Temporal and Spatial Structures and Physical Properties of Elementary Energy Release in Solar Flares

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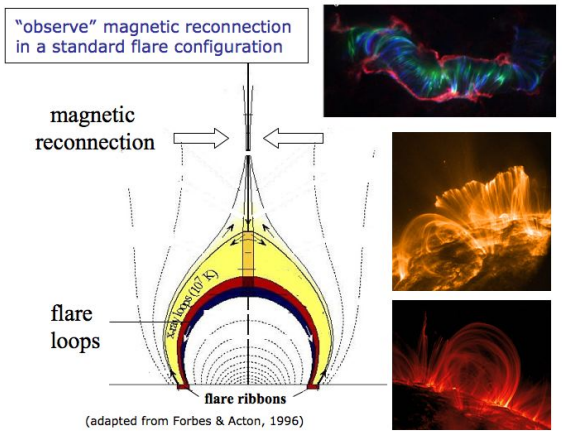
SOLAR PHYSICS

BBSO Summer School 2024



Outline

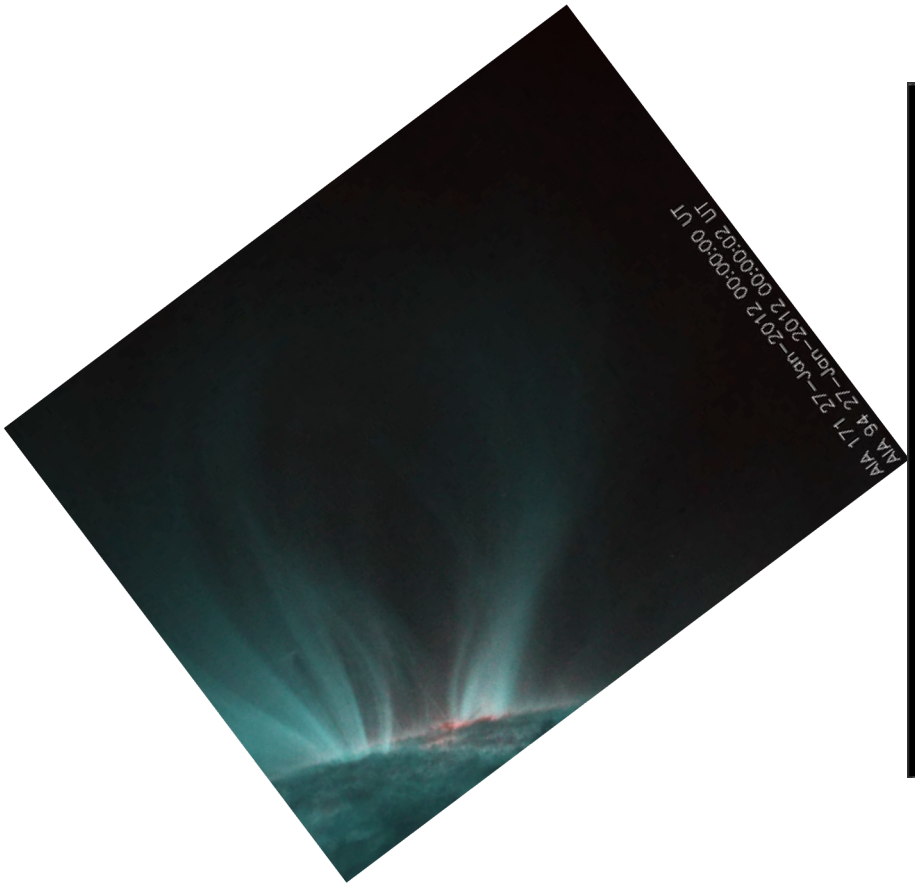
- Energy released by flare reconnection is "instantaneously" mapped and "resolved" in the chromosphere.
- Flare ribbon observations provide diagnostics of flare energetics, or the characteristics of flare heating: when, where, by how much, for how long, and through what mechanism, is the flaring atmosphere heated.
- Advanced observations + analysis + models are expected to tackle challenges coupling the chromosphere and corona, magnetically and energetically, solving outstanding problems.

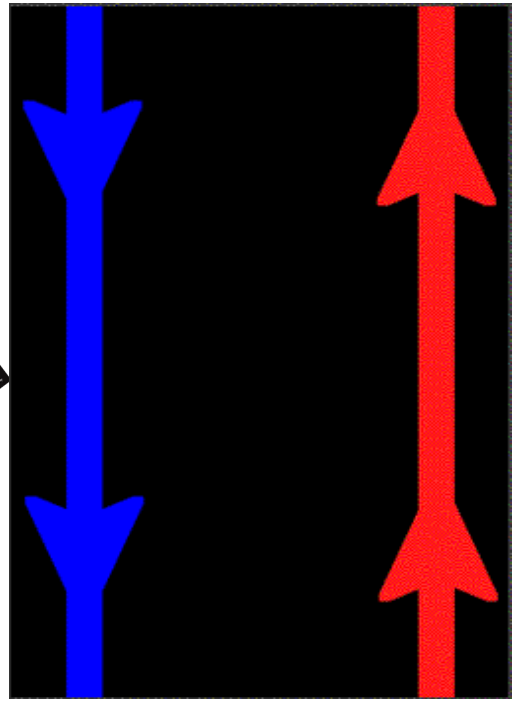
What are the Problems?

- Mechanisms storing free magnetic energy (FME): of 10^{33} erg, over days ($\tau \sim 10^{4-5}$ s), in the entire AR or beyond (L ~ 10^{10} cm).
- Mechanisms triggering the onset of FME release: the ideal or non-ideal (i.e. reconnection) debate; whether global or local, the system evolves into the instability in hours (10^3 s).
- Mechanisms converting FME to other energy (10^{29-32} erg), kinetic energy of particles and of bulk motion, ultimately to photons, in tens of minutes (10^{2-3} s) in volume of 10^{28-29} cm^3 for a typical flare.

How much is the energy used to heat flaring atmosphere, and how?

flares are events of reconnection energy release



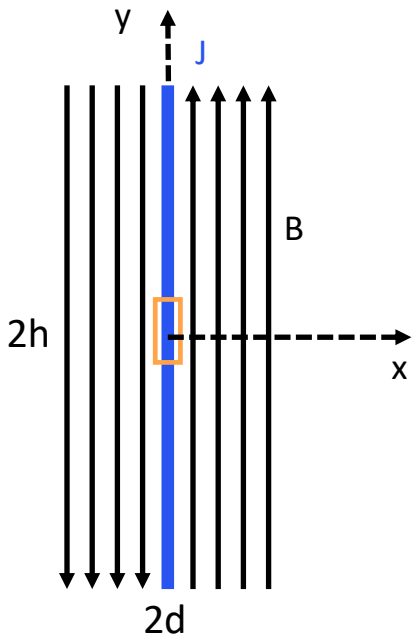


(Credit: UCR)

reconnection: change of magnetic field

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E},$$

$$\vec{J} = \nabla \times \vec{B}/\mu_0 \,, \qquad \vec{E} = \mu_0 \eta \vec{J} - \vec{v} \times \vec{B}$$



t = 0

$$\vec{B} = \pm B\hat{y}, \quad (|x| > d)$$

$$\vec{J} \approx \frac{B}{\mu_0 d}\hat{z}, \quad (|x| < d)$$

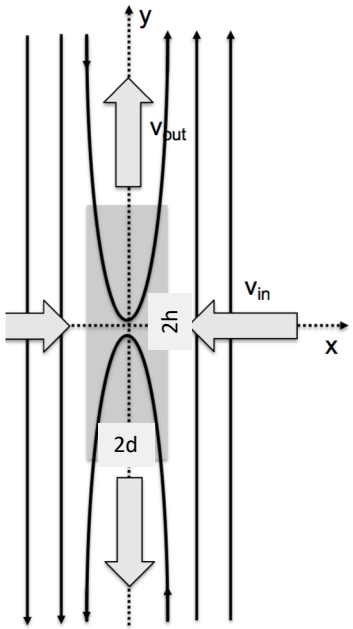
$$\vec{E} \approx \frac{B}{\mu_0 \sigma d}\hat{z} = \frac{\eta B}{d}\hat{z}, \quad (|x| < d, |y| < h)$$

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E}$$

$$\frac{\Delta \vec{B}}{\Delta t} \approx -\frac{\Delta E}{\Delta y}\hat{x} + \frac{\Delta E}{\Delta x}\hat{y}$$

$$\Delta B_x \approx \frac{E}{h} \approx \frac{\eta B}{dh}\Delta t \qquad \text{(x>0,y>0)}$$

$$\Delta B_y \approx -\frac{E}{d} \approx -\frac{\eta B}{d^2}\Delta t$$



t = Δt

reconnection: change of magnetic field

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

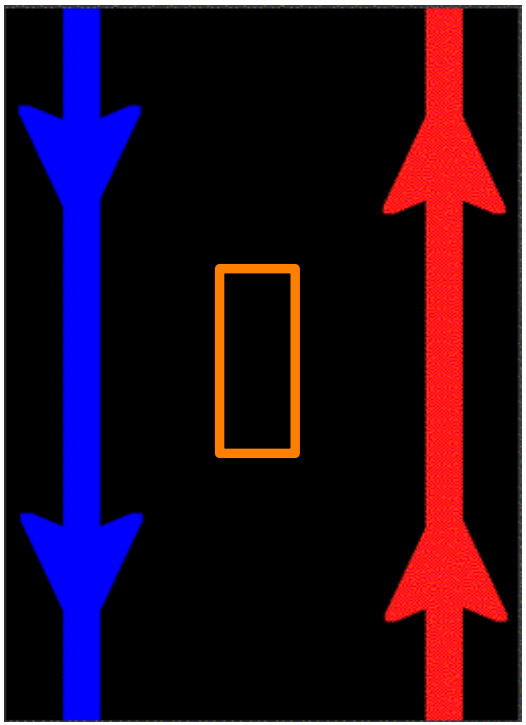
$$\frac{d\phi}{dt} = -\oint \vec{E} \cdot \overrightarrow{dl} = \frac{d}{dt}\left(\int \vec{B} \cdot \overrightarrow{da}\right)$$

$$\vec{E} = \mu_0 \eta \vec{J} + \ldots \quad \leftarrow \text{“diffusion”}$$

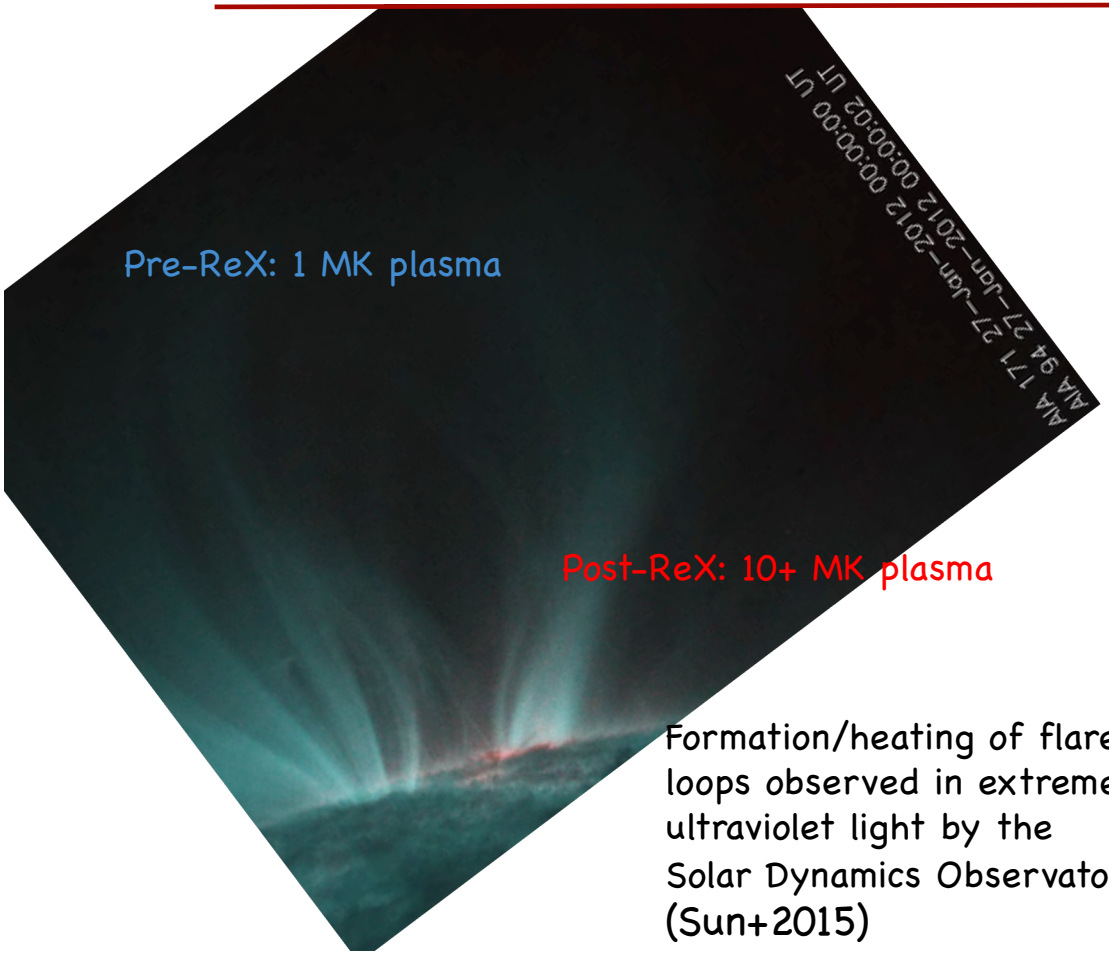
$$= -\vec{v} \times \vec{B} \quad \leftarrow \text{advection}$$

$$M_A = \frac{v_{in}}{v_A} = 0.1 \frac{E(1\ \text{V/cm})/B_{in}(10\ \text{G})}{v_A(1000\ \text{km/s})}$$

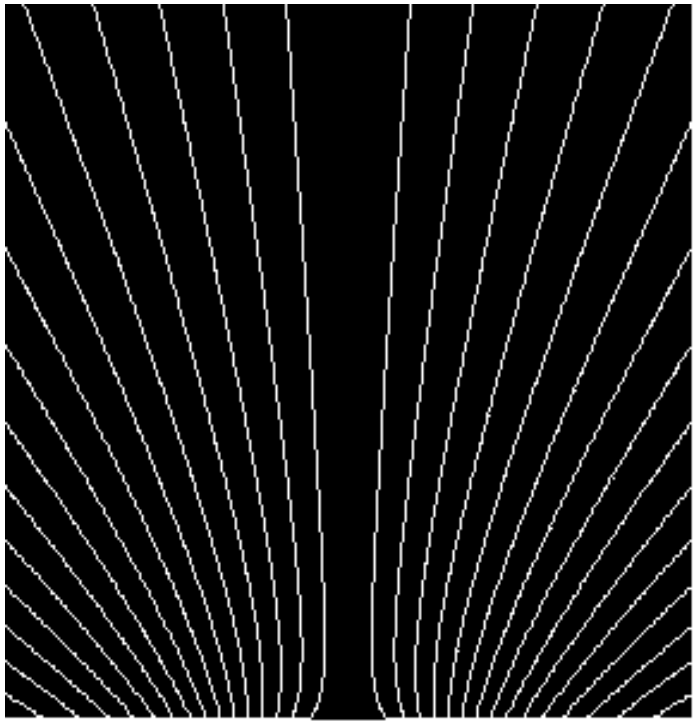
magnetic reconnection rate



magnetic reconnection forms flare arcade and ribbons



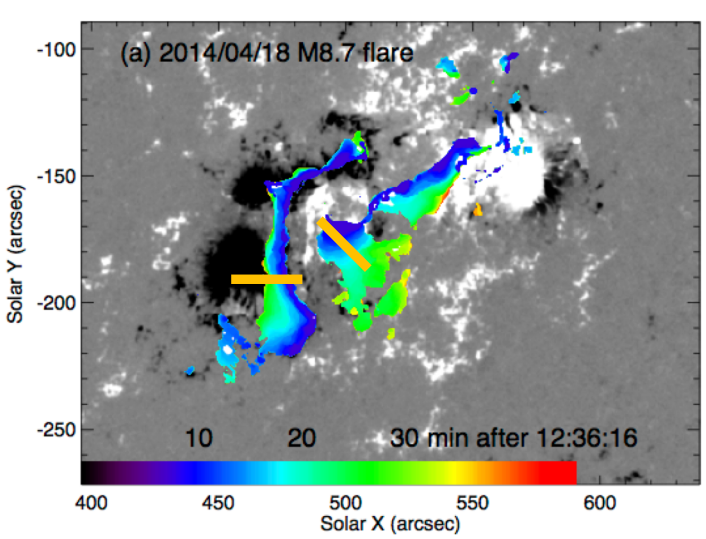
Formation/heating of flare loops observed in extreme ultraviolet light by the Solar Dynamics Observatory (Sun+2015)

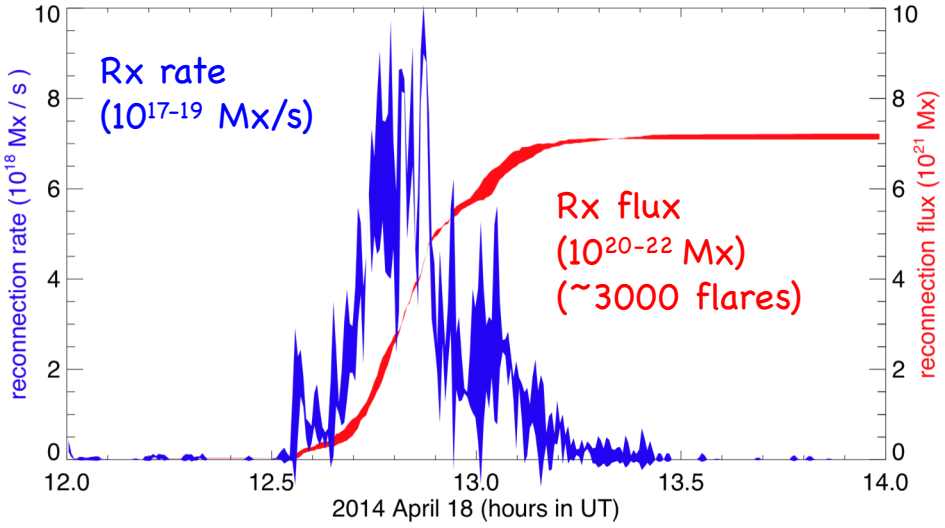


from Terry Forbes

ribbon fronts

reconnection rate inferred from chromosphere ribbons



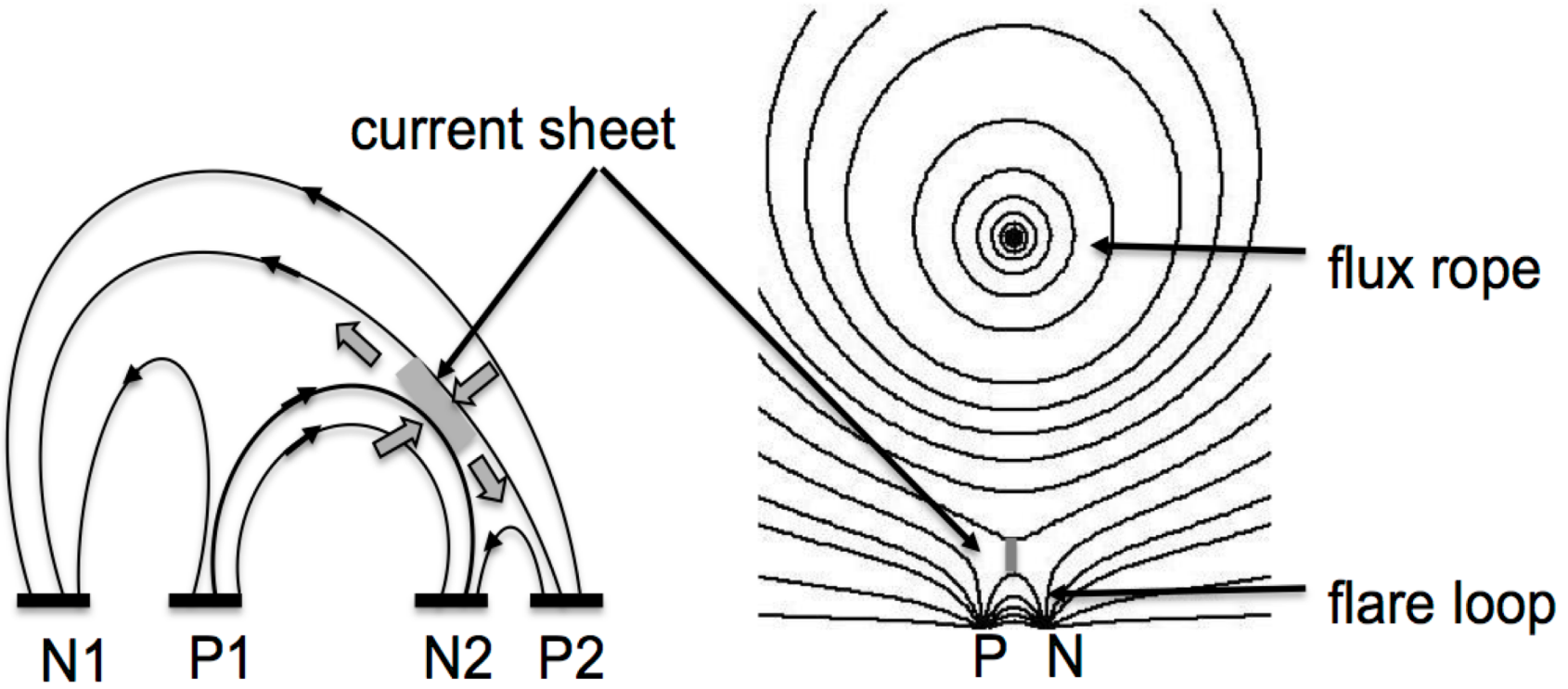


$$\frac{d\Phi_B}{dt} = \frac{d}{dt}\int B_r dA_r = \frac{d}{dt}\int B_{in} dA_{in} = -\int \vec{E}\cdot\vec{dl}\,; \quad \langle E\rangle \approx B_{in}v_{in} \approx v_R B_R \approx \frac{1}{L}\frac{d\Phi_B}{dt} \approx 500\, V/m$$

(Poletto+86, Fletcher+01, Isobe+02, Asai+02, Qiu+02, Saba+06, Jing+05, Temmer+07, … Kazachenko+17, Hintereiter+18 ..)

$$M_A = \frac{v_{in}}{v_A} = 0.1\,\frac{E(100\ V/m)/B_{in}\,(10\ G)}{v_A\,(1000\ km/s)}$$

magnetic reconnection forms flare arcade and ribbons

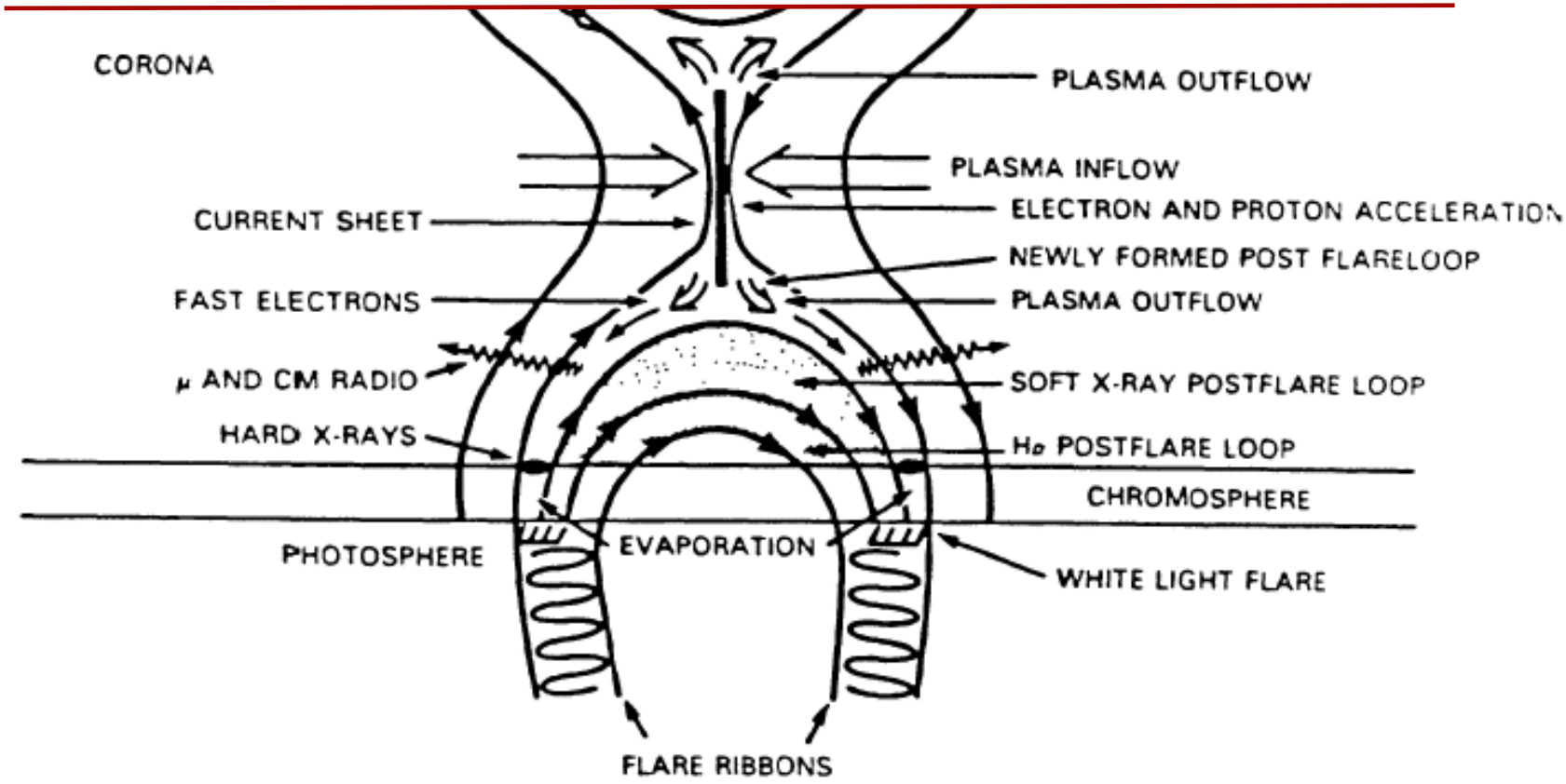


(Hayvaerts+1977)

(Lin-Forbes-Isenberg+1995)

Confined flares? Eruptive Flares?

reconnection released energy heats loops and ribbons



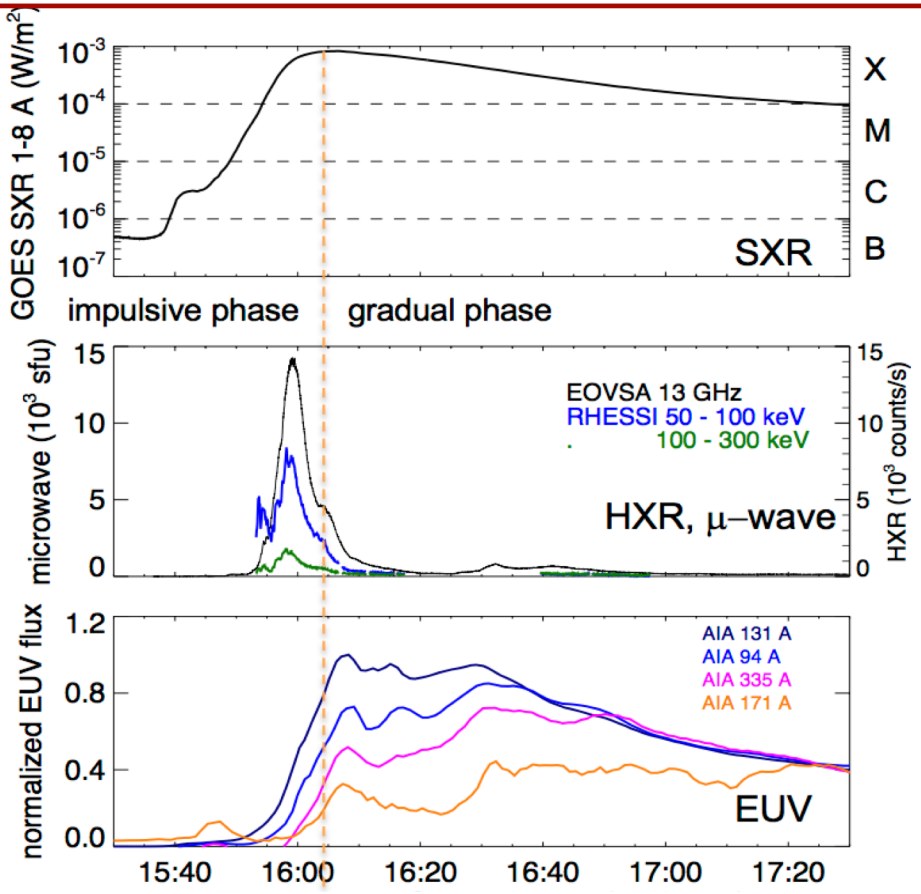
Martens & Kuin 1989 & more from the Grand Cartoon Archive
(https://www.astro.gla.ac.uk/cartoons/index.html)

a standard solar flare: radiation of all kinds

thermal bremsstrahlung (>10 MK) in the corona

non-thermal bremsstrahlung & synchrotron (10^{1-3} eV) in corona & below

lines & continuum (1 – 10 MK) in corona



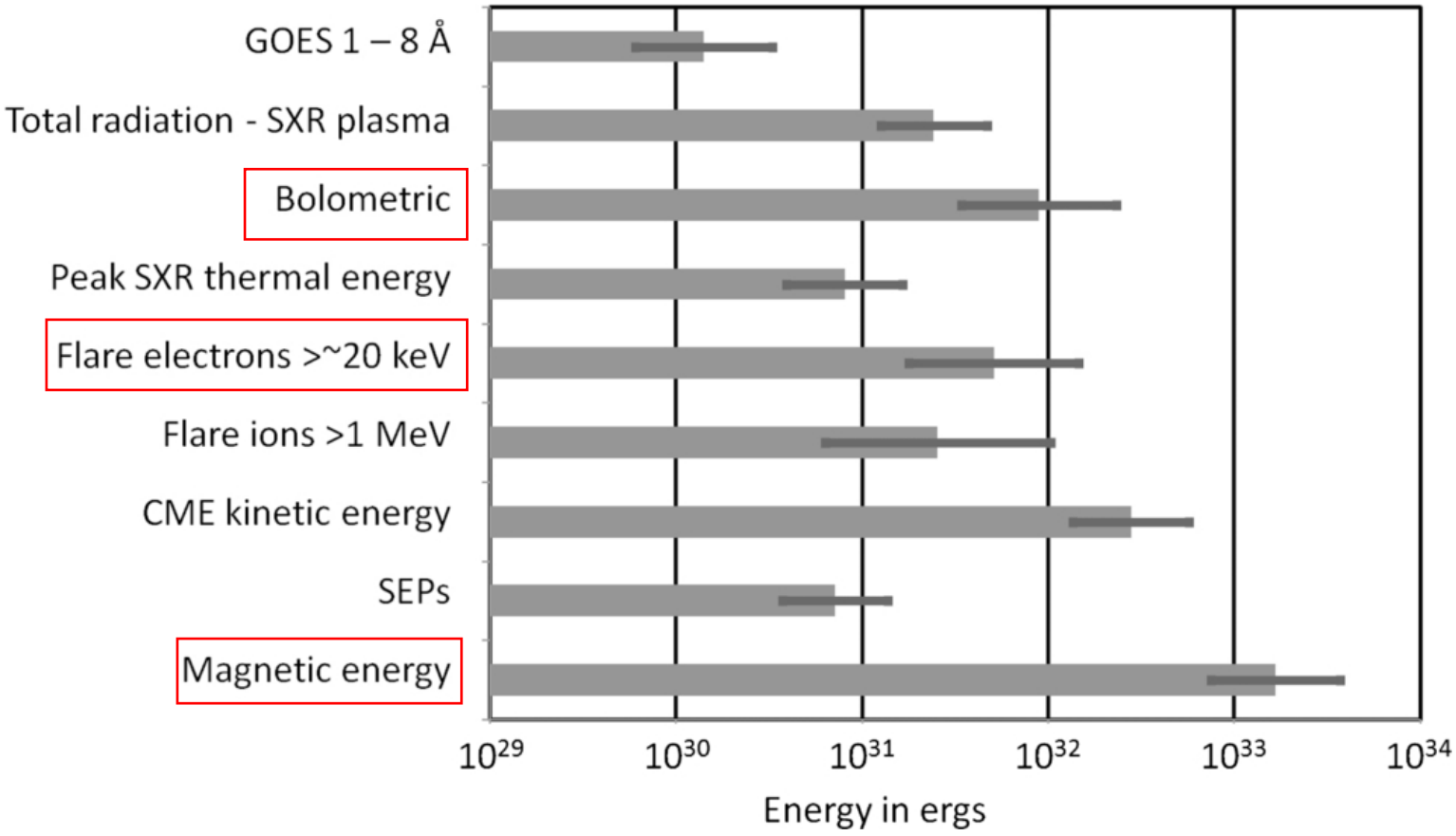
Neupert (1968) effect:

(1) All heating is in impulsive phase, by nth electrons;

(2) Chromospheric evaporation makes the corona dense & emit (~ n^2);

(3) Rest (the gradual phase) is cooling .. but somewhat slower than expected.

a standard solar flare: energy of all kinds



(Emslie+2012)

heating and cooling of flare plasmas

$$\frac{\partial}{\partial t}\left(u+\frac{1}{2}\rho v^2\right)+\nabla\cdot\left[\left(u+\frac{1}{2}\rho v^2\right)\vec{v}\right]=Q-\nabla\cdot(P\vec{v})-\nabla\cdot\vec{F}-R$$

corona plasma w/ subsonic flow

$$\frac{\partial}{\partial t}\left(\frac{3}{2}P\right)=Q-\nabla\cdot\vec{F}-n^2\Lambda(T)-\nabla\cdot\left(\frac{5}{2}P\vec{v}\right)$$

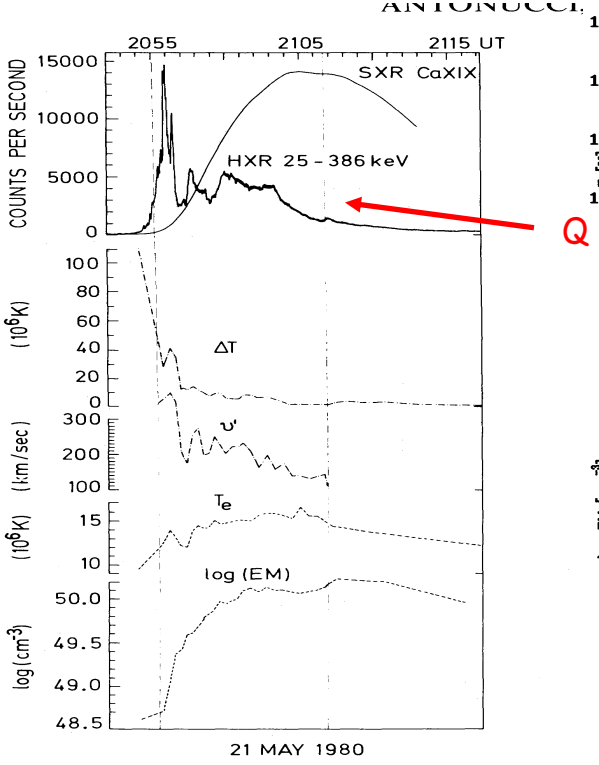
heating conduction radiation enthalpy

heating phase: corona gains energy and mass, T and n increases.
cooling phase: corona loses energy and mass, T and n decreases;

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

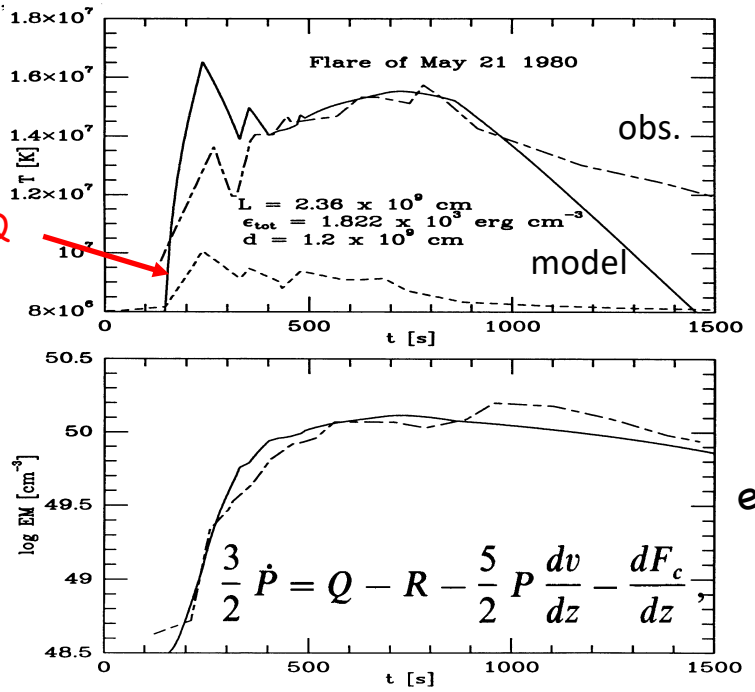
DEM: differential emission measure

heating of one big flare loop with Q …



Antonucci, Gabriel, Dennis 1984, ApJ

Q



temperature

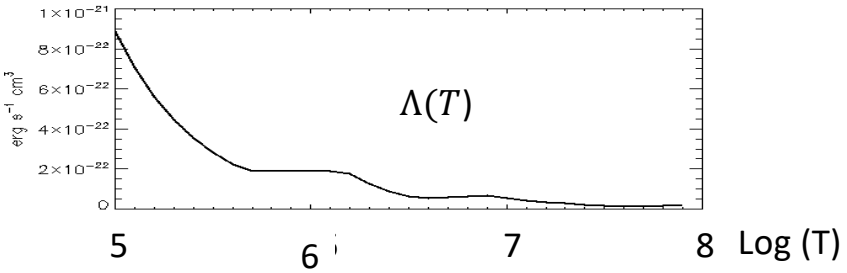
emission measure

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

the slow cooling problem

Cooling by classical thermal conduction: $\nabla \cdot \vec{F} \approx \kappa_0 \frac{T^{\frac{7}{2}}}{L^2}, \tau_{cond} \approx \frac{nk_B L^2}{\kappa_0 T^{5/2}}$

Cooling by radiation loss: $\tau_{rad} \approx \frac{k_B T}{n\Lambda(T)}$

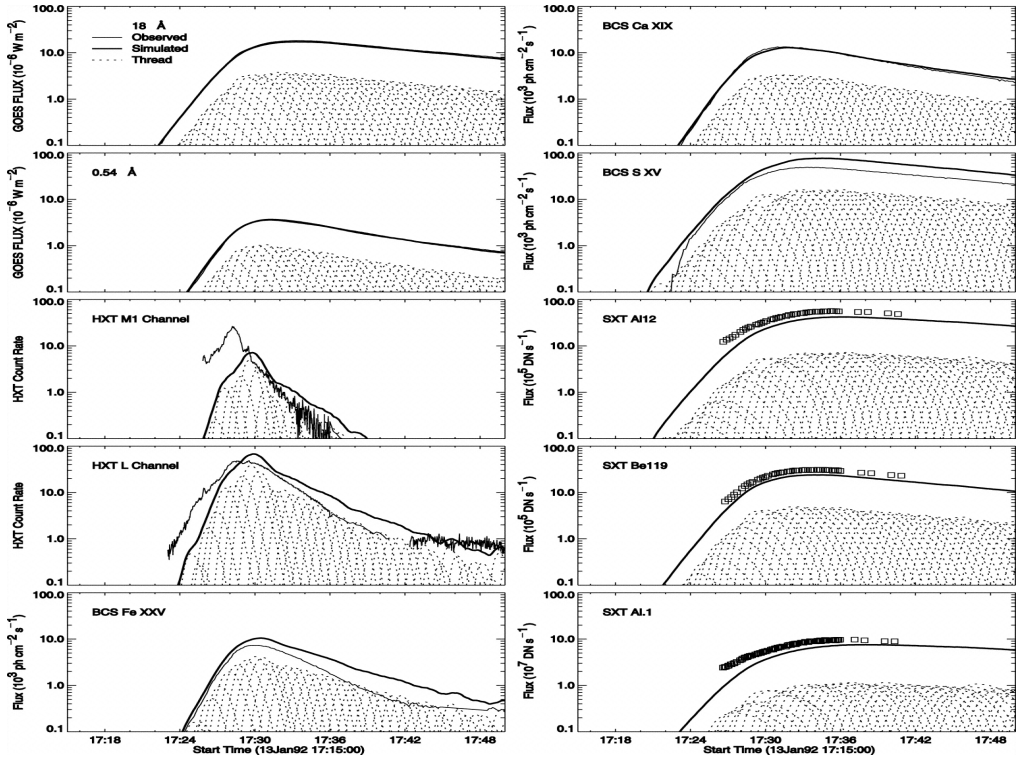


At $\mathrm{n} \approx 10^{10}\, cm^{-3}, \mathrm{T} \approx 3-10\, MK, \tau_{cond} \approx 1-100\, s, \tau_{rad} \approx 300-1000\, \mathrm{s}.$

Observed radiation at 3-10 MK often lasts tens of minutes to hours.

Why so slow?

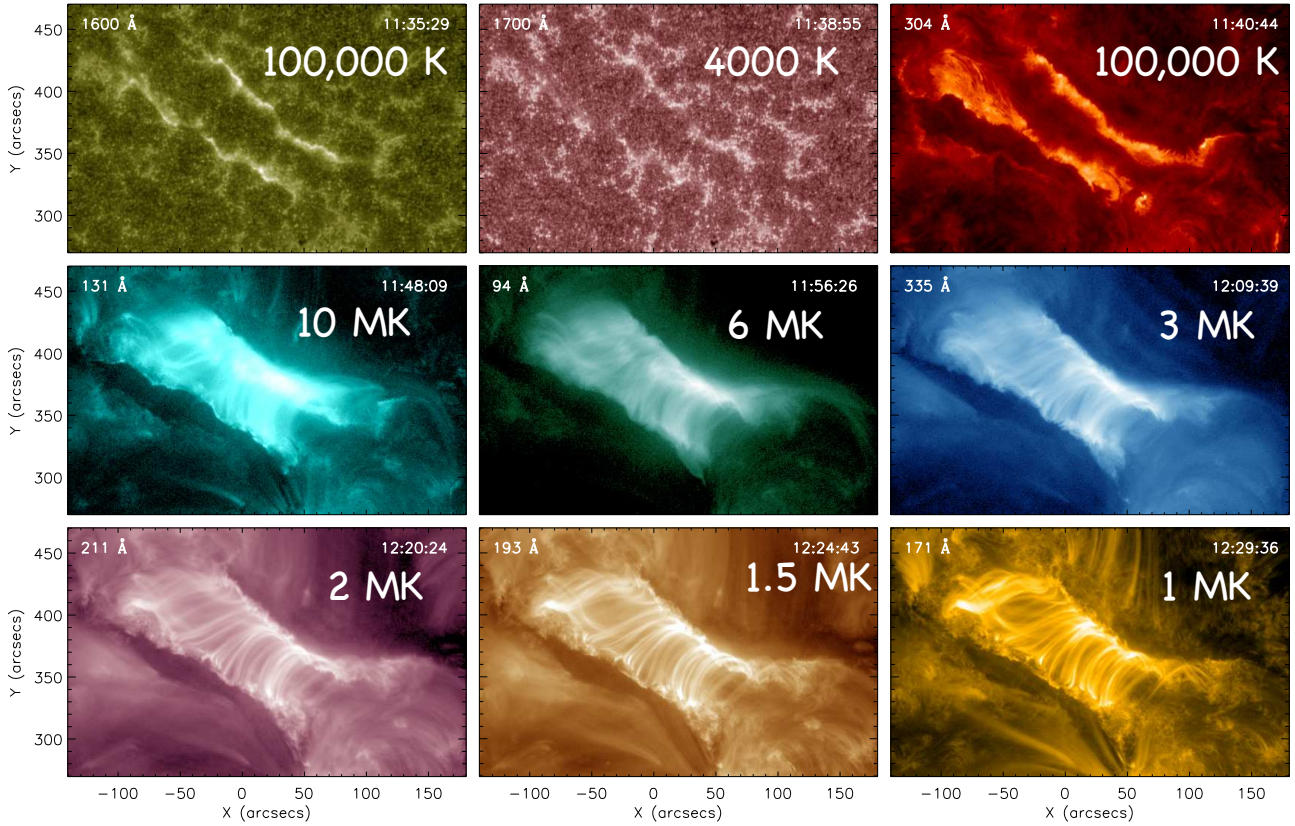
Heating of multiple flare loops



Reconnection forms and heats multiple loops during the flare evolution (Hori et al. 1997, 1998, **Warren 2006**, Longcope et al 2010 …)

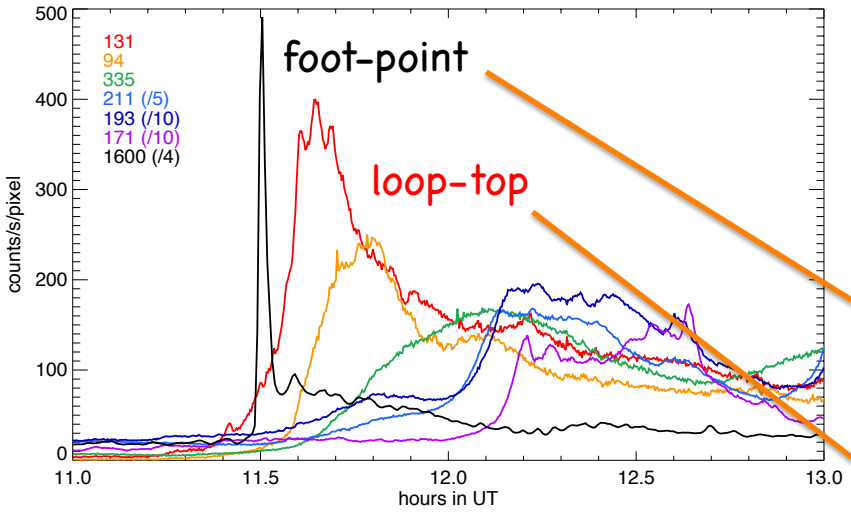
$$Q(t) = Q_0 + g(t) Q_{flare} \exp\left[-\frac{(s - s_0)^2}{2\sigma_s^2} \right]$$

A standard solar flare: spatial structure



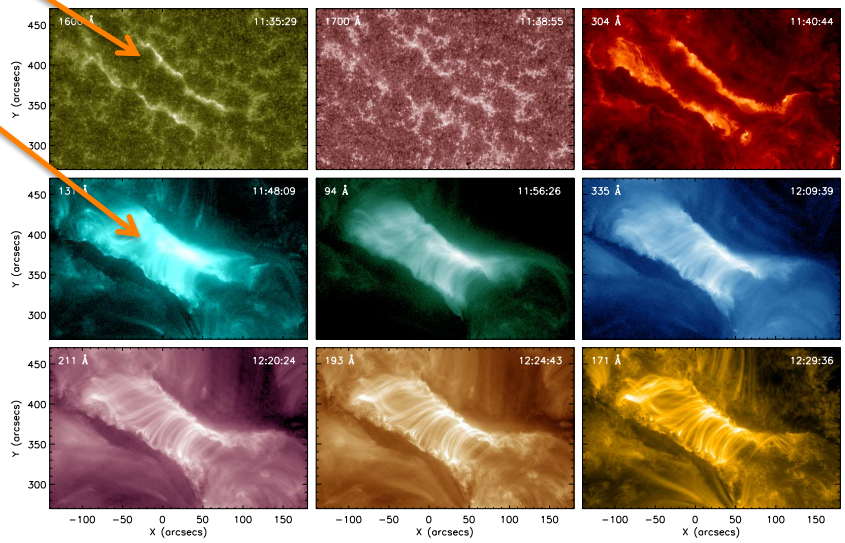
Flare loops heat up and then cool from 10 MK to 1 MK, each of them evolving independently.

Flare ribbon/kernel emissions trace the heating

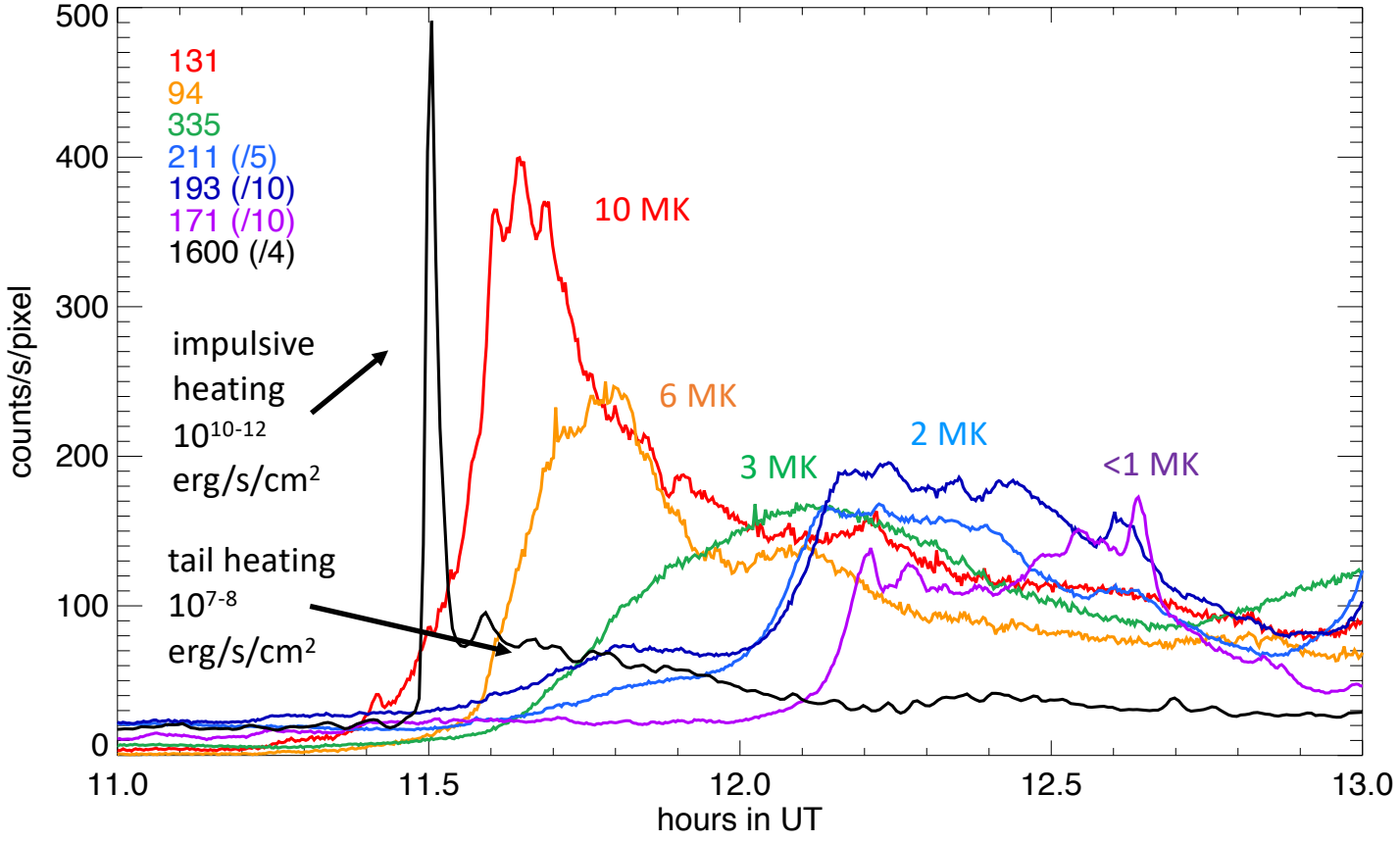


Impulsive emission at the foot-points can be used to infer heating rates (when, for how long, by how much) of instrument resolved flare loops – the UV Neupert effect (Qiu+2012-).

Reconnection forms flare loops, or packets of energy release, which are mapped at their feet, the flare ribbons.

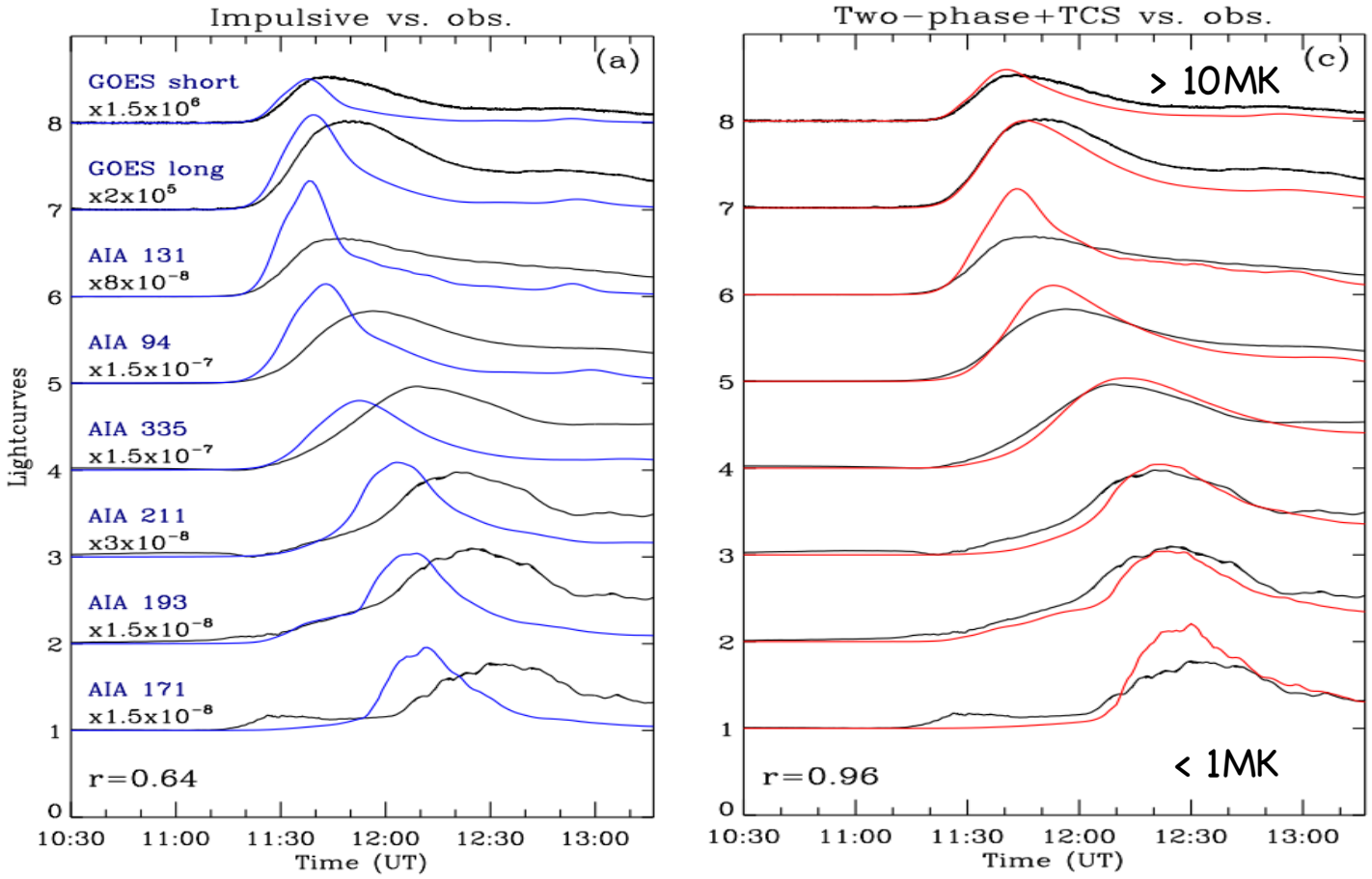


heating in AIA-scale "elementary bursts"

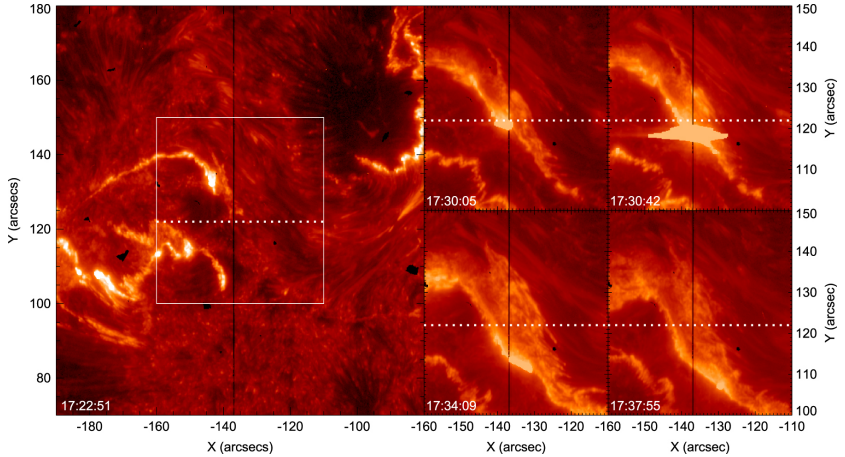


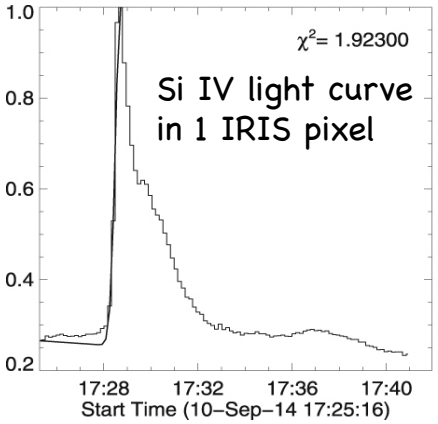
Experiments suggest two-phase heating, an impulsive intense heating followed by a low-rate tail-heating, reproduce observed prolonged decay in X-ray and EUV emissions, and the amount of tail-heating is 30-60% of the total heating energy (Qiu+16, Zhu+18, Qiu21).

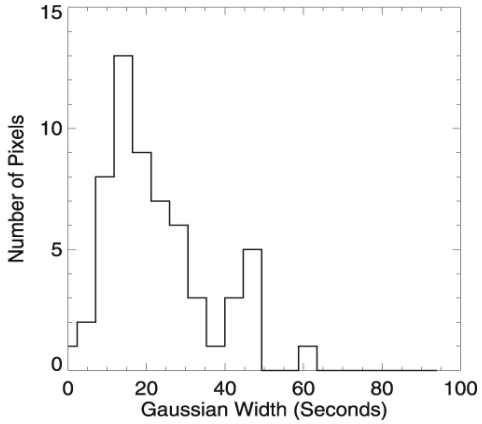
heating in AIA-scale "elementary bursts"

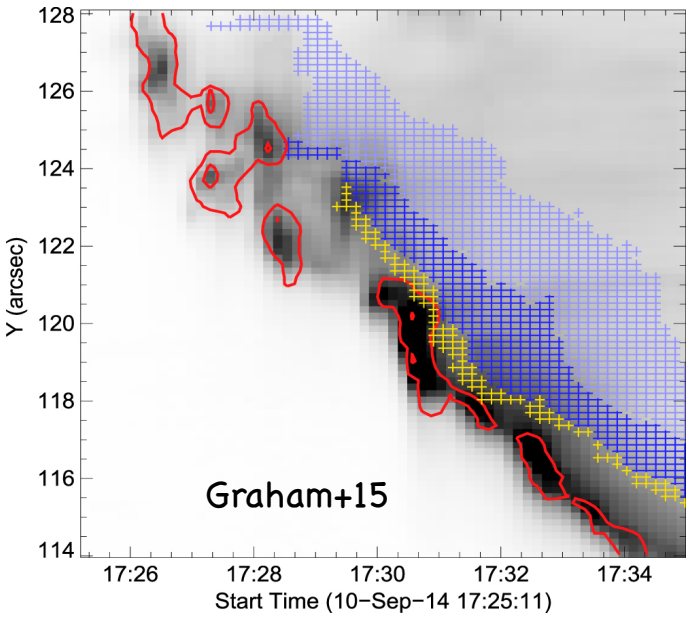


heating in IRIS-scale "elementary bursts"



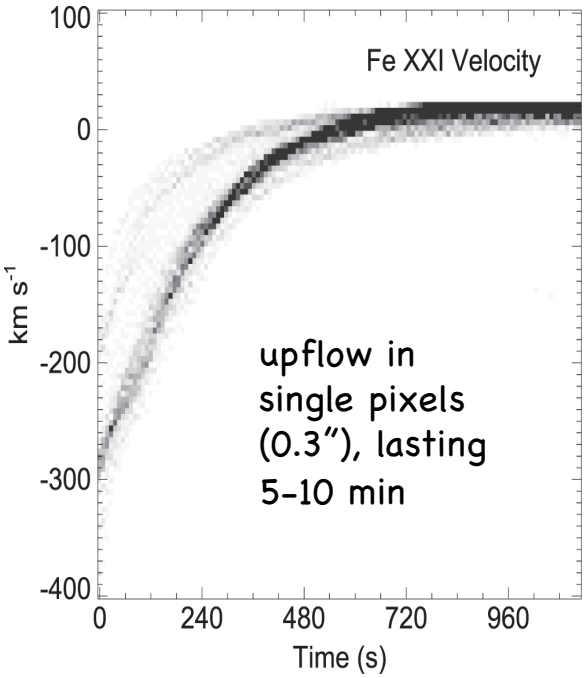


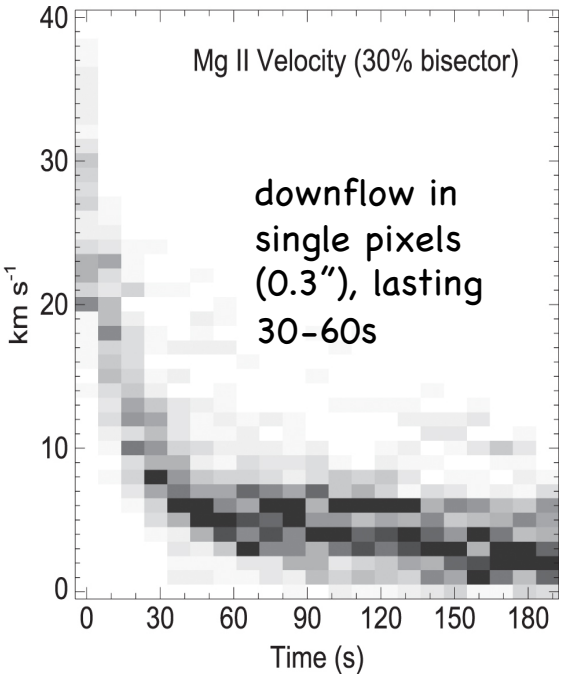




IRIS observations of an X-class two-ribbon flare reveal prototypical "elementary" bursts

heating and dynamics in IRIS-scale "elementary bursts"





Graham+15

IRIS observations of an X-class two-ribbon flare reveal prototypical "elementary" bursts (Graham+15, Brannon+15, Li+15 ...):

- entirely blue-shifted, symmetric Fe XXI line,
- Si IV line fitted to 1-2 Gaussians,
- similar dynamic patterns
- scale 150-300km (80-200km w/GST, Jing+16)

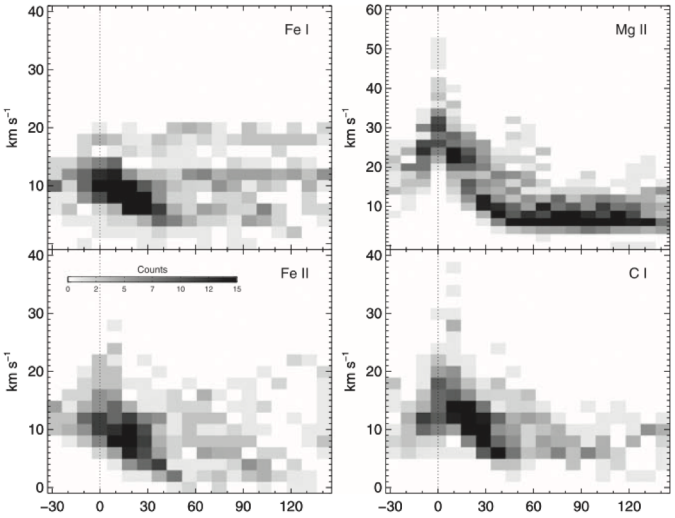
DISCUSSION

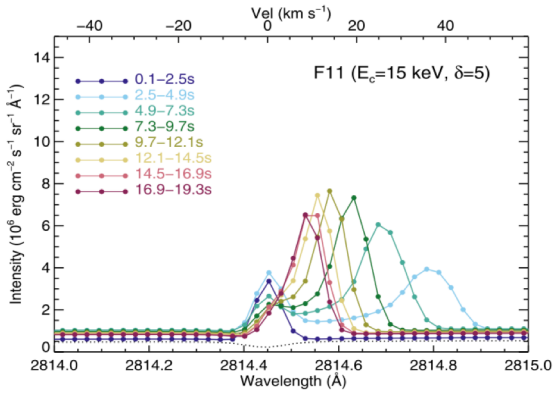
SVESTKA: I don't understand how a shock going into the chromosphere can have a duration of a few minutes.

CANFIELD: A shock going into the chromosphere at a single footpoint can have a duration – if you believe the numerical simulation – which is only approximately 30 s to one minute. So, if we were to see within a single observing pixel a strong red shift for a period of several minutes, the only possible interpretation we could make, if we believe this evaporation picture, is that in fact multiple episodes occurred within that pixel, as you might expect, for example, if reconnection is proceeding across that pixel.

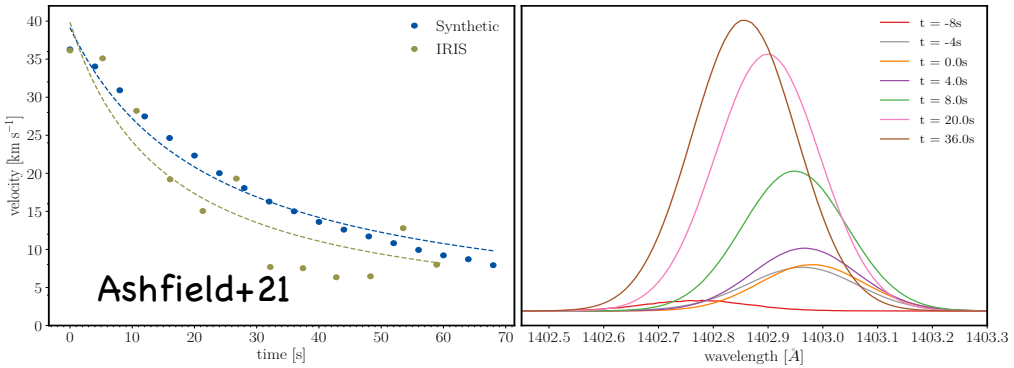
Canfield, 1987, "Optical Imaging Spectroscopy", Solar Physics, 113, 95 (1987)

downflows in IRIS-scale "elementary bursts"



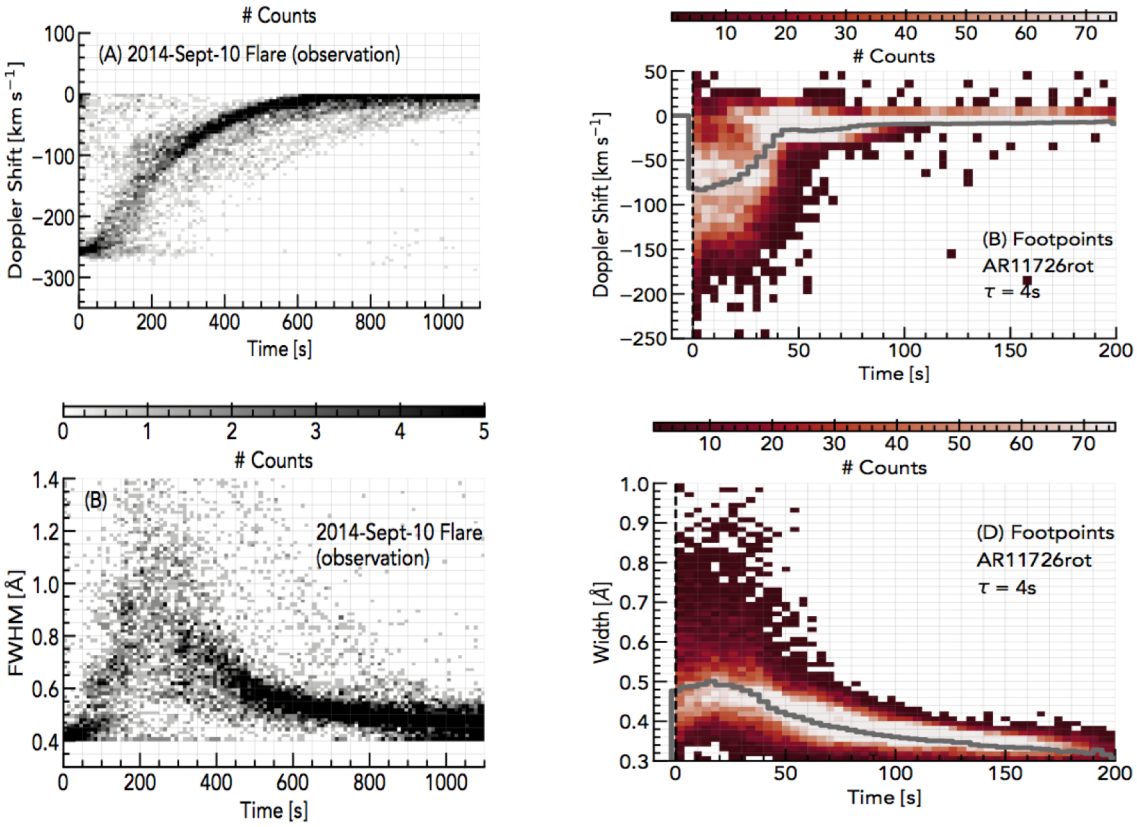


(Graham+20)



modeling with either nonthermal electron heating (Graham+20) or conduction heating (Ashfield+21) reproduces the downflow (condensation) of timescale ~30s, even with longer heating necessary for the long radiation.

upflows in IRIS-scale "elementary bursts"

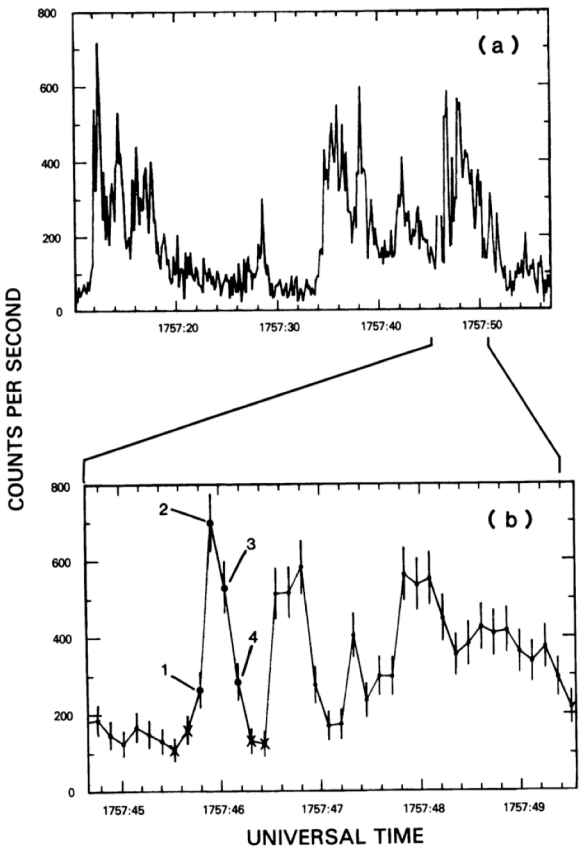


observed (Graham+20, Kerr+20) model

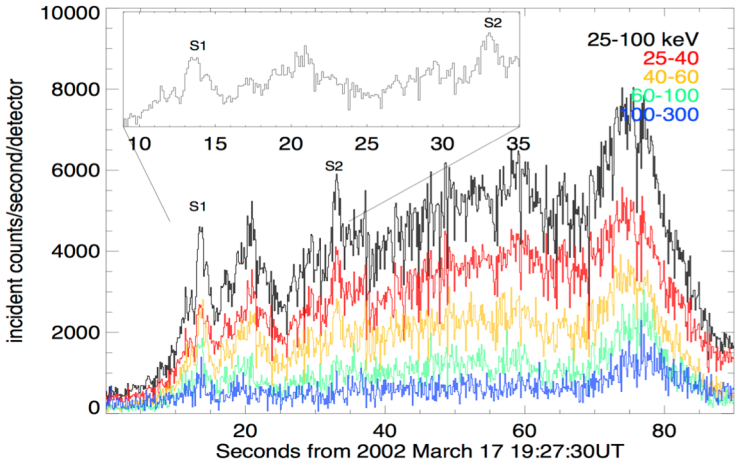
RH modeling (with impulsive nonthermal electron heating) of spectra & photometry of the observed IRIS-scale "elementary" bursts reproduces the condensation of ~30s, yet the evaporation upflow and X-ray radiation timescales are too short.

- additional heating?
- structure of heating?
- mechanism of heating?

next-order scale of "elementary bursts"



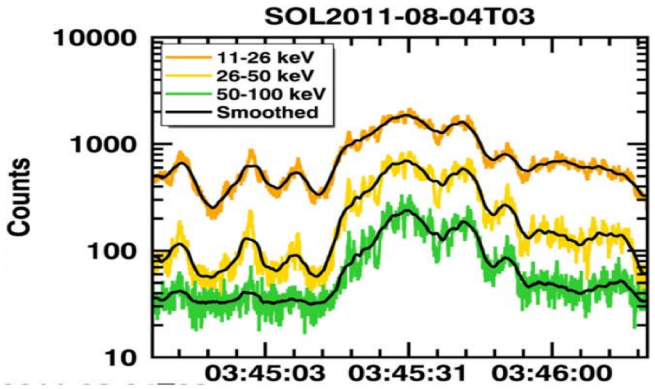
BATSE, Kiplinger+89



RHESSI Qiu+12

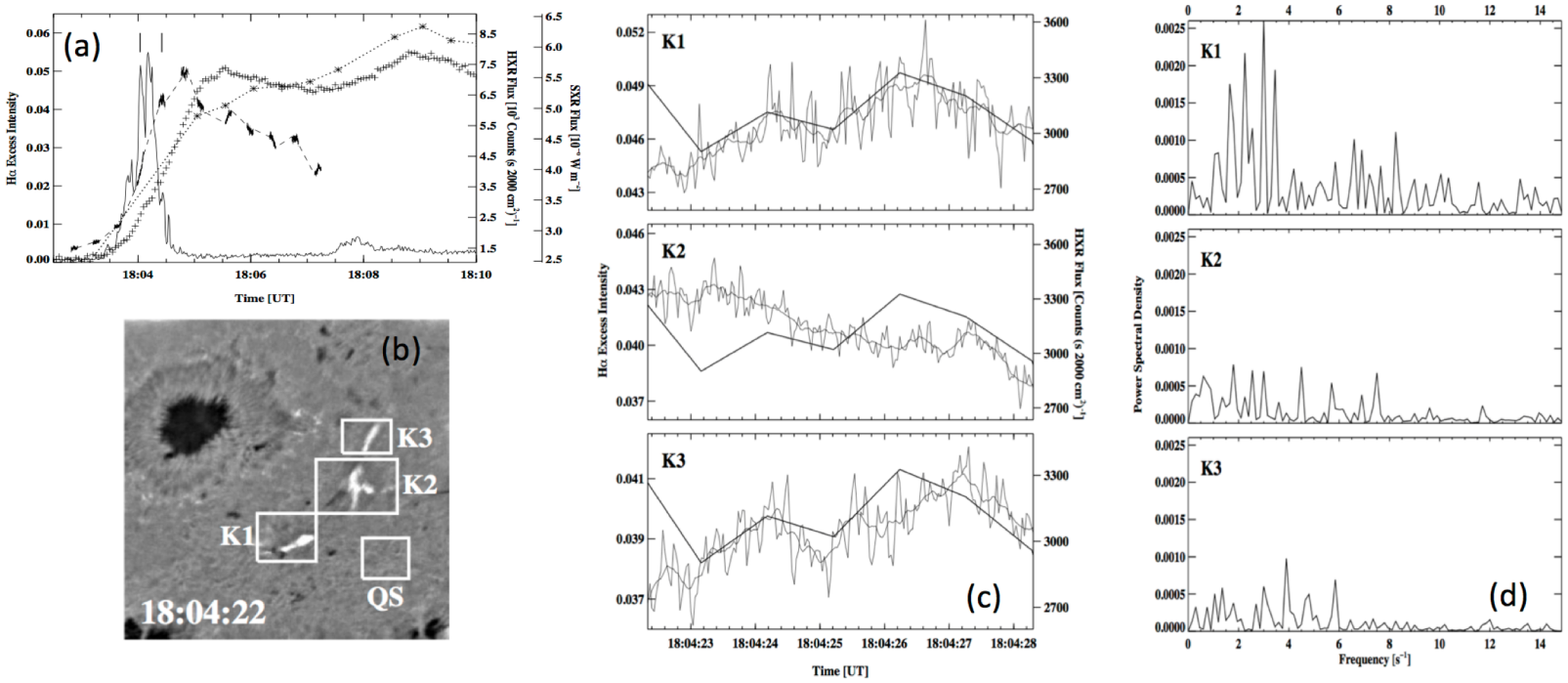
HXR elementary bursts observed by three generations of HXR observing instruments, all illustrating bursty HXR emissions at sub-second scales.

Where are they?



Fermi, Knuth+20

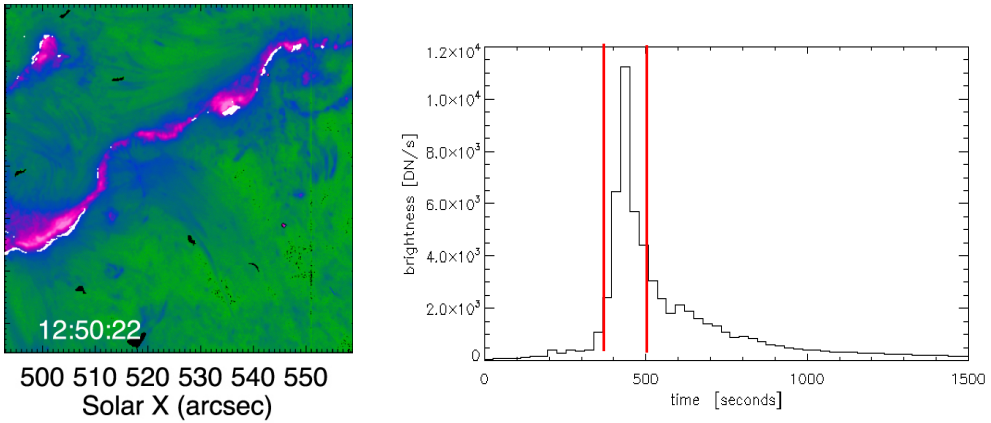
next-order scale of "elementary bursts"



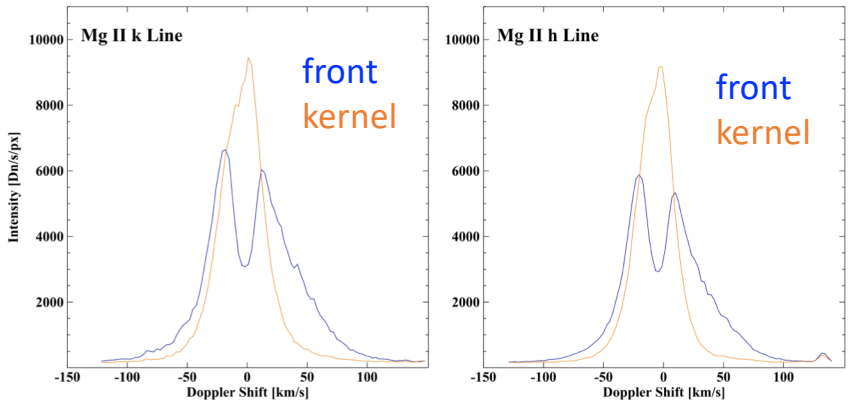
In one study (Wang+00), HXR bursts of ~1 sec is located on only one flare kernels, indicating that not all places be heated by bursty HXR electrons. Thermal conduction? Alfven waves? XUV irradiation?

next-order scale of "elementary bursts"

Spatio-temporal structure of ribbon (Naus+22)

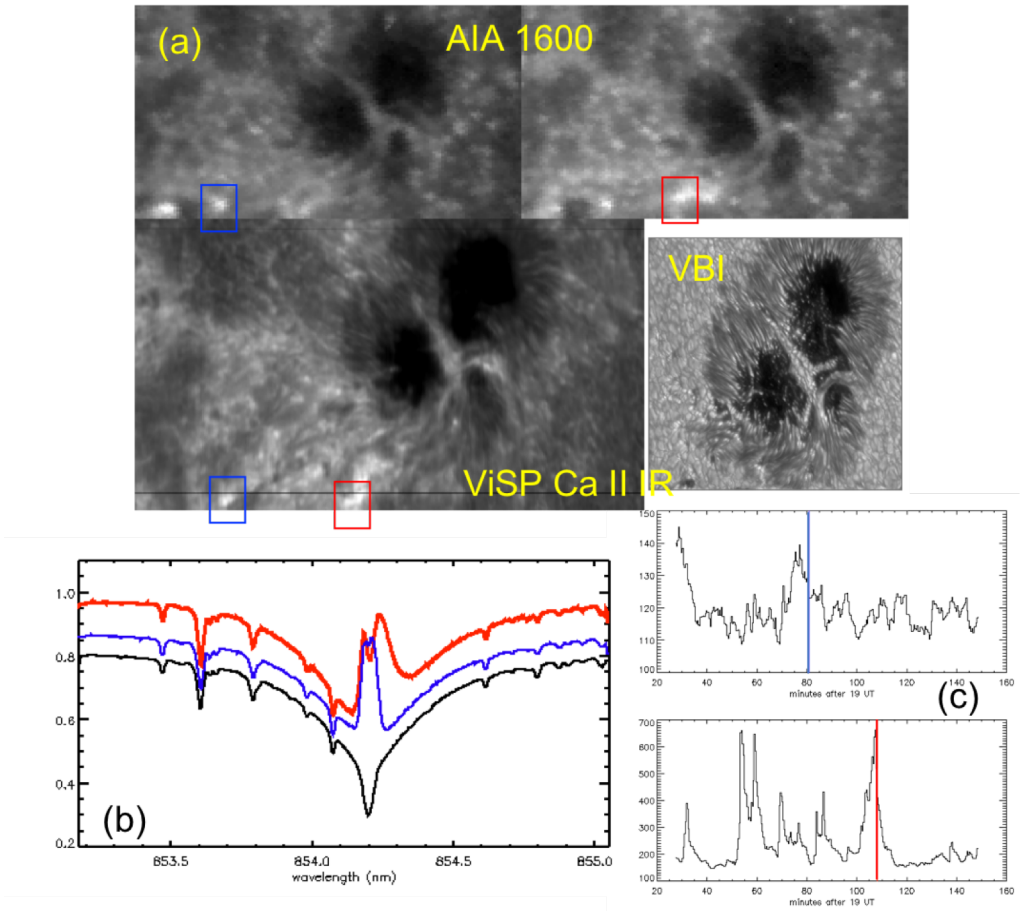


Spectra of ribbon front and kernel (Xu+16)



High-resolution, high-cadence imaging spectral observations may help diagnose heating mechanisms at fine scales of different spatial structures, such as the ribbon front or kernel (Xu+16, Kerr+20,24, Polito+23), and also during the evolution of these structures.

next-order scale of "elementary bursts"

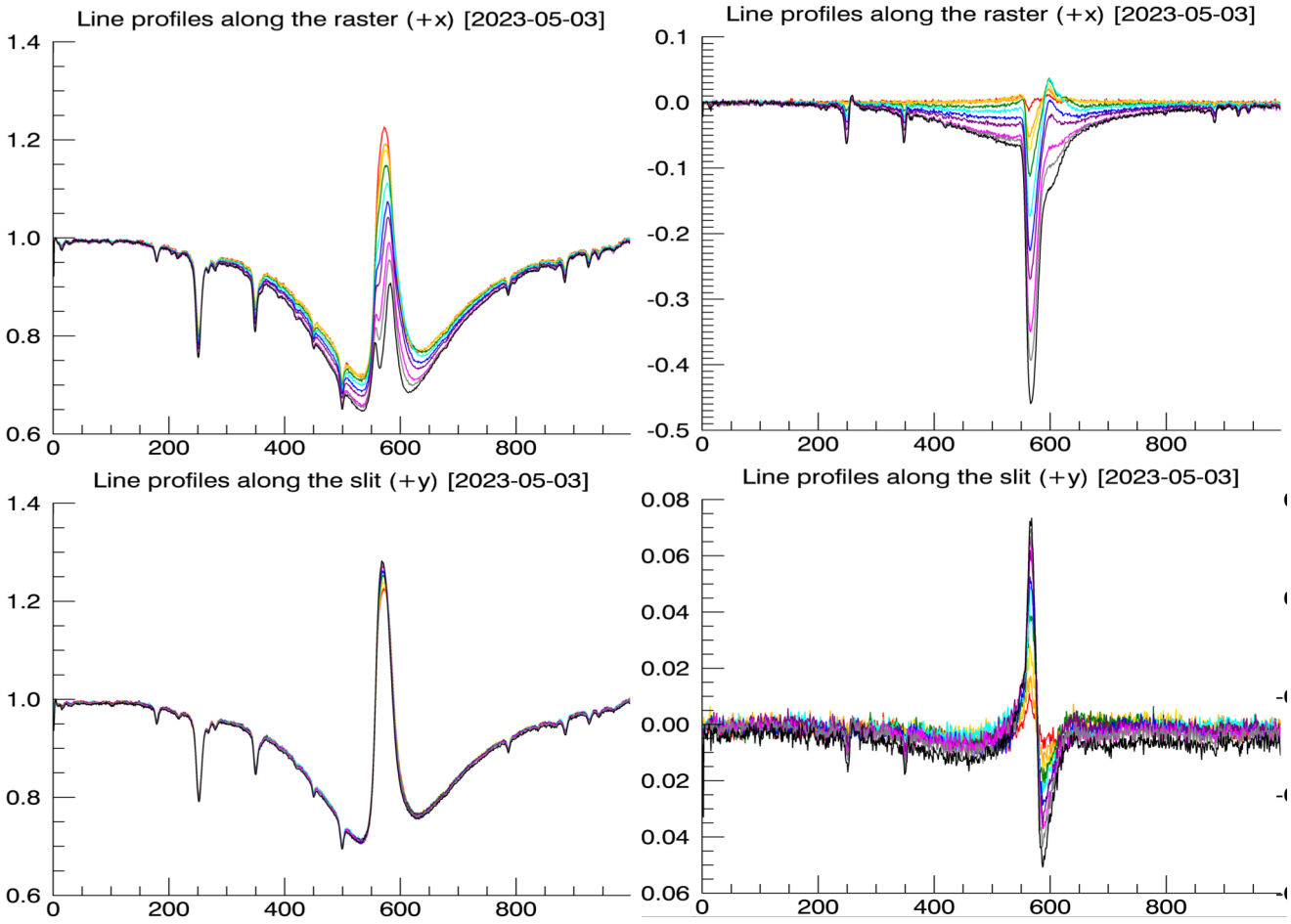


High-resolution, high-cadence imaging spectral observations at multiple lines may help diagnose heating mechanism at fine scales and during the evolution of an "elementary burst".

Riley+24

next-order scale of "elementary bursts"

Ca II IR line profiles of adjacent flaring pixels. across the ViSP slit (0.1", 1.5s) and along the slit (0.02").



Difference spectra of adjacent pixels across and along the slit.

Riley+24

Summary:

Flare energy release occurs in a large number of packets, or "elementary bursts", which may be "resolved" and traced in the chromospheric observations.

Observations of the flaring chromosphere, aided with other observations, provide diagnostics of energetics, or the characteristics of flare heating: when, where, by how much, for how long, and through what mechanism, is the flaring atmosphere heated.

With progress made in understanding these processes, we are still left with some basic questions regarding flare heating.

- can optical/UV spectroscopy determine heating mechanism?
- what is the nature of slow "cooling"?
- are non-thermal electrons ubiquitous?
- what governs the production of nth electrons?