# Heating and Dynamics of the Corona:

## Why We Need to Observe Very Hot & Faint Plasmas

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# Key Points

- These comments apply to all forms of heating
  (“ordinary” coronal heating, flares, CMEs, X-ray jets, ….)
- We have yet to observe directly the energy release process
  - e.g., we have never seen a reconnection outflow jet
- Reconnection is a fundamental process, yet we do not know its basic properties
  - Is it simple (Petschek) or complex (tearing islands)?
- All heating is impulsive when viewed properly
- Heated plasma is initially very hot and faint
- Hot plasma cools very quickly
  - Important information is lost by the time it reaches “traditional” coronal temperatures

# All Heating is Impulsive

- To understand how plasma responds to heating (and produces observed radiation), we need to consider individual magnetic field lines (flux strands).

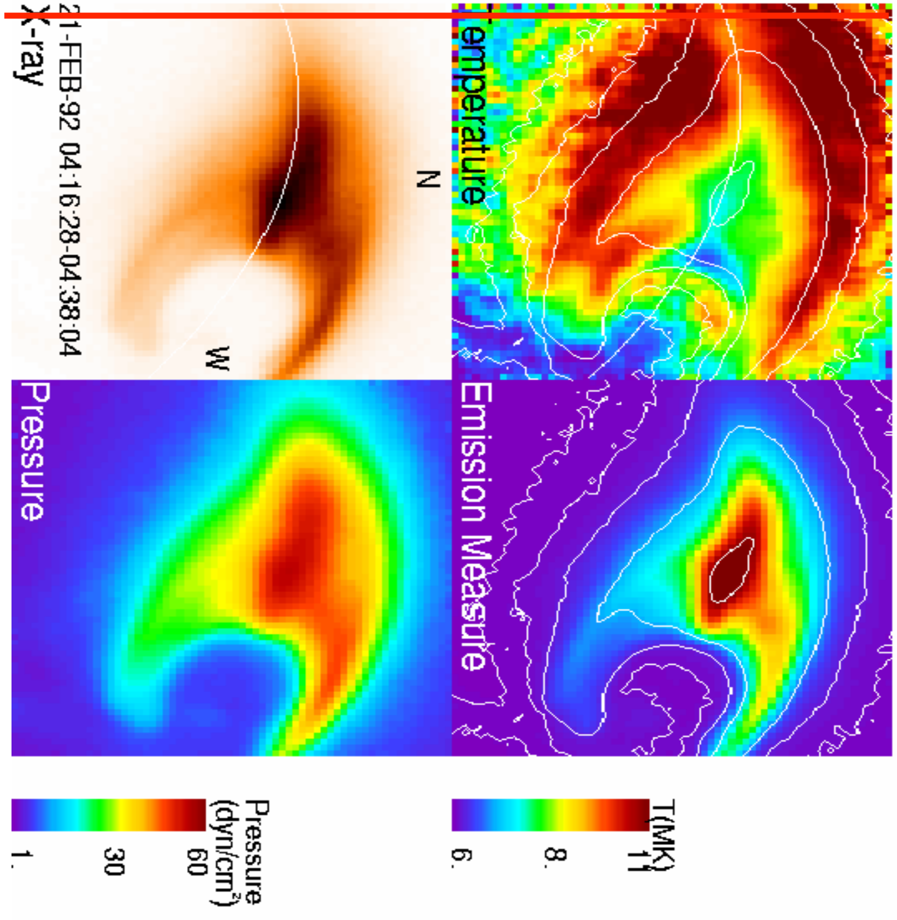
- Plasma and heat flow along the field, so strands behave like independent, thermally insulated flow tubes.

- The heating on individual field lines is impulsive even when the heating over a large volume is steady.

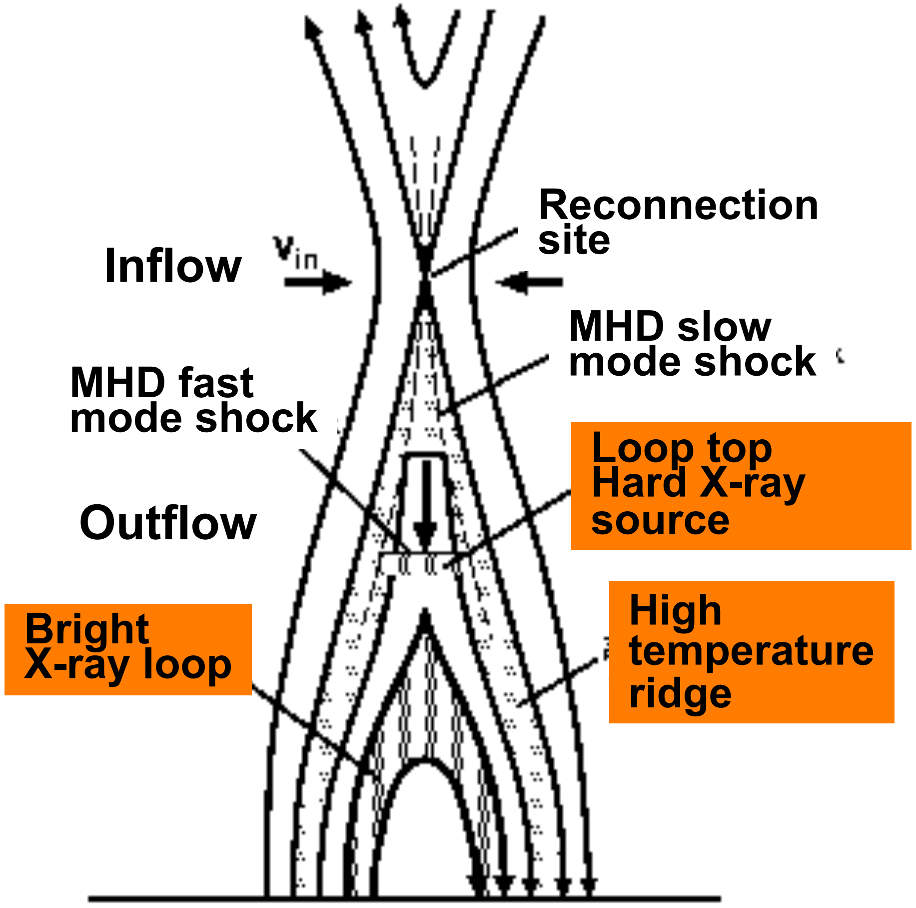
- Three examples:
  1. Long duration flare
  2. Secondary instability
  3. Resonant wave absorption

# Courtesy of Tsuneta-san (modified)

(Tsuneta, ApJ, 456, 840, 1996)



Reconnected field lines move rapidly away from the X-point. Heating occurs only while they are in contact with standing slow mode shocks (~ 10 sec): *impulsive*.


**Reconnection site**

**Inflow** $v_{in}$

**MHD slow mode shock**

**MHD fast mode shock**

**Loop top Hard X-ray source**

**Outflow**

**Bright X-ray loop**

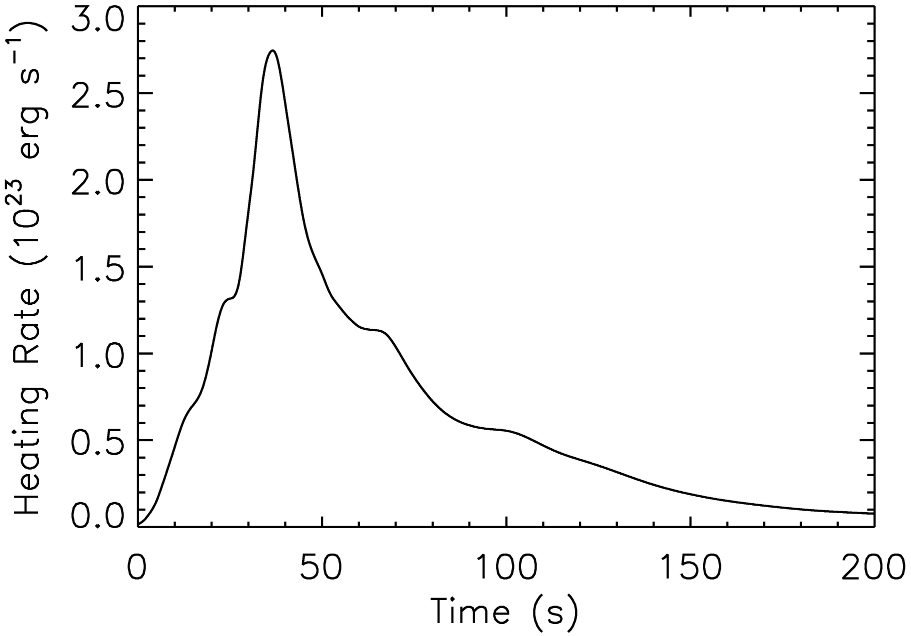
**High temperature ridge**

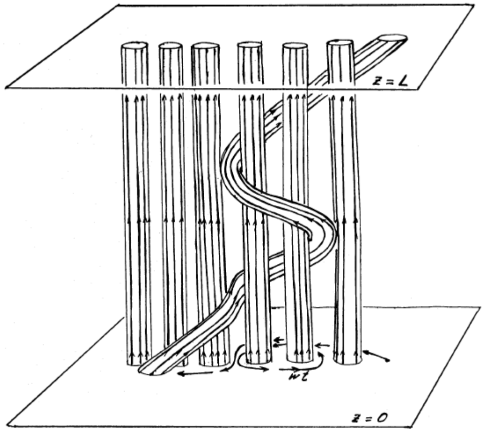
Standard 2-D picture of solar flares

# Secondary Instability

- ***Impulsive*** heating occurs at current sheets when the magnetic field is sufficiently sheared

- e.g., at the interface between adjacent flux strands in a coronal field that is tangled by photospheric convection (Parker picture)





Dahlburg, Klimchuk, & Antiochos (2003, 05, 08)

# Resonant Wave Absorption

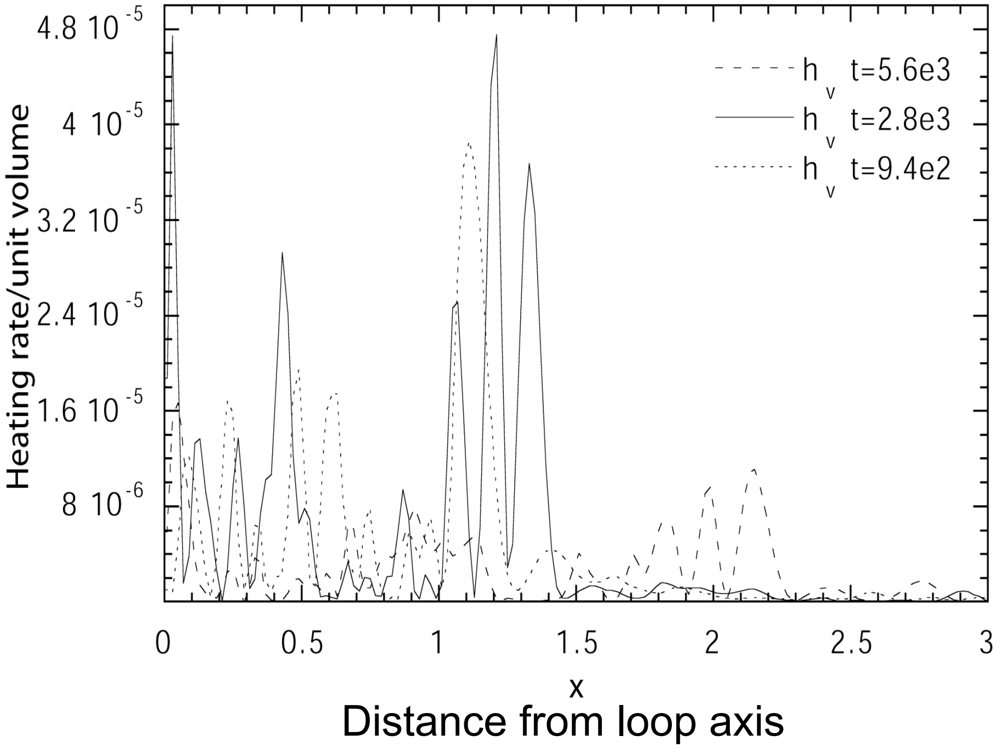
- Usual damping mechanisms are not efficient for low frequency ($\tau \sim 100$ s) waves.

- Resonant absorption occurs on magnetic field lines where the local resonance frequency matches the global loop oscillation frequency.

- Resonance conditions change as the plasma responds to the heating

- Resonance layers drift across the loop, heating field lines ***impulsively*** as they pass by.

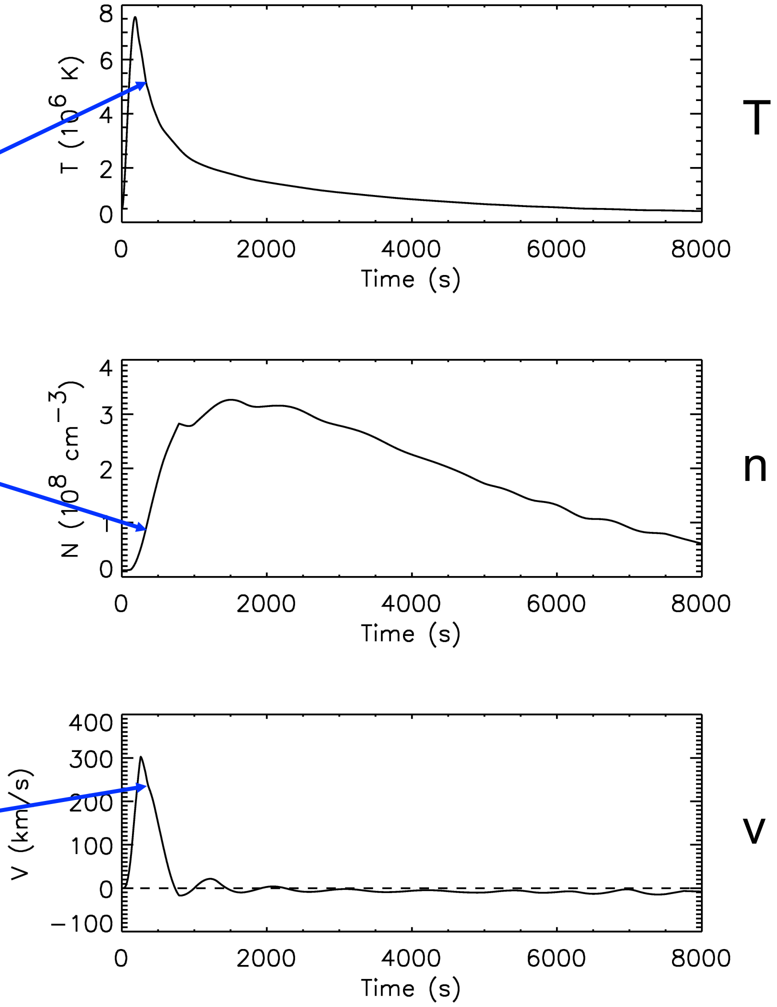
Heating Profile at 3 Times



Ofman, Klimchuk, & Davila (1998)

# Consequences of Impulsive Heating

- Temperature rises rapidly to very high values.
- Plasma cools rapidly initially. Valuable information is lost.
- Density and emission measure are small.  Evaporation takes time to fill a strand.
- Plasma is faint due to combination of small EM and short lifetime.
- High velocity evaporative upflows (only when plasma is hot and faint).



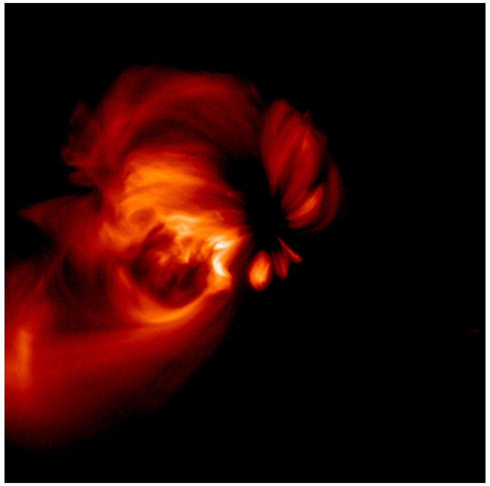
500 s nanoflare simulation

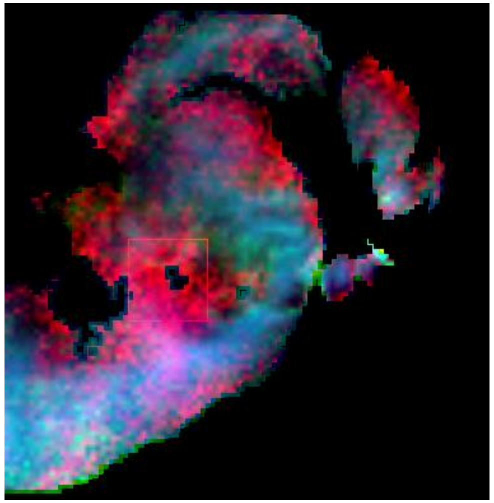
# What Do Observations Show?

- So far, we only observe plasma that has cooled appreciably
- Strong evidence that many coronal loops are bundles of unresolved strands that are heated by “storms” of nanoflares
  - Hinode 2 talk in Boulder
  - Klimchuk (2006, Solar Phys., 234, 41)
- True of all loops? True of the diffuse corona?
- We do ***not*** know the details of the energy release
  - e.g., magnitude and duration of the nanoflare
- Some clues starting to come from Hinode/XRT

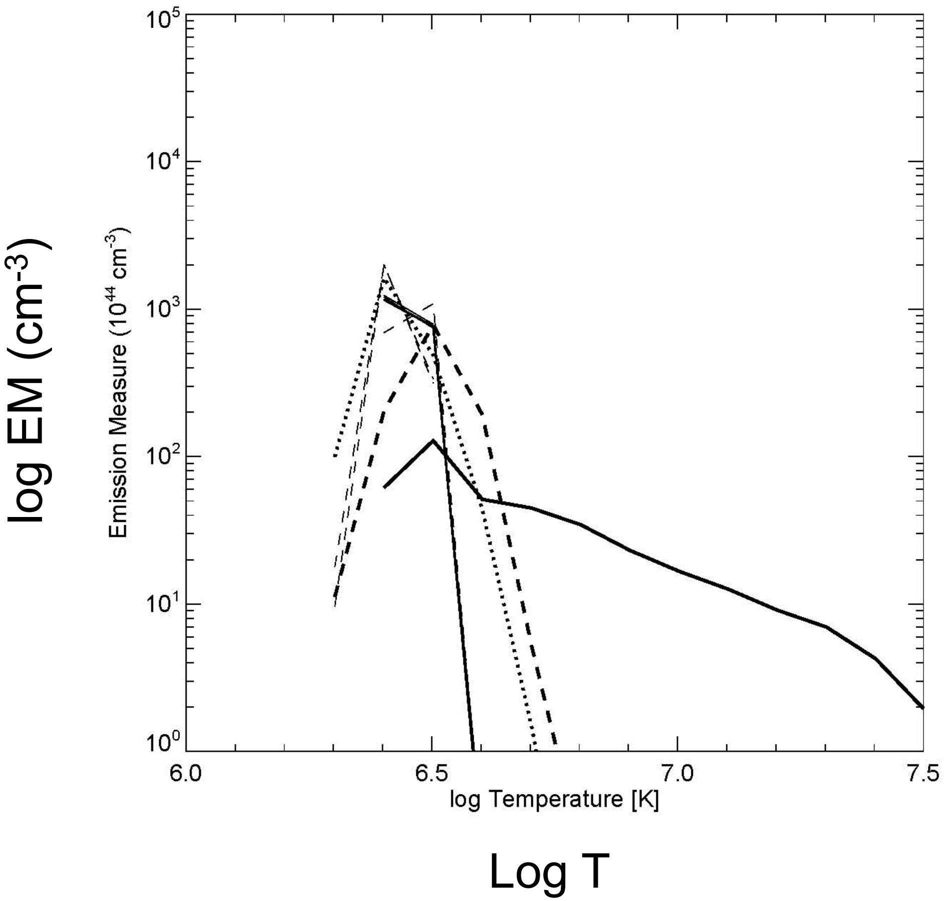
# Hinode / XRT  (Reale et al. 2008)

Be_med Image



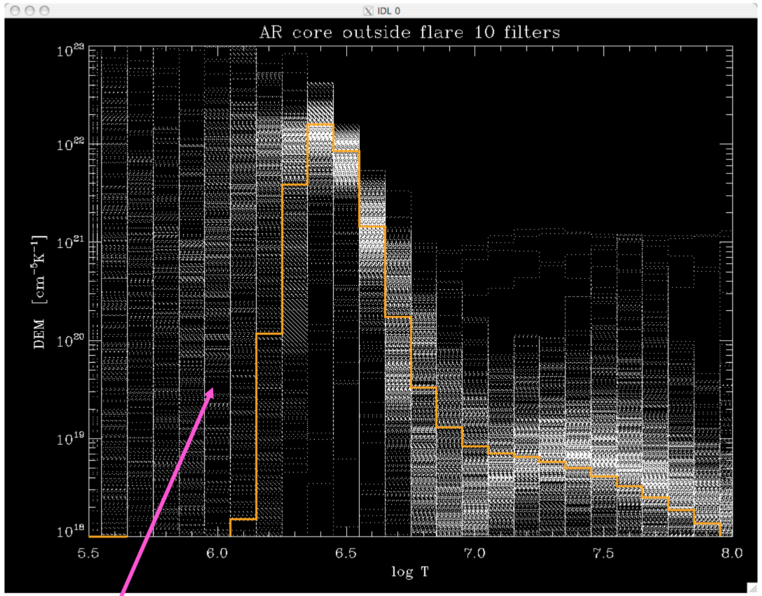


T map

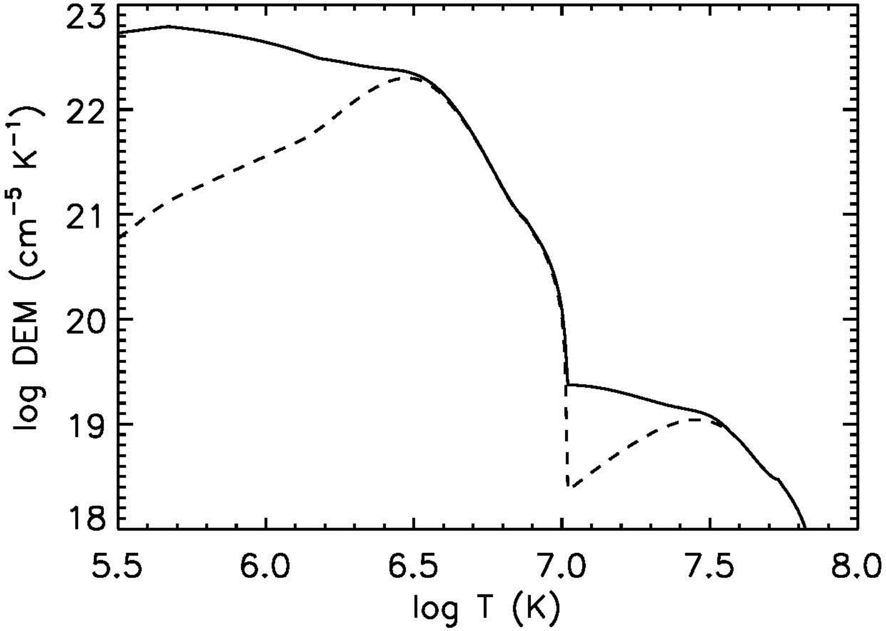


# Hinode / XRT (Schmelz et al. 2008)

Observation



Simulation



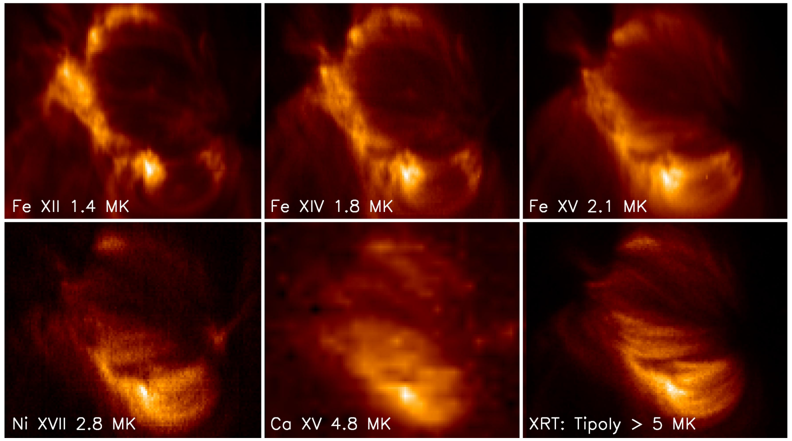
Cool part not constrained by observations

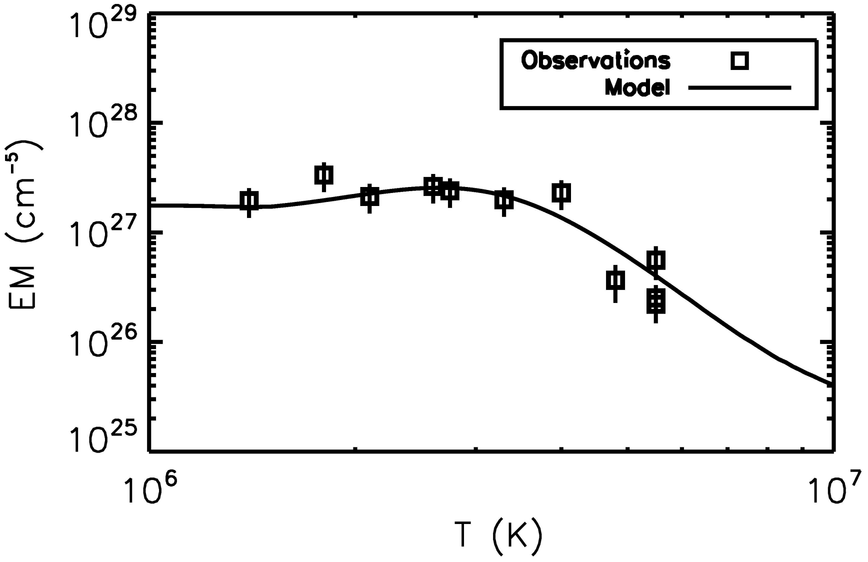
Two component model (large and small nanoflares)

Steady heating ***not*** plausible

20 MK equilibrium loop requires:

Energy flux ~ $10^9$ erg cm$^{-2}$ s$^{-1}$
Footpoint velocity ~ 100 km s$^{-1}$





Hinode/EIS:

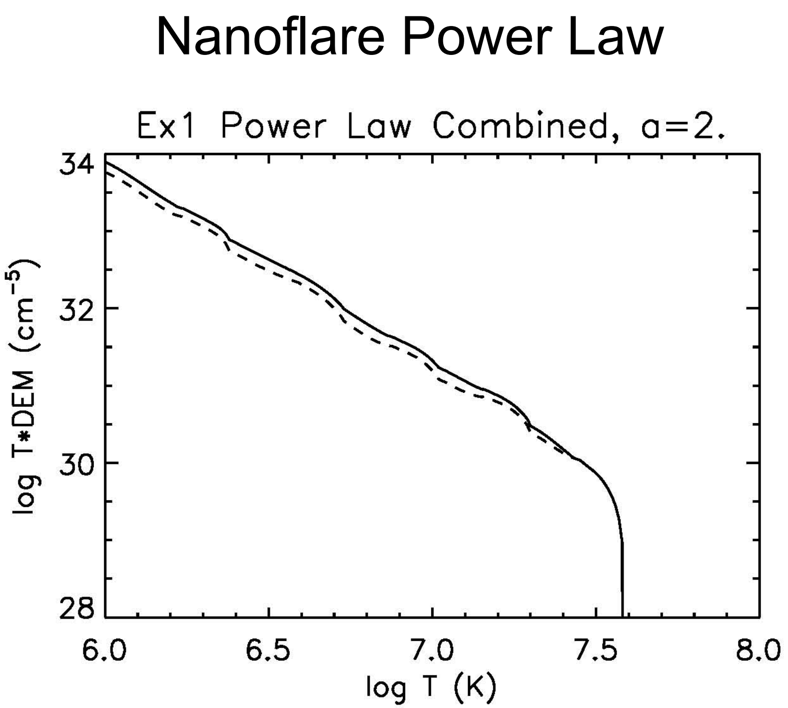
Fe XII – XVII
Ca IV – VI
Ni XVII

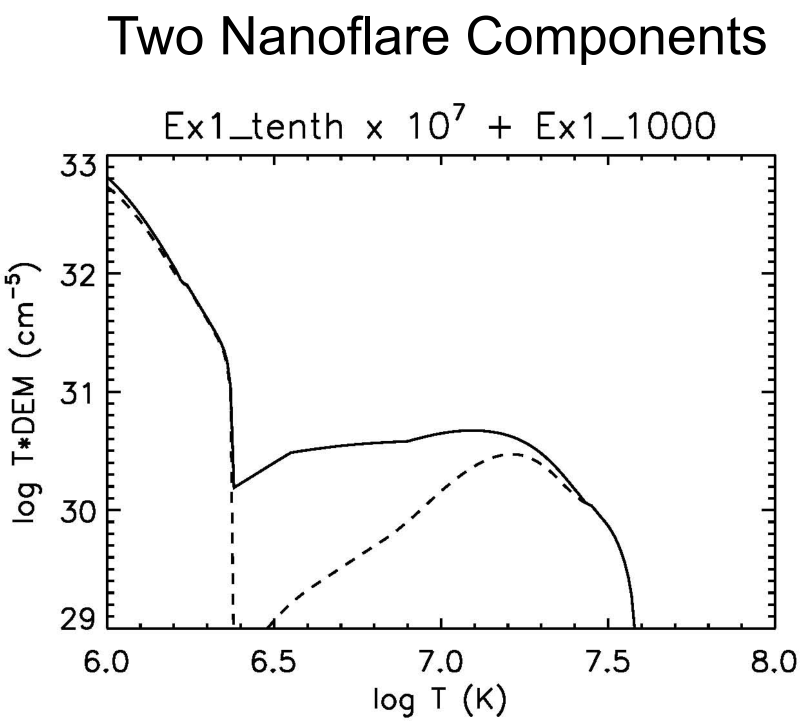
Patsourakos & Klimchuk (2008)

# What can we learn by observing hot plasma?

- DEM(T) reveals the distribution of nanoflare energies
- Dynamics of the energy release depend on the mechanism:
  - Alfvenic jets (Petschek reconnection)?
  - Turbulence (secondary instability)?
  - Large-amplitude oscillations (resonance absorption layer)?
- Velocity signatures *disappear* by the time the plasma cools to "traditional" coronal temperatures
- Flows revealed by spectral line profiles or by direct imaging in large events (flares, CMEs)
  - First ever observation of reconnection outflow
  - Simple jet or tearing islands?
- Evaporative upflows are a sensitive diagnostic of heating

# DEM(T) depends on nanoflare energy distribution


Nanoflare Power Law


Two Nanoflare Components

Seems to best fit the observations.
Surprising! Important!
Uncertain. Need Solar-C!

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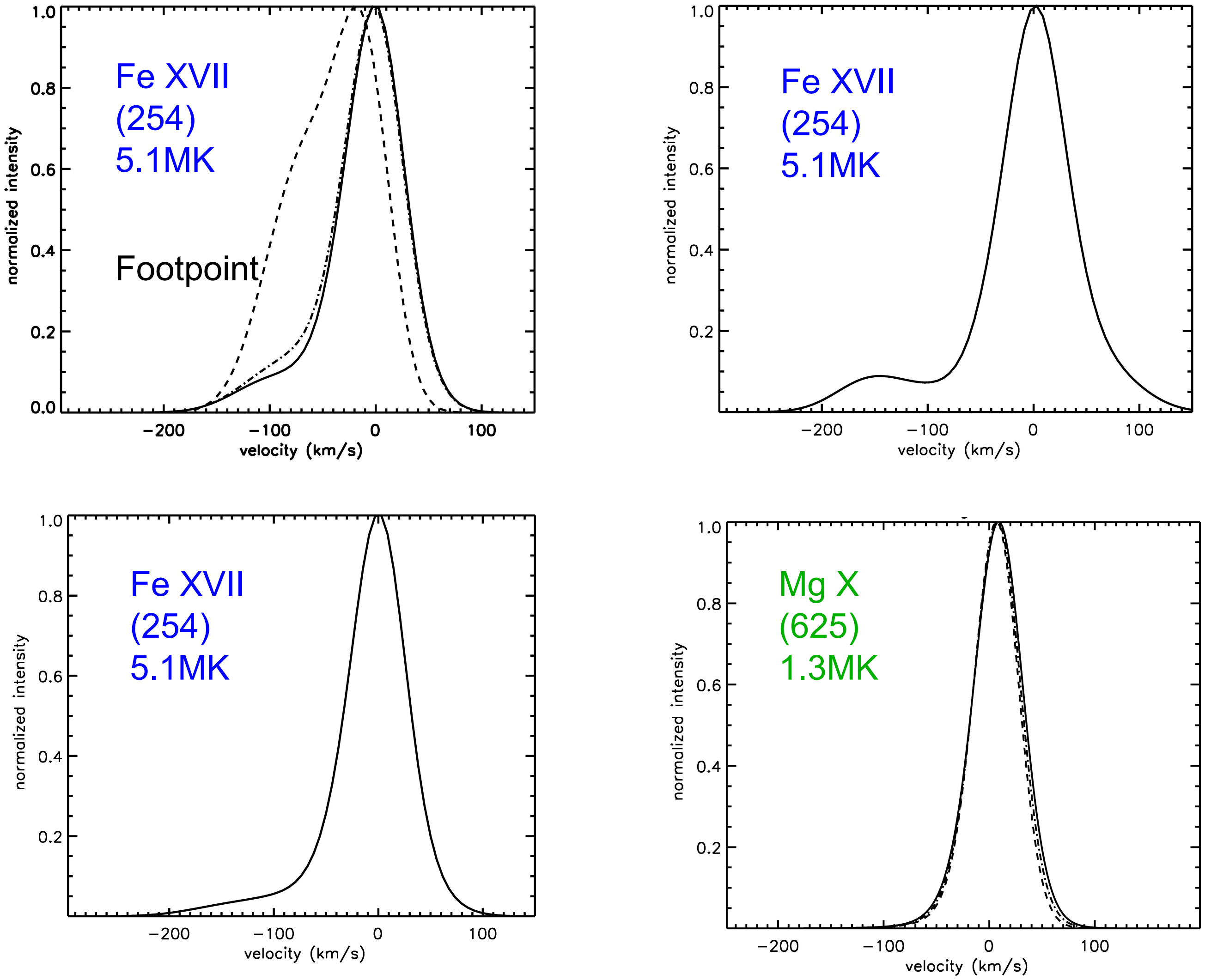
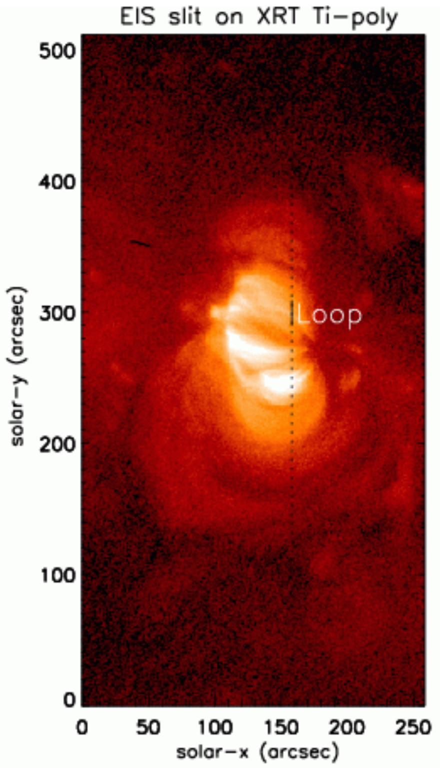
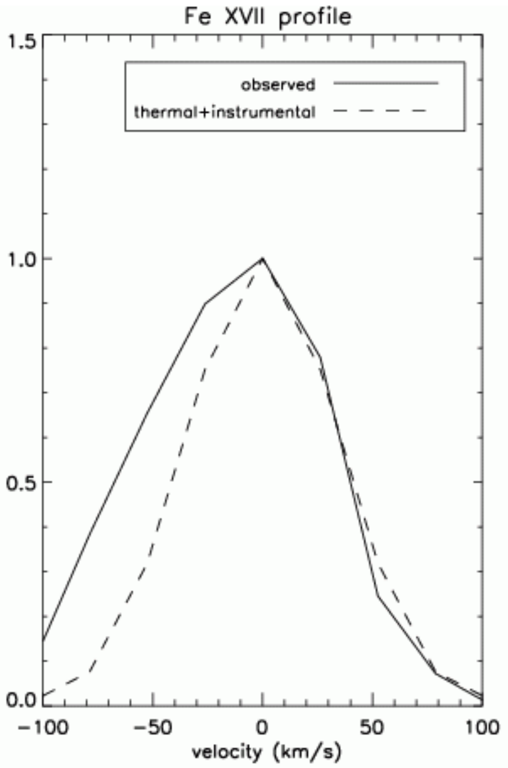
# Simulated Line Profiles



Patsourakos & Klimchuk (2006)

# Observed Fe XVII Profile





EIS sit and stare observations

Line is ***very faint***

Proposed x100 increase in throughput is a quantum improvement

See also Hara et al. (2008)

# Observational Priorities

1. Sensitivity to faint hot emission (high throughput)
    - T ~ 5-10 MK minimum, 10-30 MK desired
    - $DEM(T) \sim 10^{19}\ cm^{-5}\ K^{-1}$

2. Temperature discrimination
    - $\Delta T \sim 1$ MK
    - Ability to distinguish faint hot emission from bright cool emission along the l-o-s

3. Spatial resolution
    - 0.1 arc sec (100 km) for elemental coronal flux strands
    - Short-lived hot plasma reduces l-o-s overlap problems
    - Tremendous progress possible with much coarser resolution

4. Temporal resolution
    - None required for DEM(T) over large areas
    - 100 s for coronal loops
    - 1-10 s for spatially resolved reconnection outflows (flares, CMEs)

# BACKUP SLIDES

# Predicted Hot Line Intensities

DEM(T) = $10^{18}$ cm$^{-5}$ K$^{-1}$
0.1 x 0.1 arcsec$^{2}$ pixel
100 s exposure

| Wave. | Intensity* | Ion | logT |
|---|---|---|---|
| 15.0150 | 5.68e-01 | Fe XVII | 6.6 |
| 15.2620 | 1.61e-01 | Fe XVII | |
| 16.0760 | 1.13e-01 | Fe XVIII | 6.8 |
| 16.7770 | 3.27e-01 | Fe XVII | |
| 17.0500 | 4.17e-01 | Fe XVII | |
| 17.0970 | 3.48e-01 | Fe XVII | |
| 93.9232 | 7.29e-01 | Fe XVIII | |
| 101.5498 | 1.74e-01 | Fe XIX | 6.9 |
| 102.2172 | 1.30e-01 | Fe XXI | 7.0 |
| 103.9370 | 2.64e-01 | Fe XVIII | |
| 108.3555 | 5.56e-01 | Fe XIX | |
| 117.1543 | 3.28e-01 | Fe XXII | |
| 117.4996 | 1.18e-01 | Fe XXI | |
| 118.6801 | 2.98e-01 | Fe XX | 7.0 |
| 119.9836 | 1.49e-01 | Fe XIX | |
| 121.8448 | 5.84e-01 | Fe XX | |
| 128.7526 | 7.49e-01 | Fe XXI | |
| 132.8405 | 8.29e-01 | Fe XX | |

| Wave. | Intensity* | Ion | logT |
|---|---|---|---|
| 132.9065 | 3.29e-01 | Fe XXIII | 7.2 |
| 135.7912 | 3.22e-01 | Fe XXII | 7.1 |
| 192.8198 | 3.57e-01 | Ca XVII | 6.7 |
| 204.6655 | 1.01e-01 | Fe XVII | |
| 254.3466 | 1.12e-01 | Fe XVII | |
| 302.1902 | 2.49e-01 | Ca XVIII | |
| 320.5660 | 2.85e-01 | Ni XVIII | |
| 344.7605 | 1.29e-01 | Ca XVIII | |
| 350.4782 | 1.19e-01 | Fe XVII | |
| 353.9203 | 1.18e-01 | Ar XVI | 6.7 |
| 567.8666 | 2.08e-01 | Fe XX | |
| 592.2357 | 2.54e-01 | Fe XIX | |
| 721.5593 | 3.76e-01 | Fe XX | |
| 845.5715 | 2.29e-01 | Fe XXII | |
| 974.8602 | 8.46e-01 | Fe XVIII | |
| 1118.0575 | 4.57e-01 | Fe XIX | |
| 1354.0665 | 9.17e-01 | Fe XXI | |

* photons cm$^{-2}$ sr$^{-1}$

# Significant Heating Occurs *in the Corona*

- Coronal magnetic field becomes tangled and twisted by random footpoint motions associated with photospheric convection.
- "Reconnection" between coronal flux strands is necessary to prevent a monotonic buildup of magnetic stress and energy.
- Reconnection between a coronal flux strand and a short magnetic carpet loop **increases** the tangling (makes the problem worse).
- There is **no** magnetic carpet in active regions, so cannot heat there.

Hinode / SOT G-band