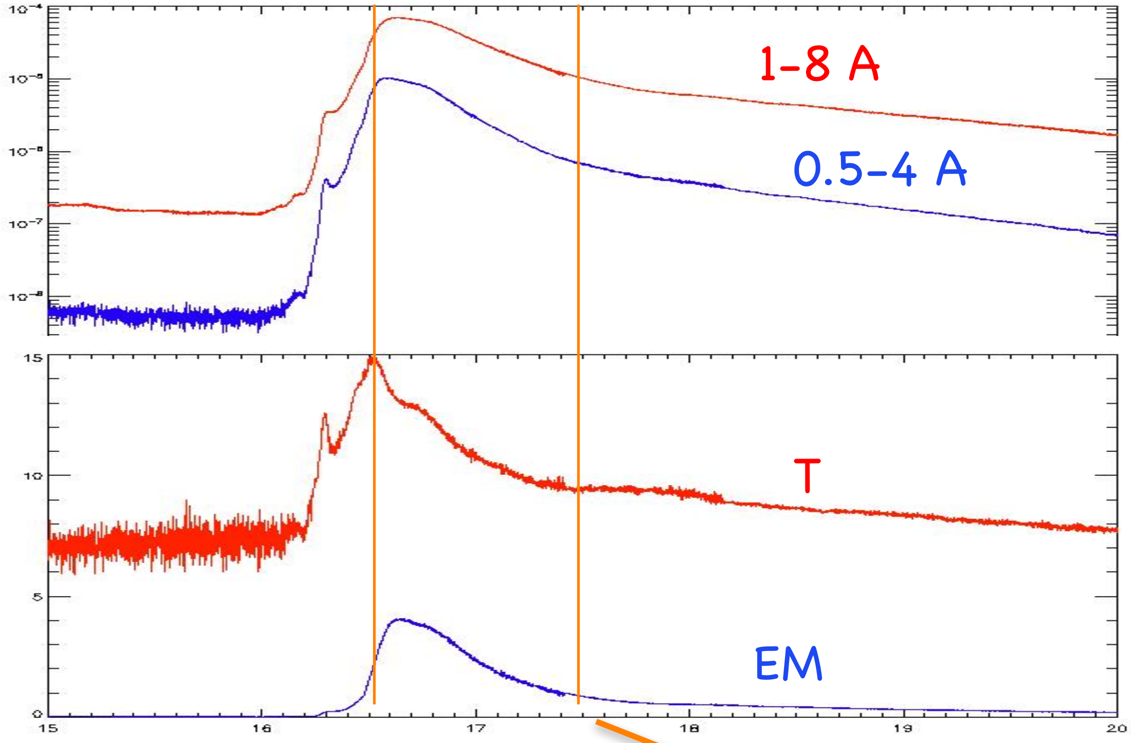
The Neupert Effect: what is not working

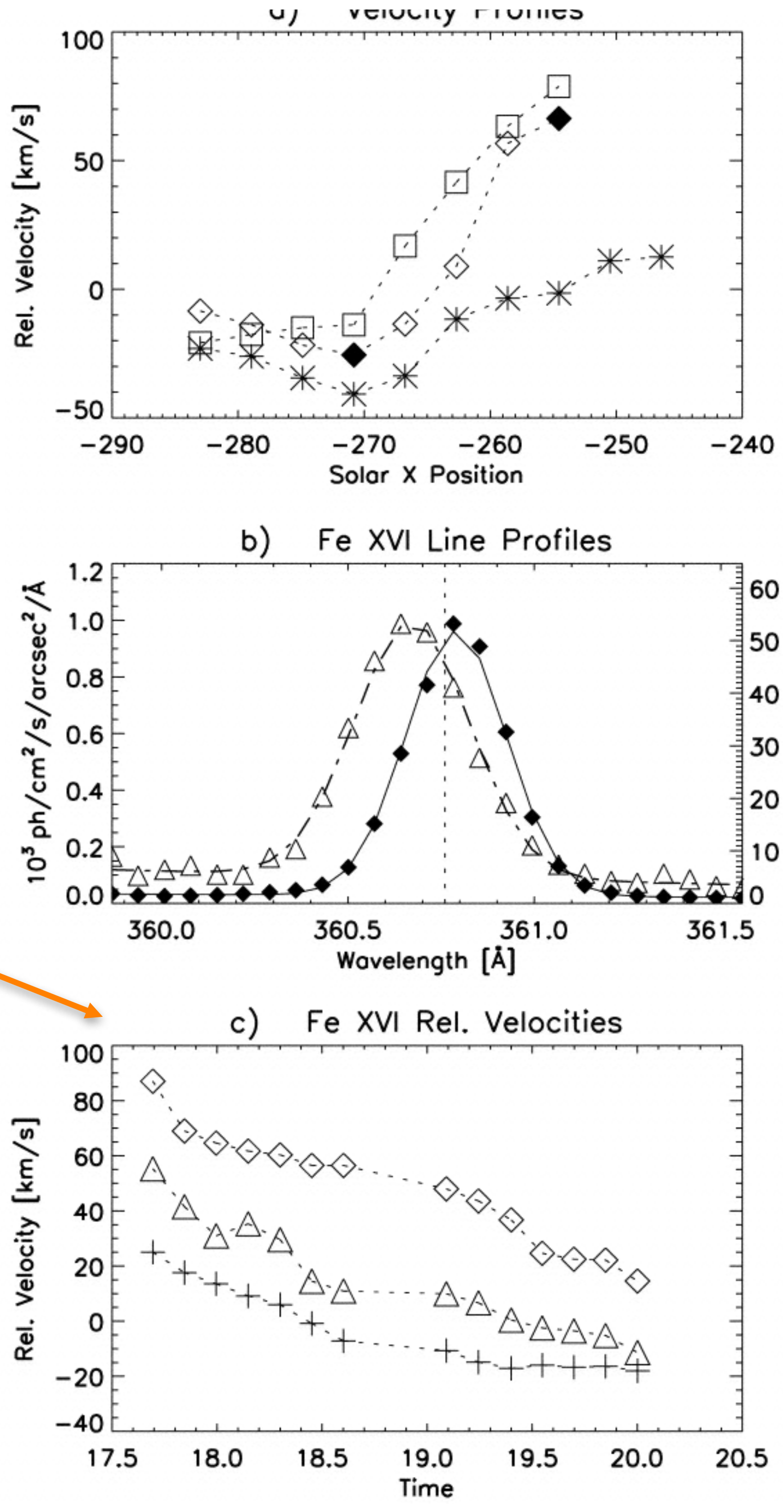
(1) “Cooling” is slower than expected: decay is not all about cooling (models & observations).

(2) Reconnection, energy release, and dynamics well into the decay phase;

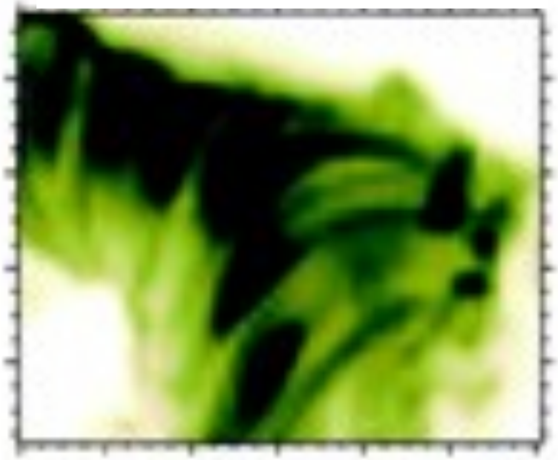
(3) Perhaps not all places are heated the same way.

(4) A good fraction of events do not follow the Neupert effect (Feldman et al. 1982, Veronig et al. 2002).



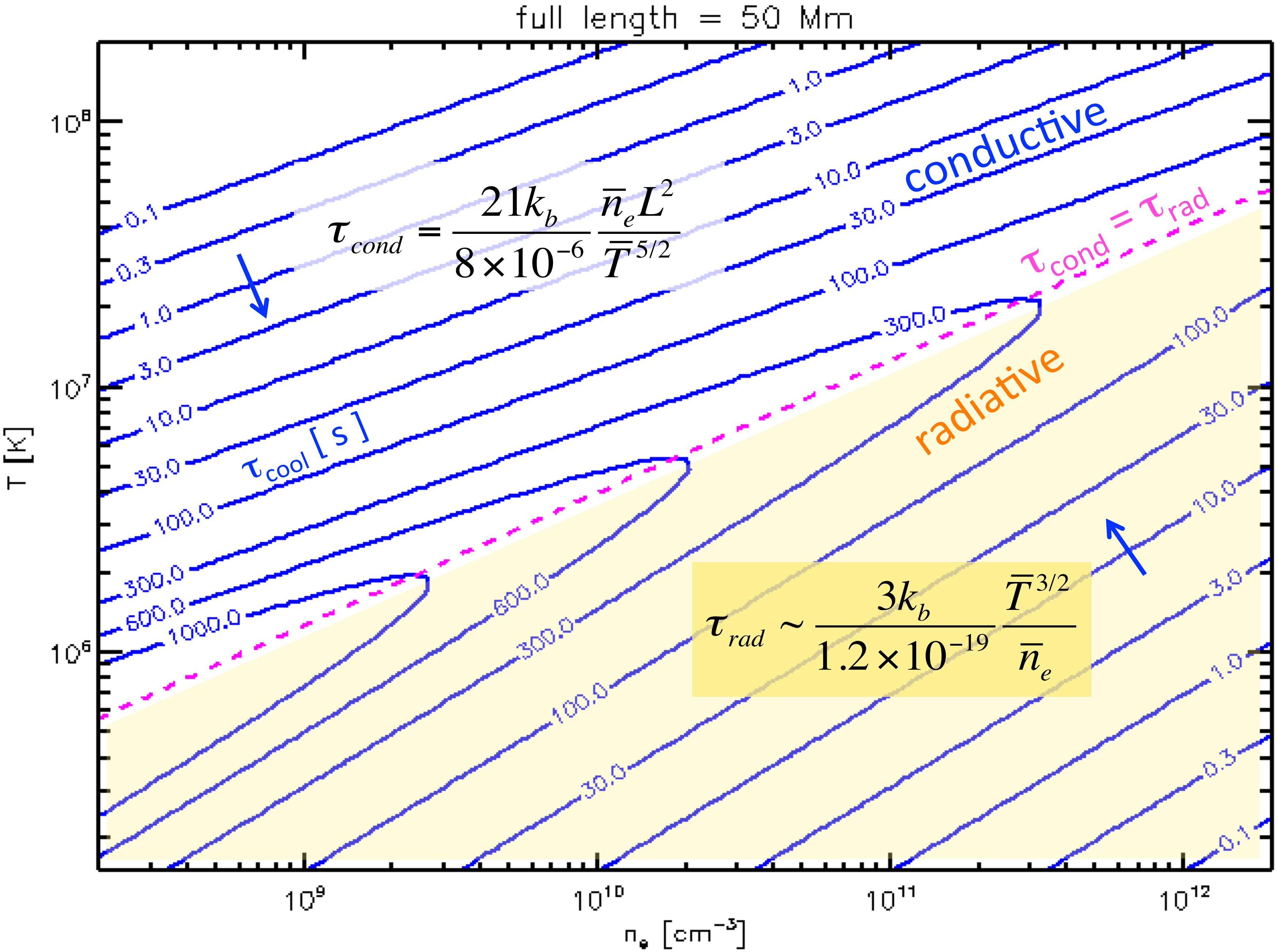


EIT 195 intensity



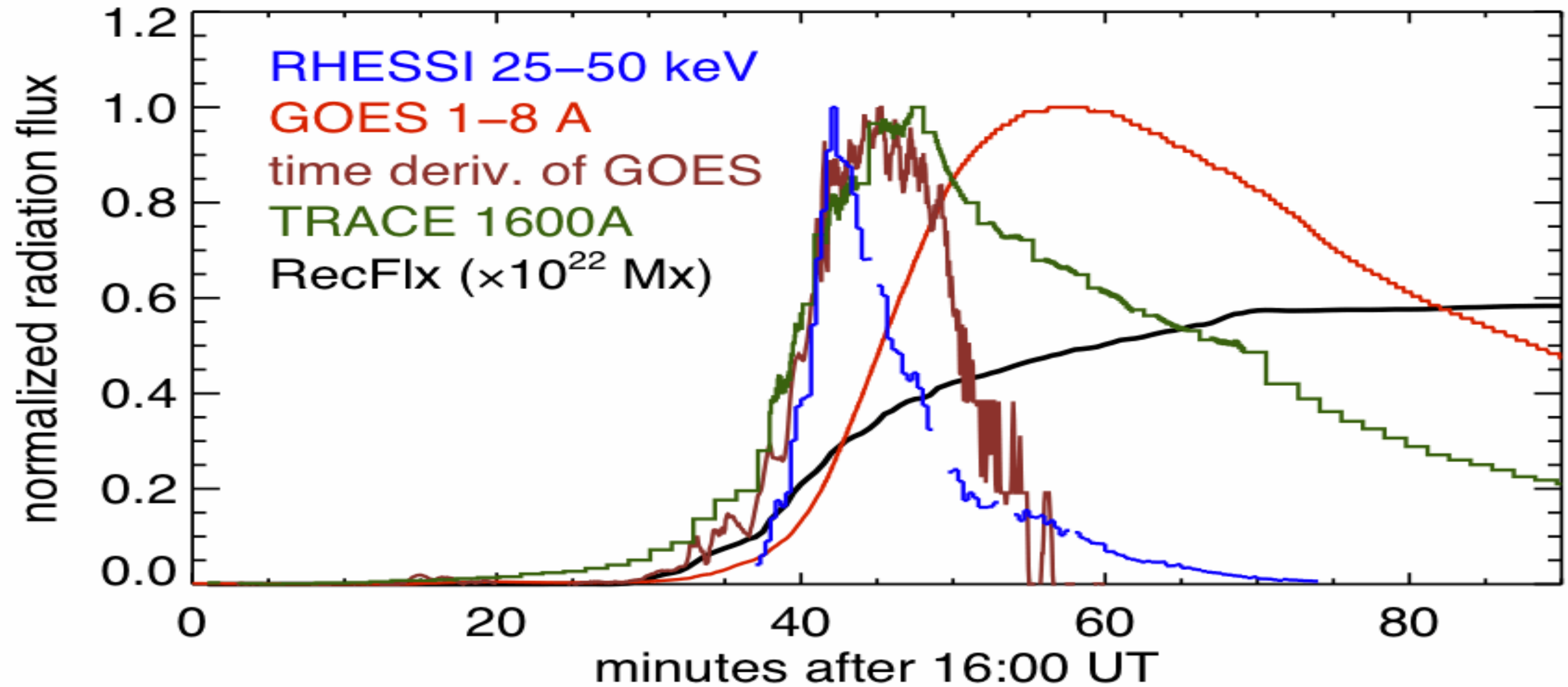
Fe XVI velocity

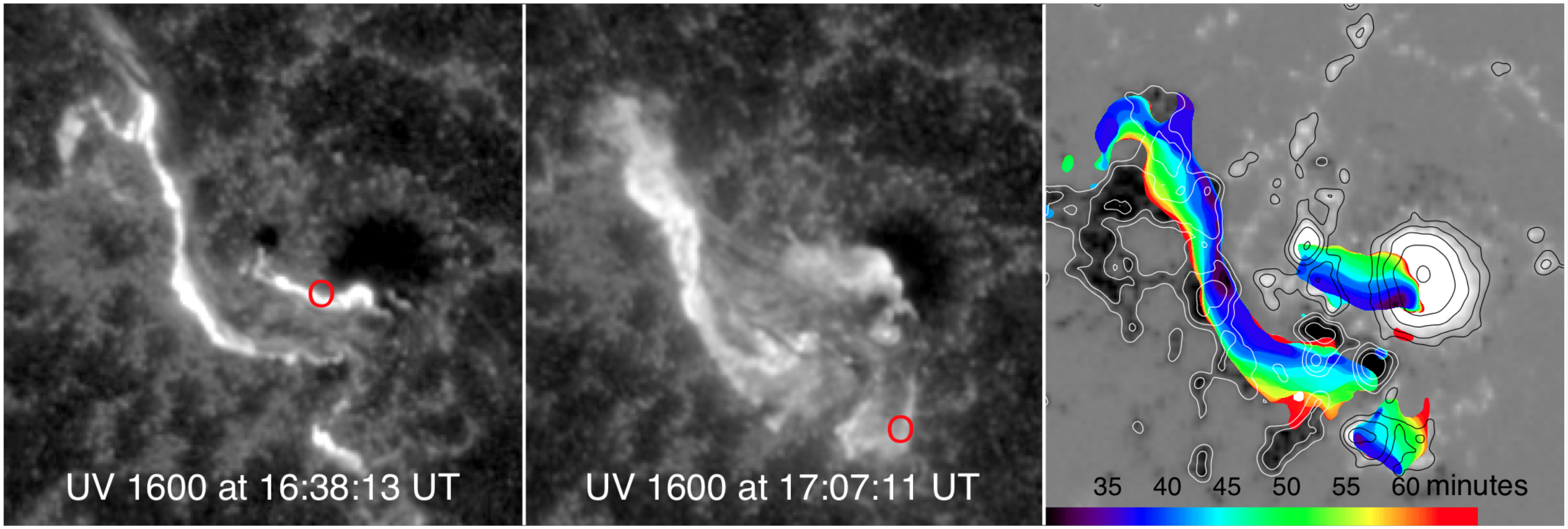
Czaykowska et al. 1999



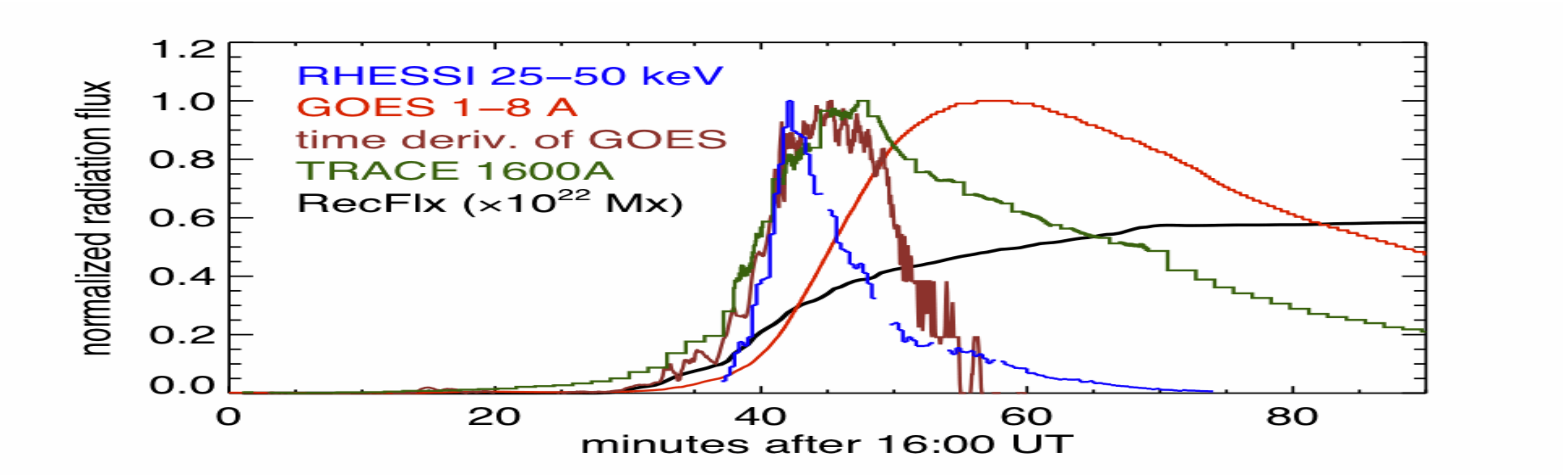
$$\tau_{cond} = \frac{21k_b}{8\times10^{-6}}\frac{\bar{n}_e L^2}{\bar{T}^{5/2}}$$

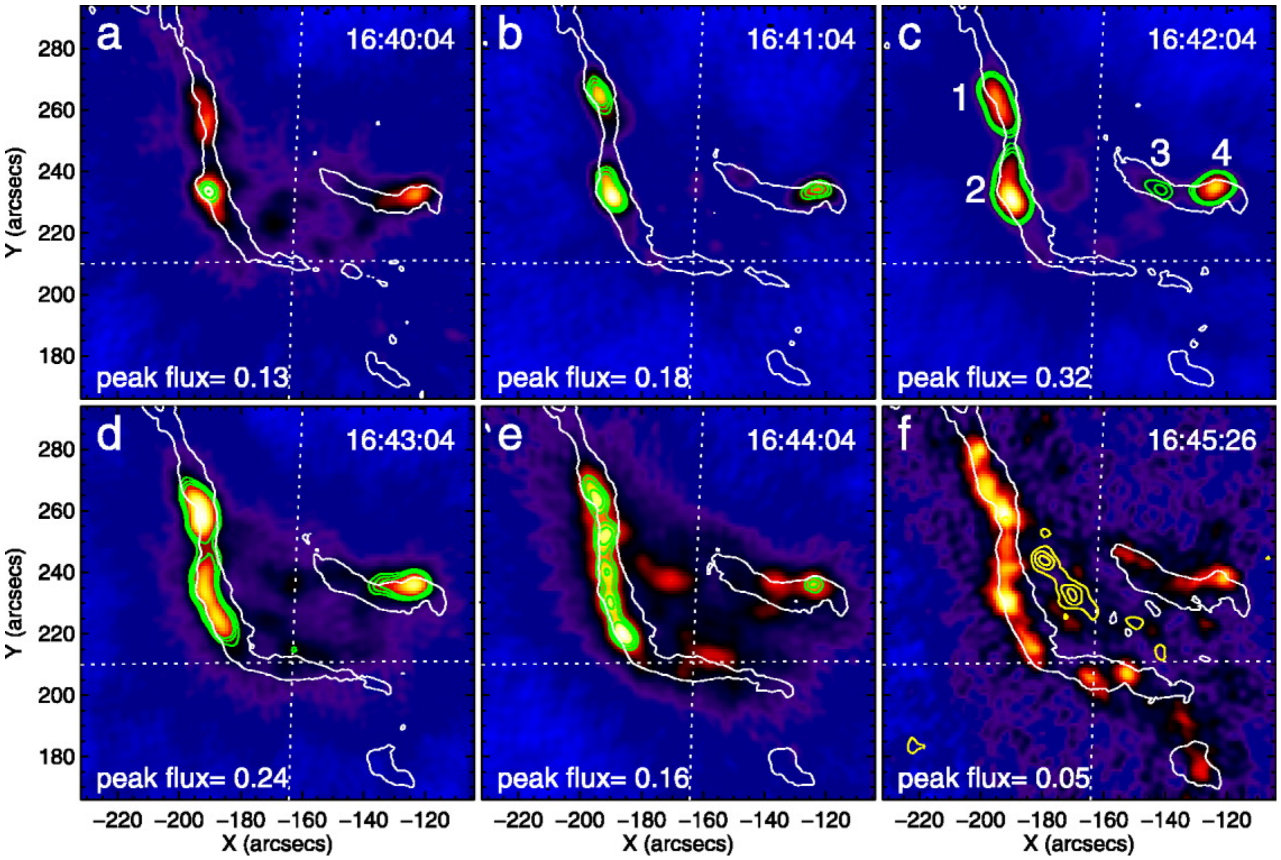
$$\tau_{rad} \sim \frac{3k_b}{1.2\times10^{-19}}\frac{\bar{T}^{3/2}}{\bar{n}_e}$$


RHESSI 25–50 keV
GOES 1–8 A
time deriv. of GOES
TRACE 1600A
RecFlx (×10²² Mx)
normalized radiation flux
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
minutes after 16:00 UT


UV 1600 at 16:38:13 UT
UV 1600 at 17:07:11 UT
35
40
45
50
55
60 minutes

(Liu+, 2013)

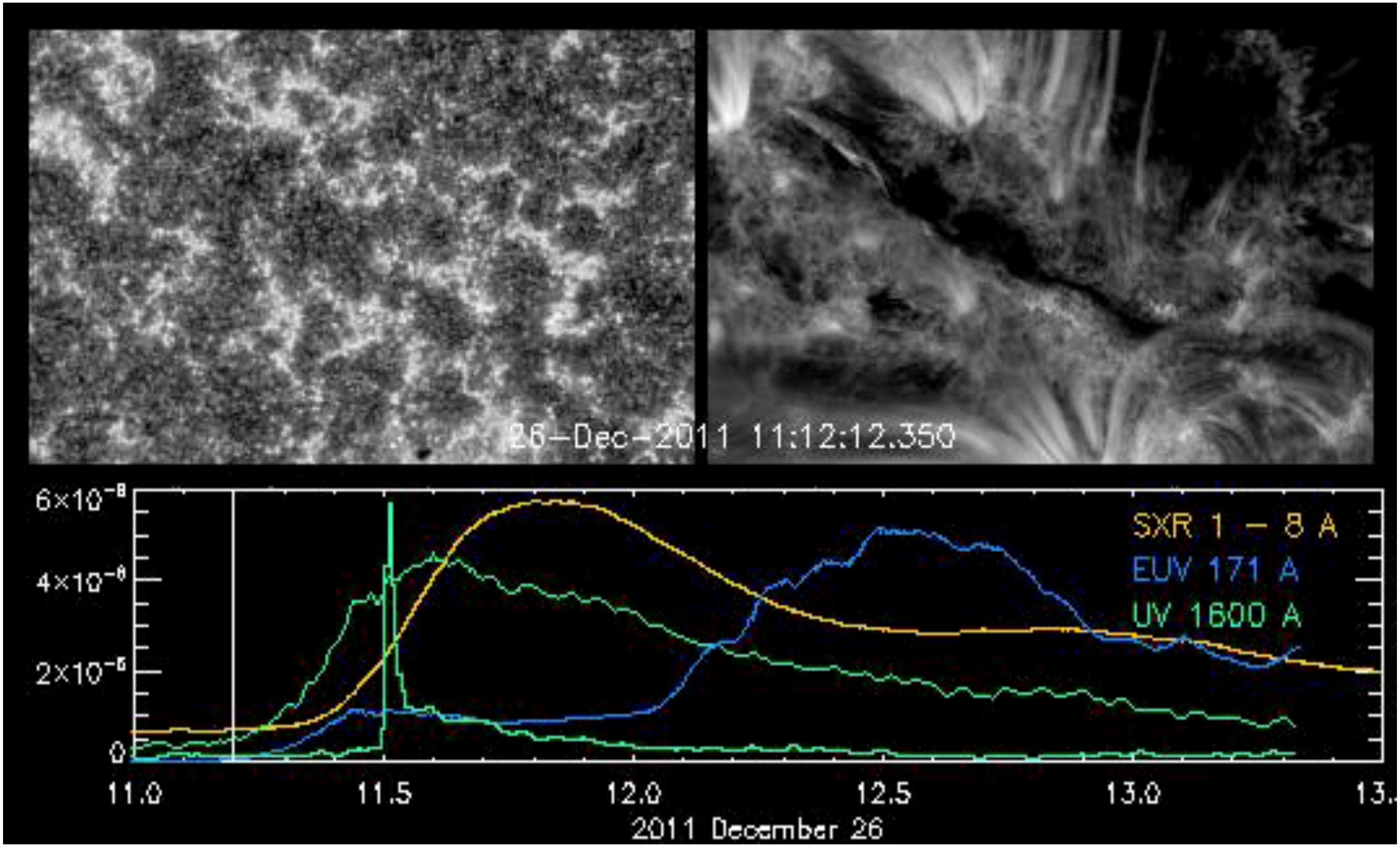




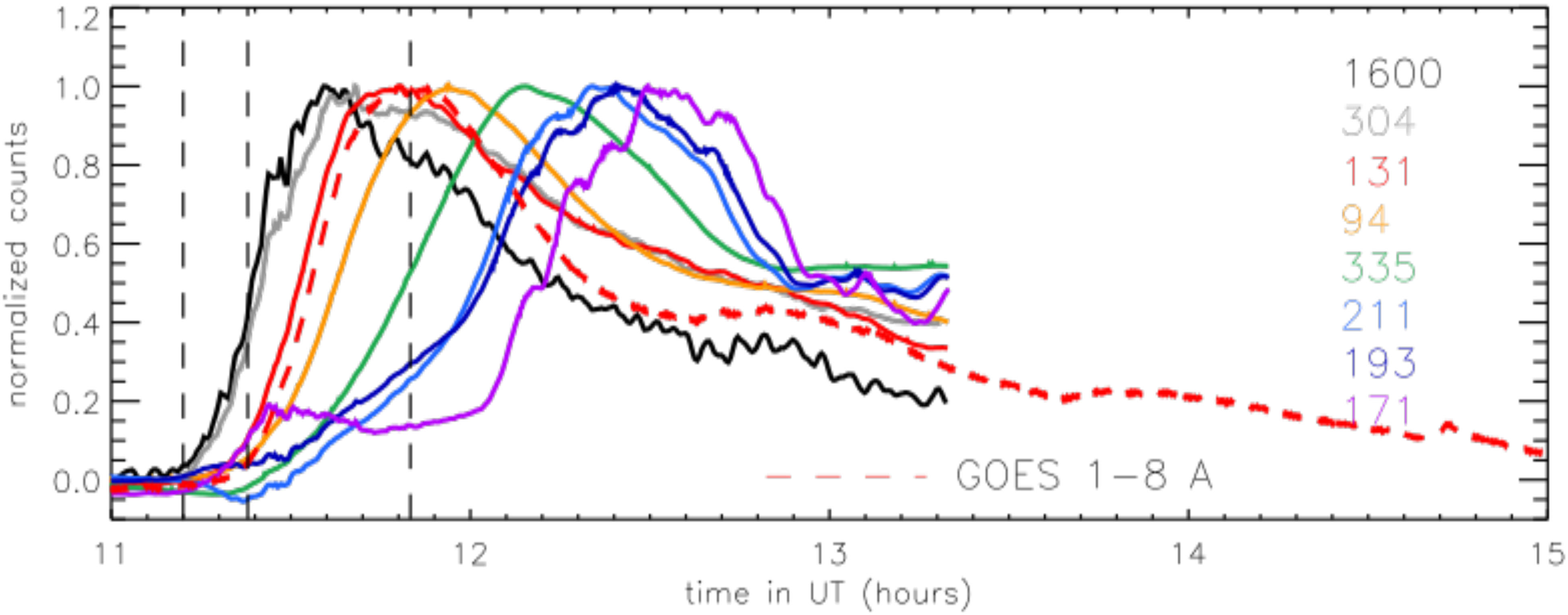
Thick-target HXR is not found along the entire flare ribbon.

(Liu et al ,2007)

Loops are formed and heated sequentially

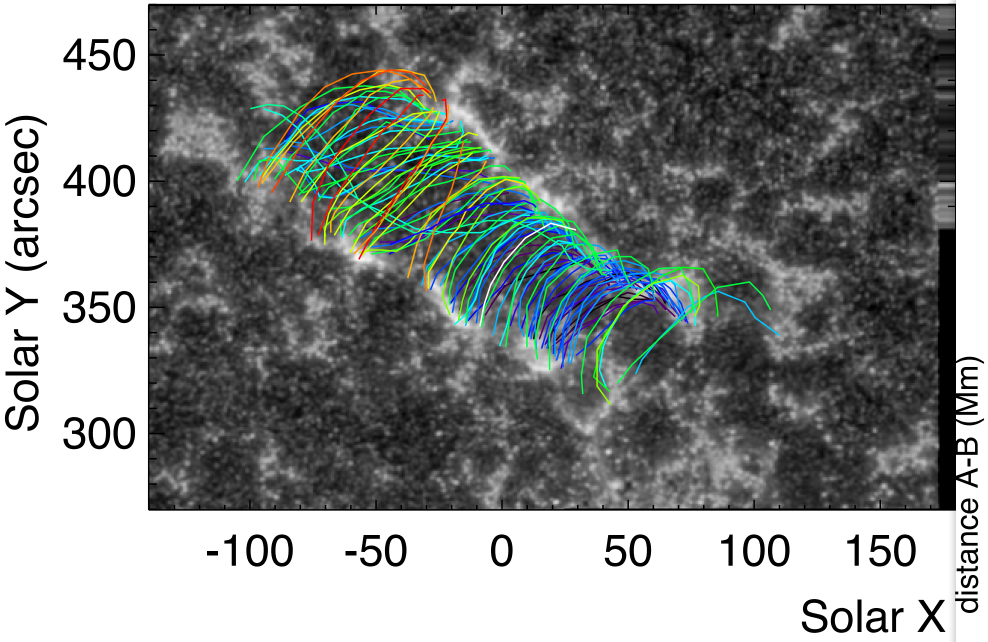


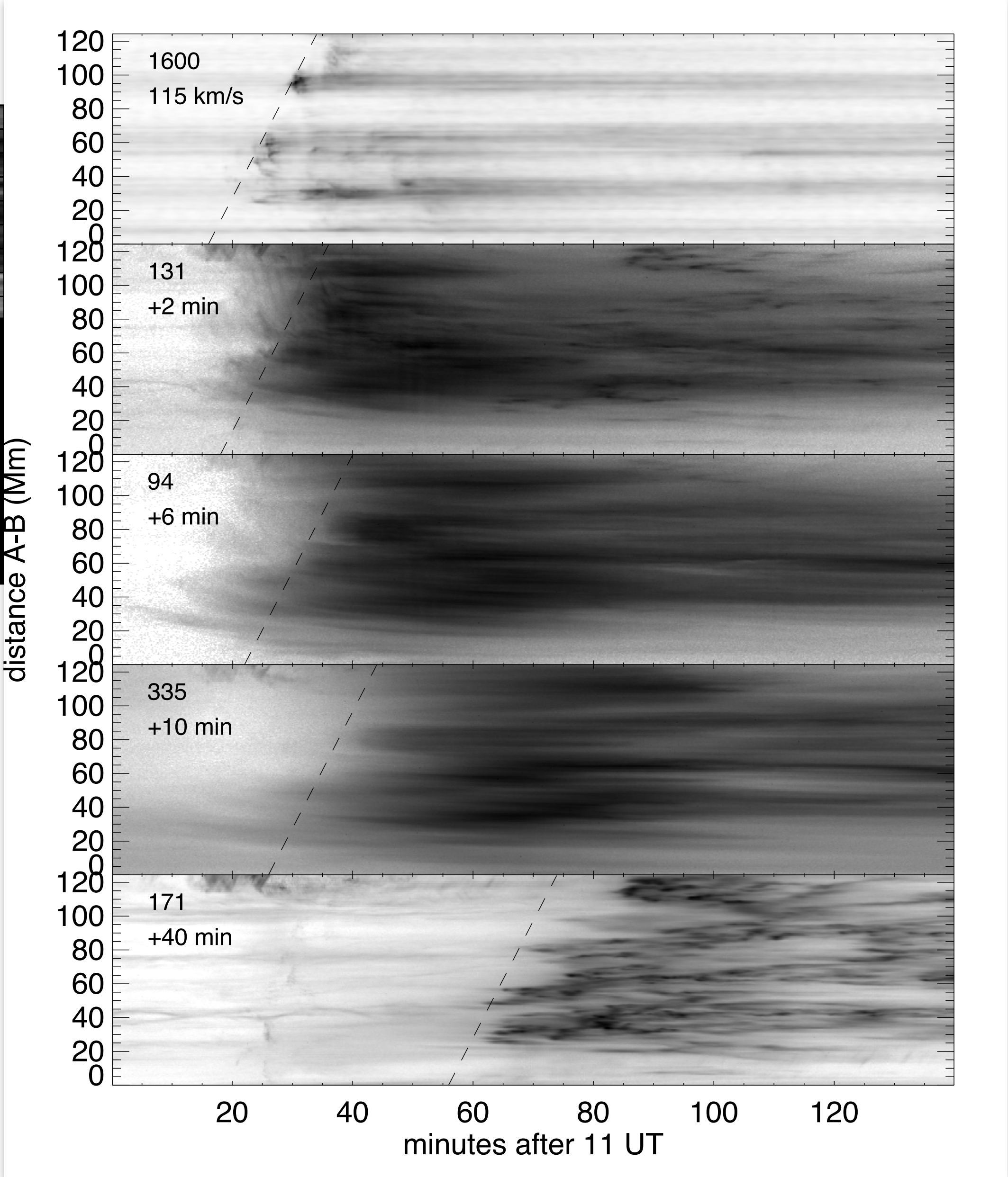
Heating (?) and cooling sequence



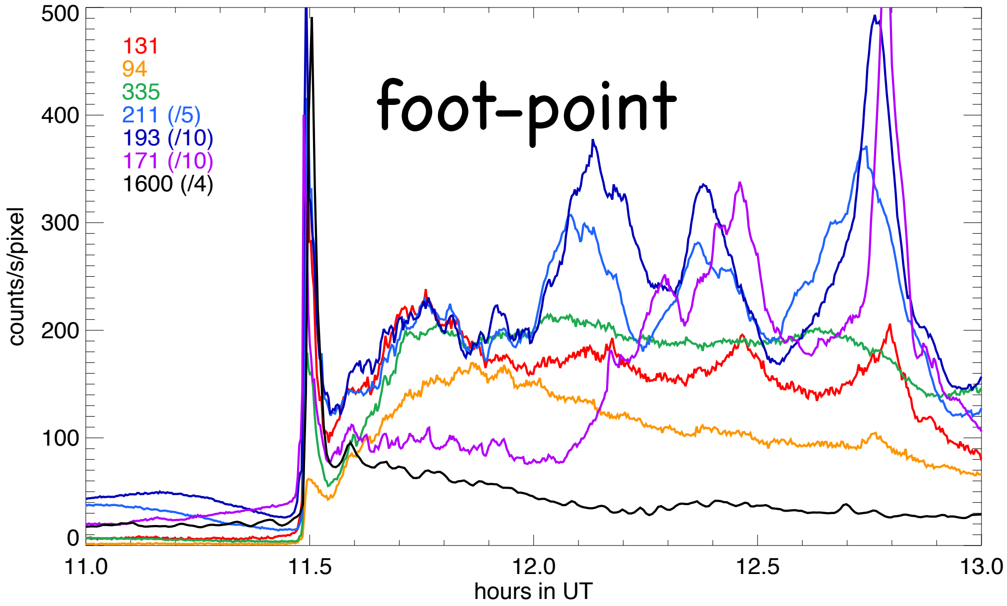
The order of peak emission: chromosphere 0.1 MK – corona 10 – 6 – 3 - 2 – 1 MK, with time lags of 10, 10, 15, 15, 10 min, duration of each ~ 50 min.

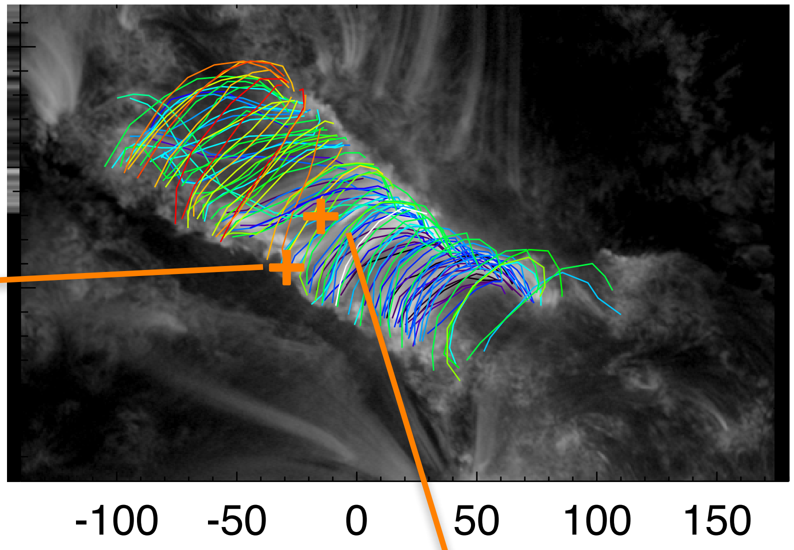
Heating (?) and cooling sequence



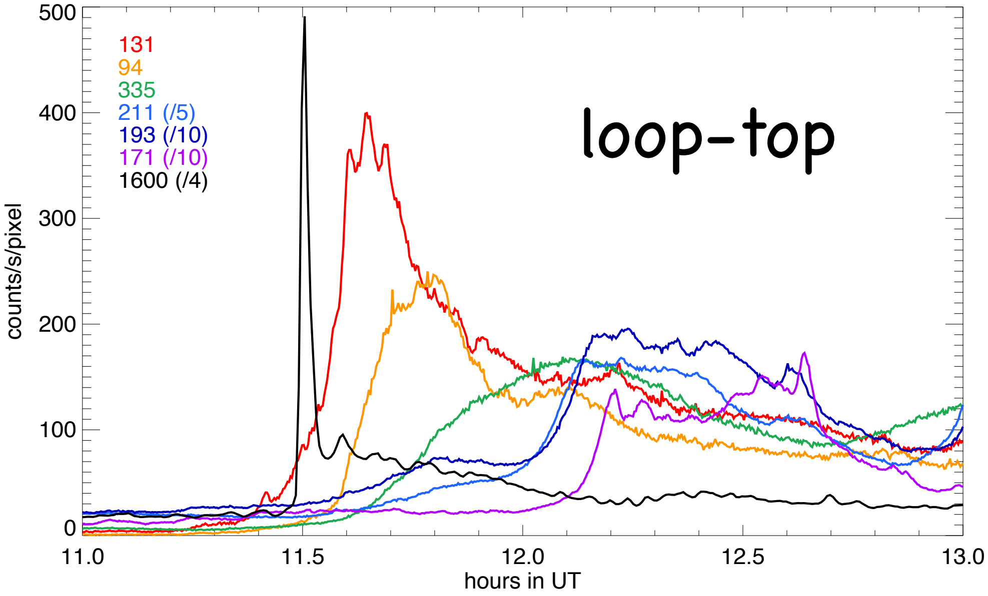


Flare loops heat (and cool) at different times.



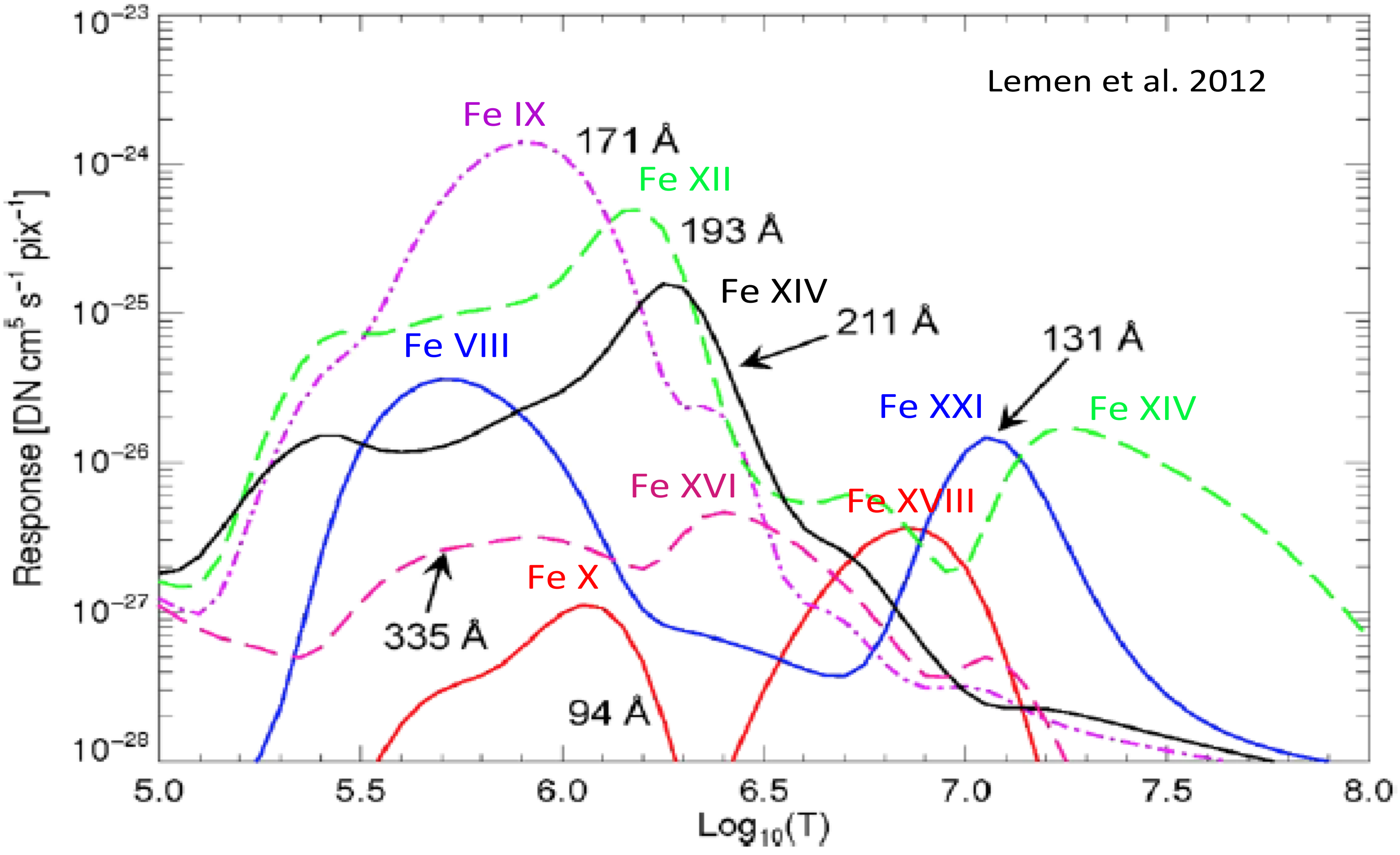


The order of peak emission: chromosphere 0.1 MK – corona 10 – 6 – 3 – 2 – 1 MK, with a little shorter time lags and duration.



Differential Emission Measure in single pixels

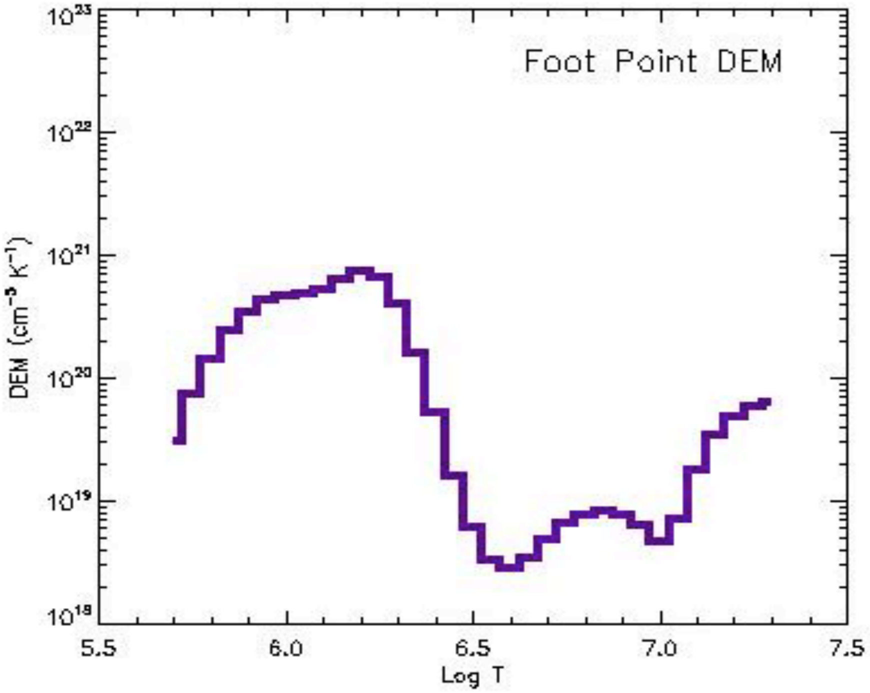
SDO/AIA – coronal Swiss Army knife

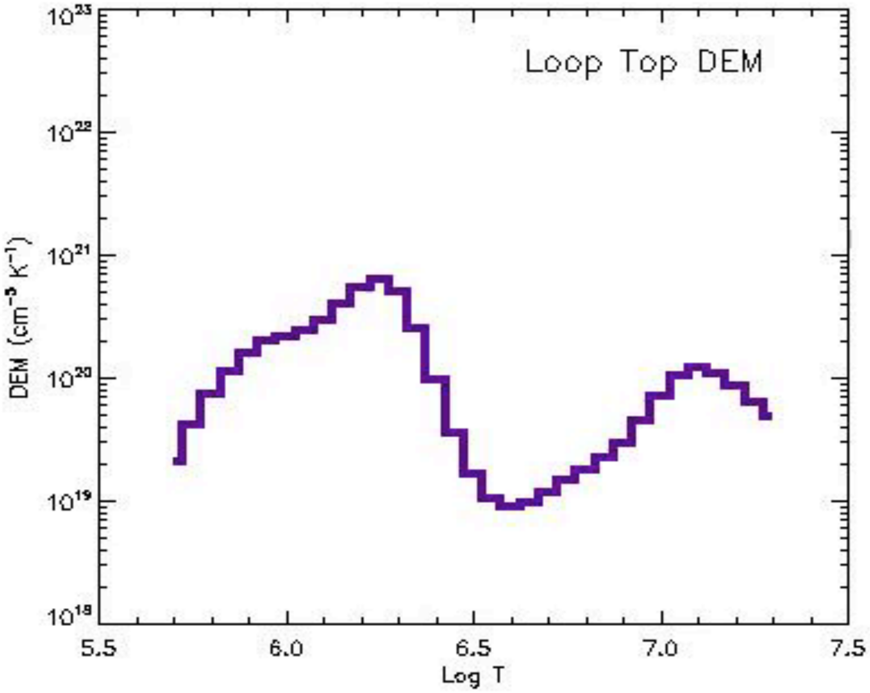


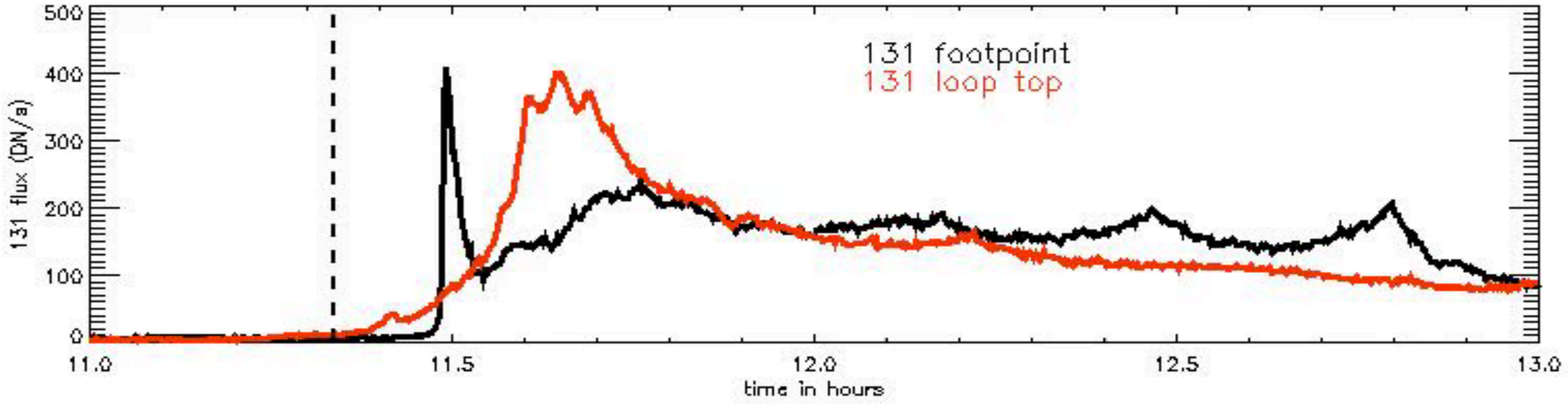
Lemen et al. 2012

$$C_\lambda(t) = \int R_\lambda(\log T) n^2(\log T) \frac{dl}{d\,(\log T)} d\,(\log T)\,,$$

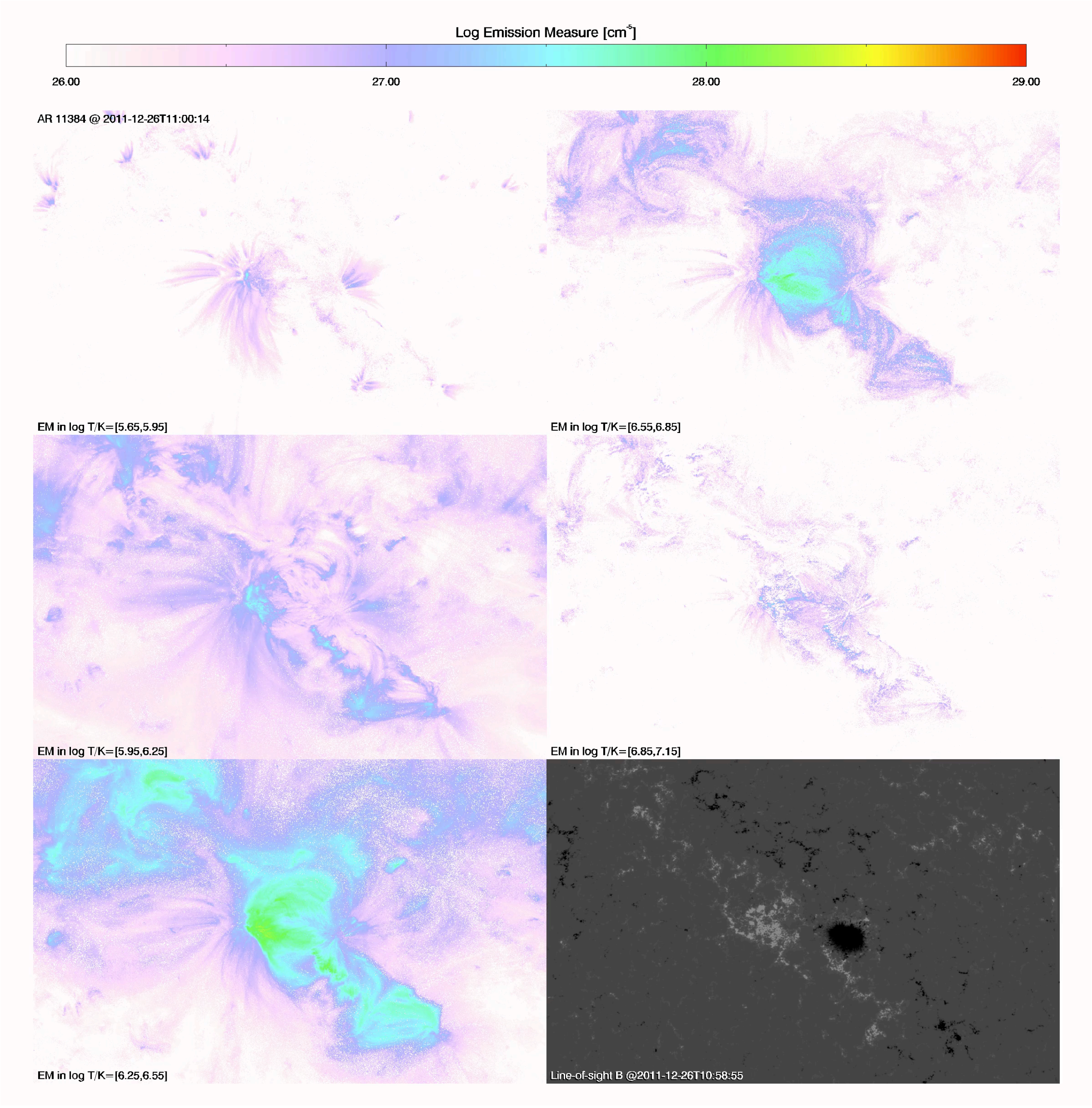
Differential Emission Measure in single pixels







(Hannah & Kontar 2012 ……)



0.5-1 MK

4-7 MK

1-2 MK

7 - 14 MK

2-4 MK

Differential Emission Measure by Mark Cheung (Cheung et al. 2015)

Summary

Multi-wavelength observations make it possible to measure physical quantities, Q(t, x), T(t, x), n(t, x), DEM(t,x) to test or constrain gas dynamic models and probe heating mechanisms.

Finding out what exactly is Q(t, x) is where physical understanding starts.

When: not necessarily only during the rise ..
Where & what: non-thermal particle produced chromosphere evaporation is part of the story;
How much: log(EM) ~49, H ~ 10^{8-12} erg/s/cm^2 -- a flare has as much mass and energy as a CME.