Why We Need Spectroscopy to Solve the Coronal Heating Problem

James A. Klimchuk

Nicholeen M. Viall

NASA Goddard Space Flight Center

Helen Mason is a mistress of the spectroscopic techniques that are required to diagnose and understand the spatially unresolved structures that comprise the solar atmosphere.

Objectives

1. Emphasize that most emission is in a diffuse component, not distinct loops
   (Both components are comprised of unresolved strands)

2. Highlight especially useful diagnostics

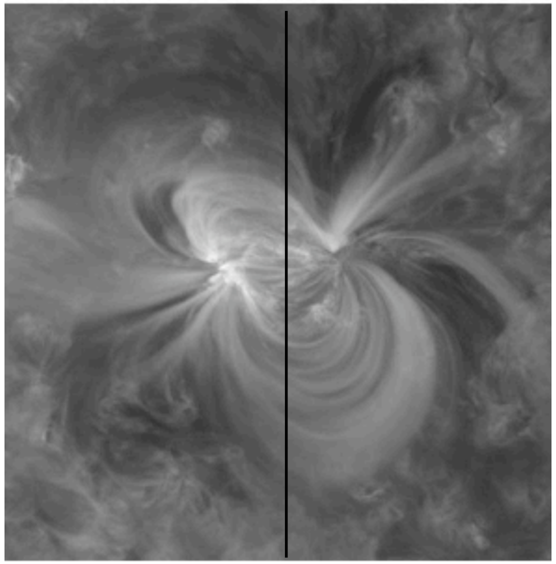
   - Emission Measure Distribution, EM(T)
   - Line core Doppler shifts
   - Line profile details (blue wing enhancements)

3. Examine the arguments for steady heating (and against impulsive heating) in the cores of ARs.

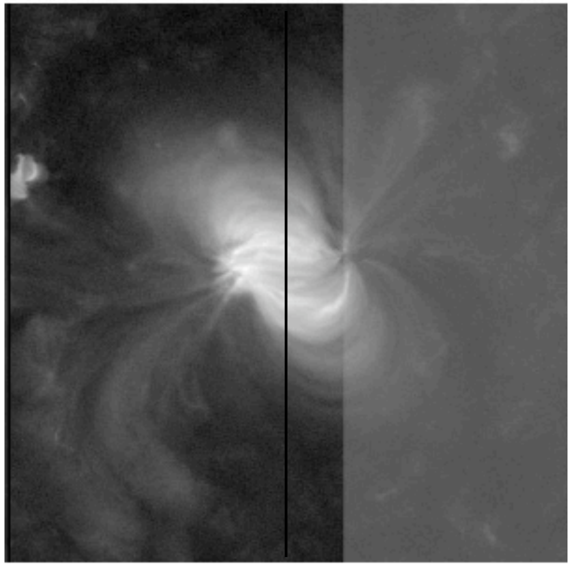
   - Lack of variability
   - Poor correlation between warm (1 MK) and hot (3 MK) plasma
   - Absence of very hot (> 4 MK) plasma
   - Very small Doppler shifts

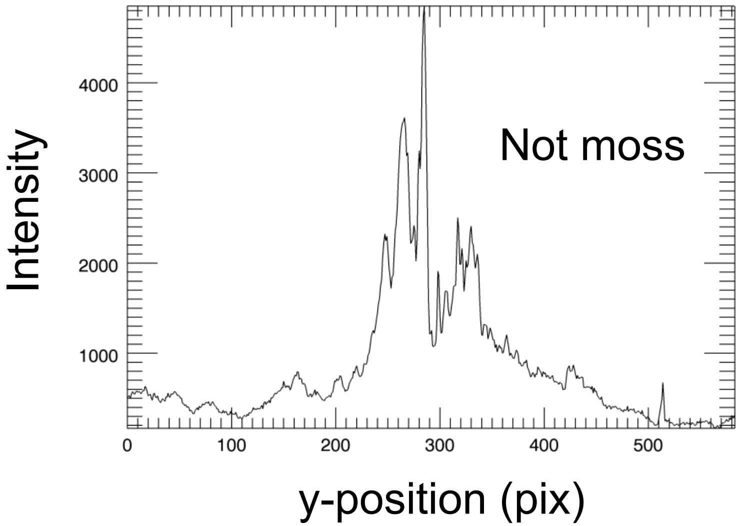
SDO / AIA

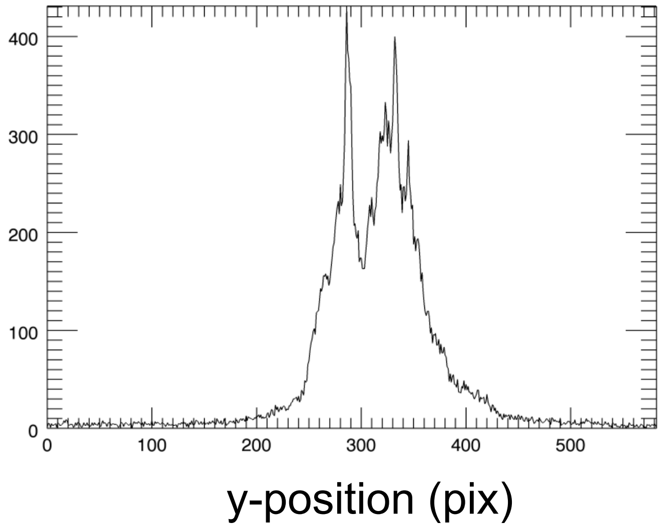
171 (1 MK)



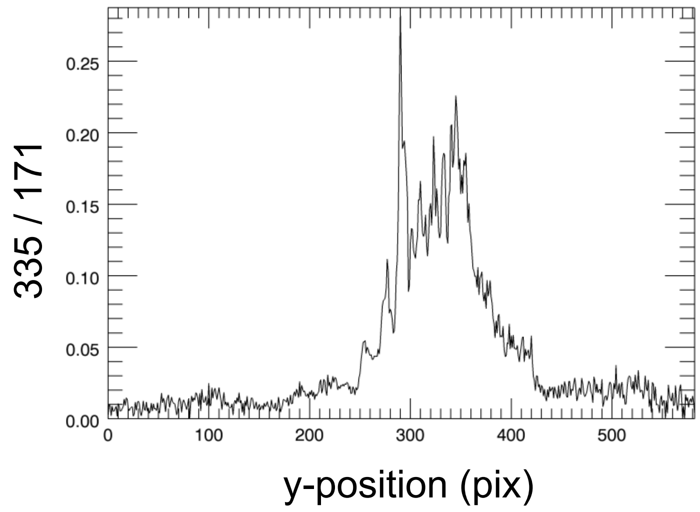
335 (3 MK)

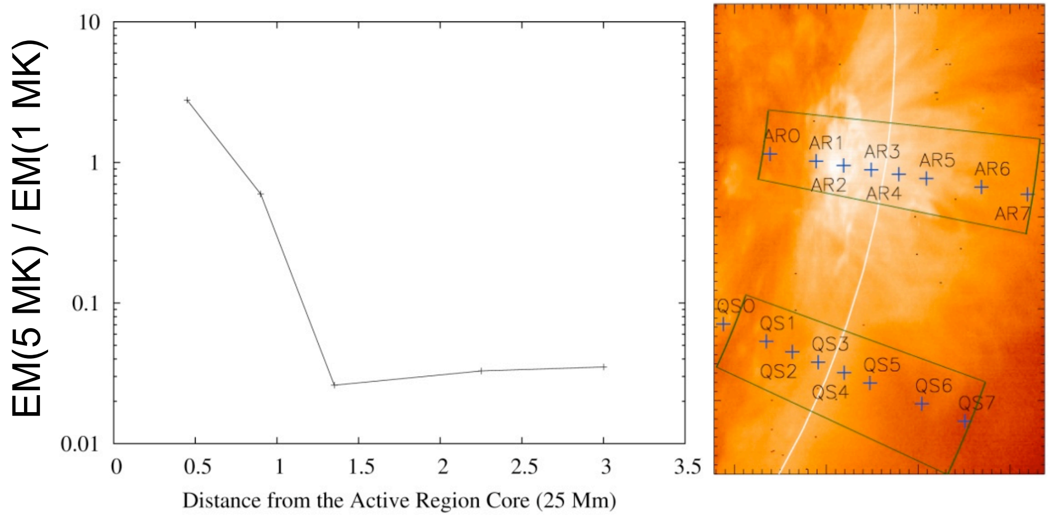






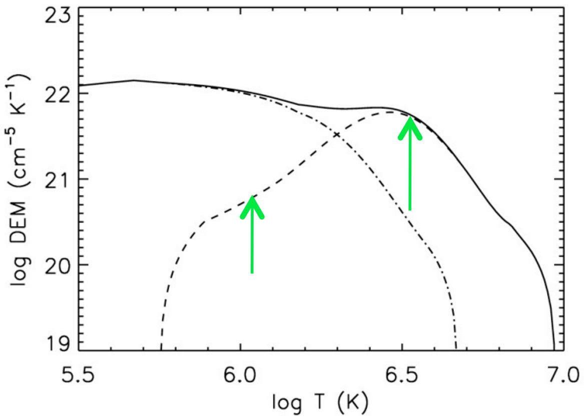
Hot / Warm Emission Ratios



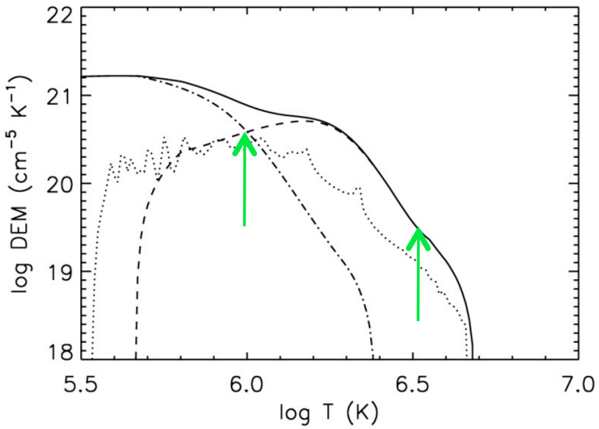


O'Dwyer, Mason, et al. (2010)

Strong Nanoflares



Weak Nanoflares



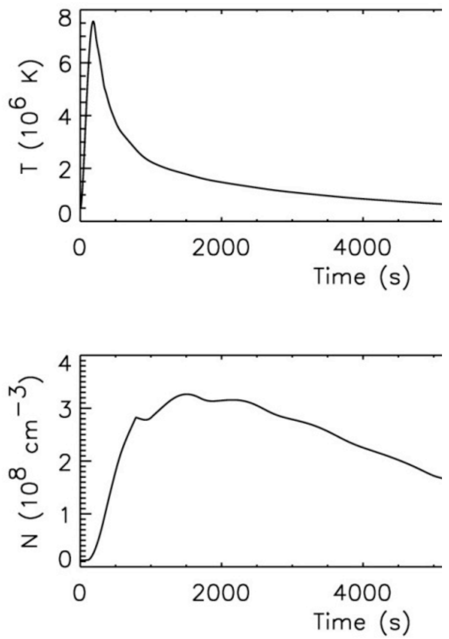
Klimchuk et al. (2008)

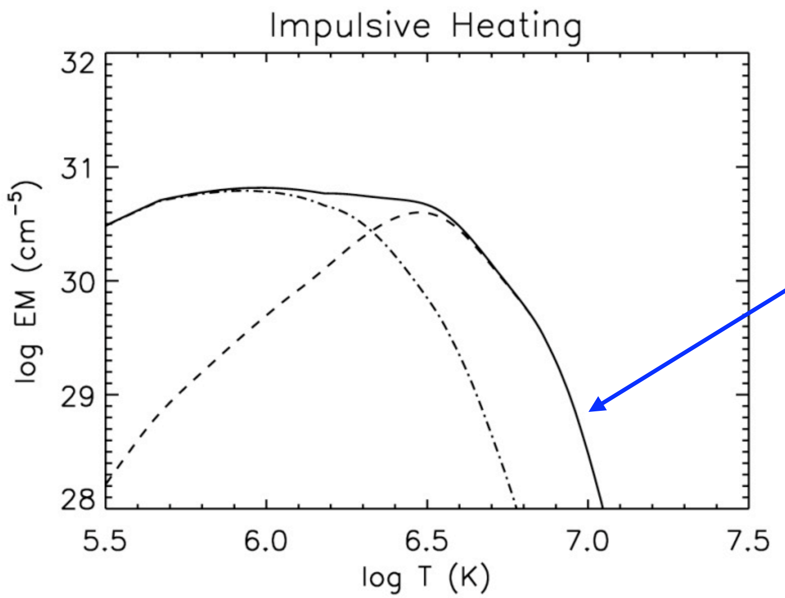
dash: corona, dot-dash: footpoints, solid: combined

Very Hot (> 4 MK) Plasma

Expected to be very faint:

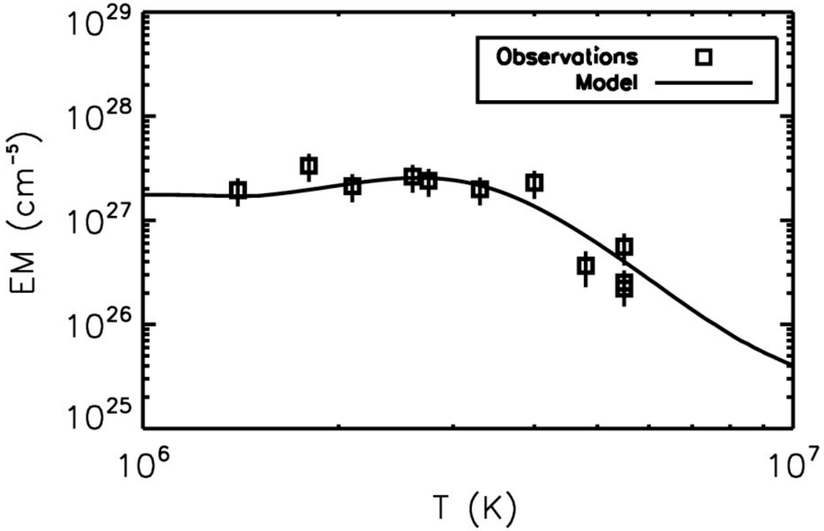
- Short lived (rapid cooling)
- Small density and EM (little time for evaporation)
- Ionization nonequilibrium (Steve Bradshaw talk)

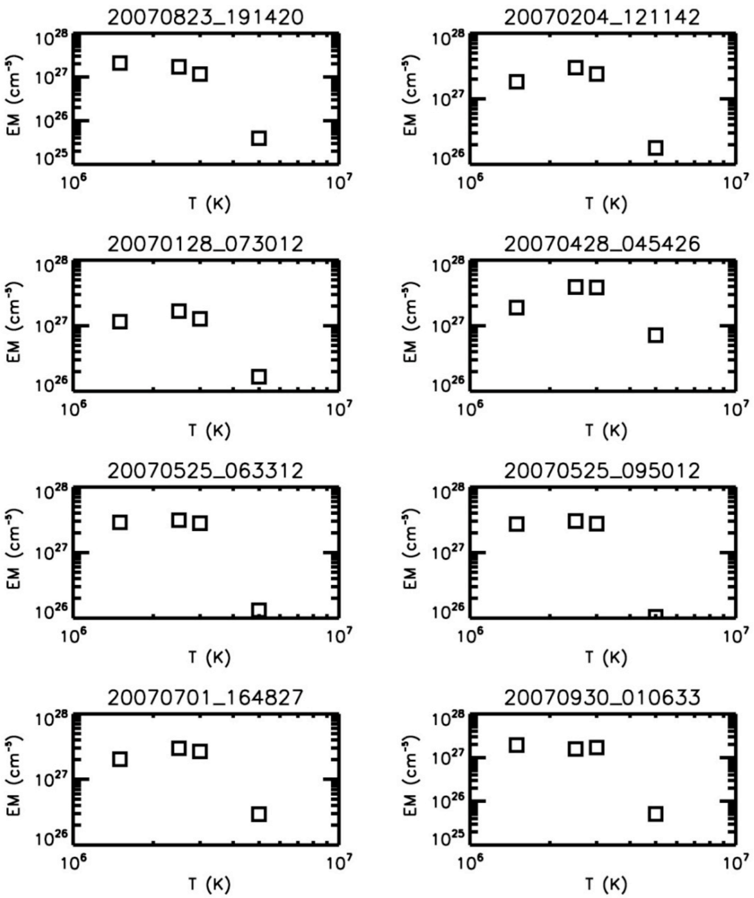




Faint very hot emission

Active Region EM(T)

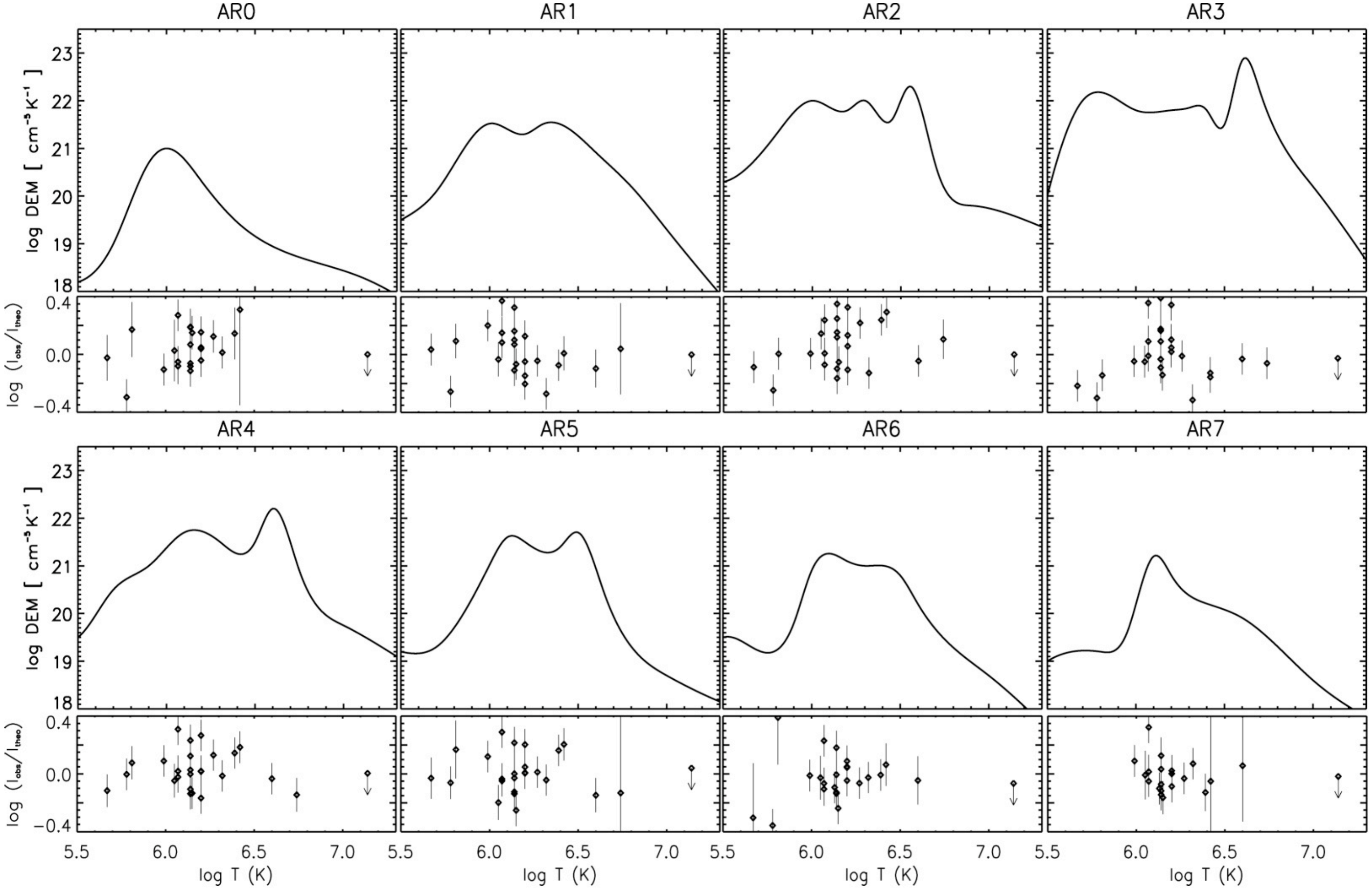




Fe XII, Fe XV, Ni XVII, Fe XVII

Patsourakos & Klimchuk (2008)

Active Region DEM(T)

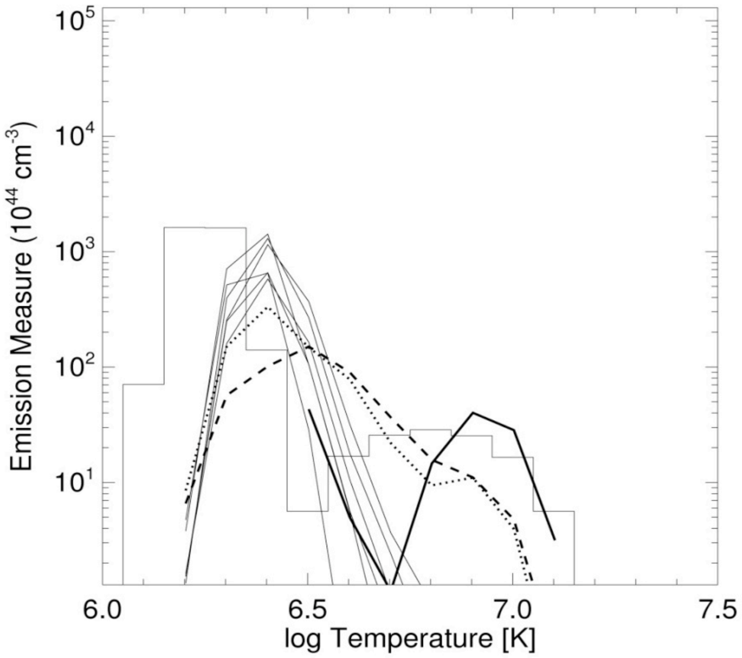


EM(T) = T x DEM(T)

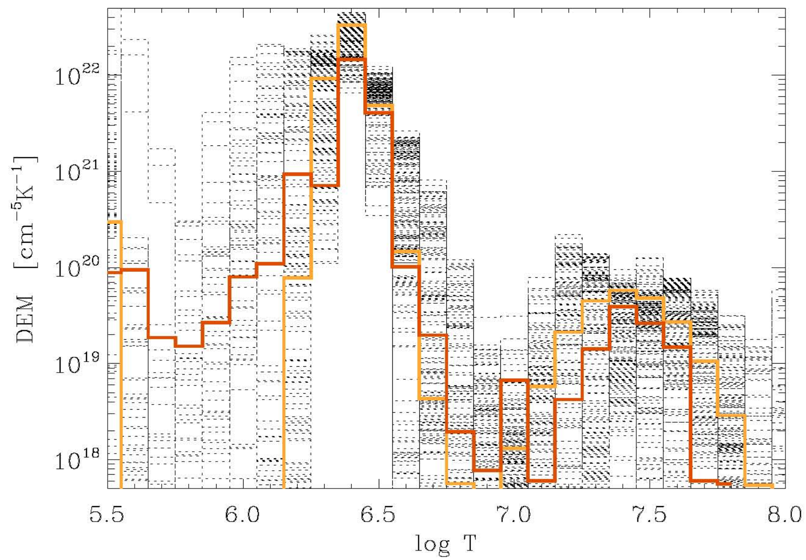
O'Dwyer, Mason, et al. (2010)

Super Hot (~10 MK) Plasma

Hinode / XRT



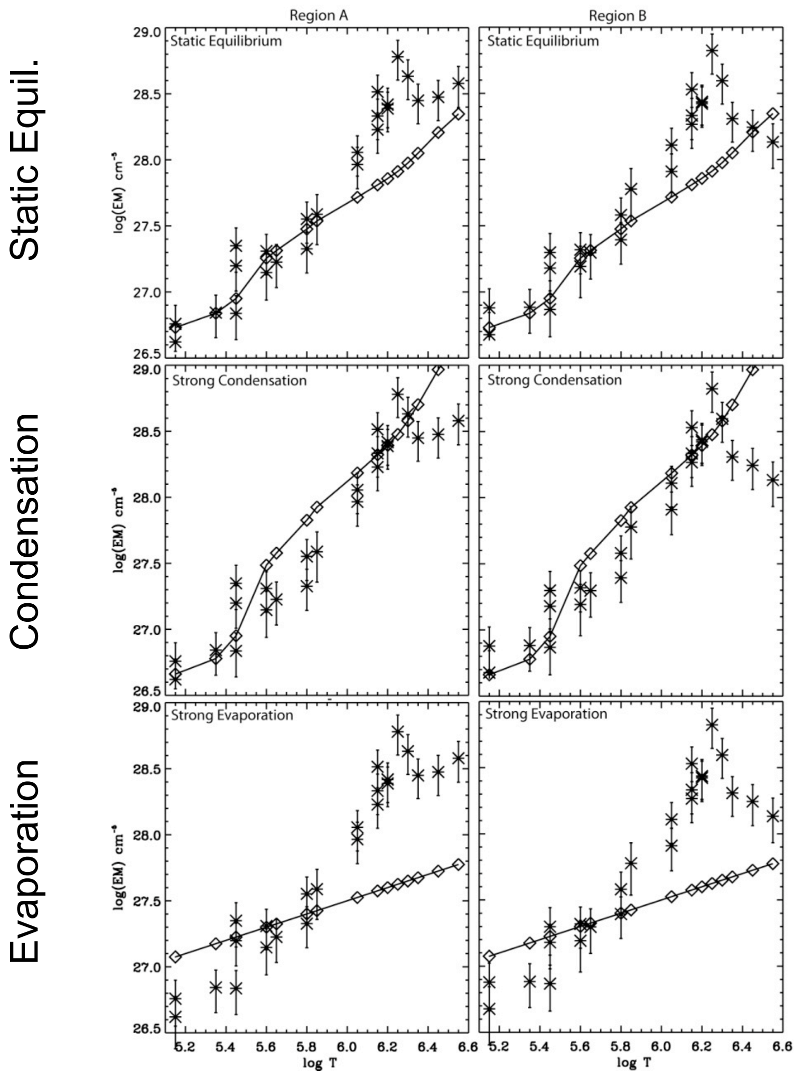
Reale et al. (2009)

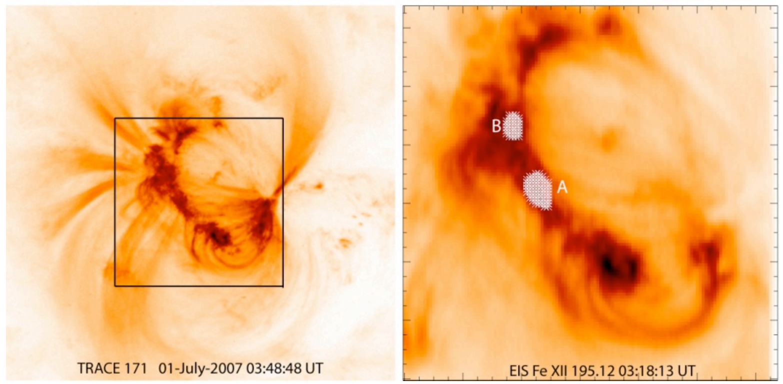


Schmelz et al. (2009)

CORONAS-F (Zhitnik et al. 2006; Sylwester et al. 2010)
RHESSI (McTiernan 2008; Reale et al. 2009)
XRT (Siarkowski et al. 2008)

Active Region Moss (Transition Region)





$$EM_{se} \propto P\,\Lambda(T)^{-1/2}\,T^{3/4}$$

$$EM_{con} \propto J\,\Lambda(T)^{-1}\,T$$

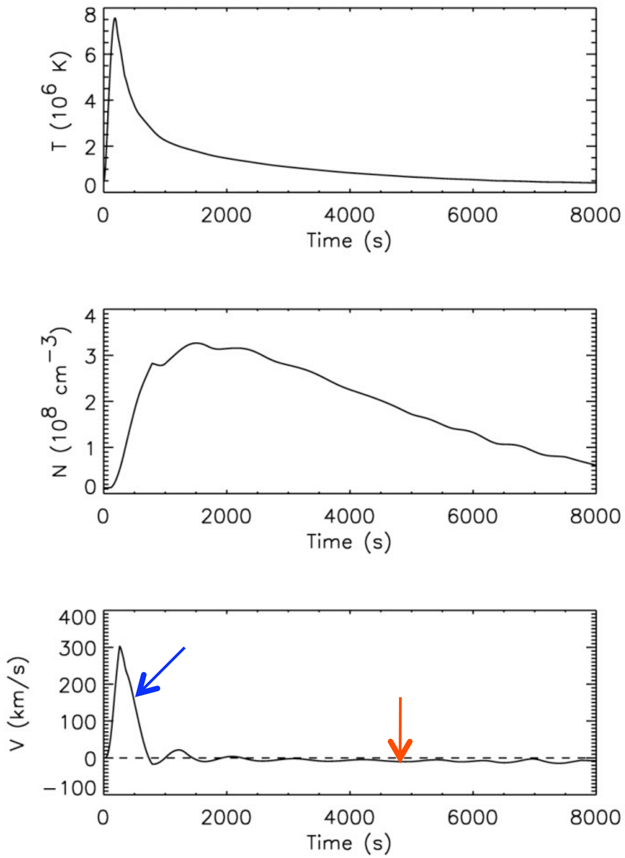
$$EM_{ev} \propto P^2\,J^{-1}\,T^{1/2}\,,$$

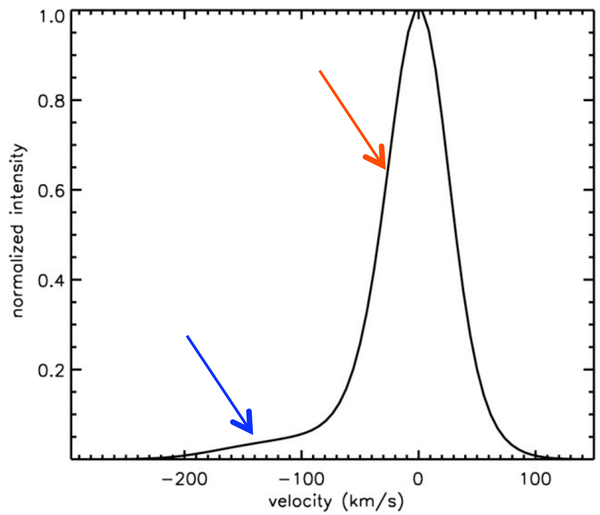
P = pressure
J = mass flux
Λ(T) = rad. loss fctn.

Tripathi, Mason, & Klimchuk (2010)

Flows

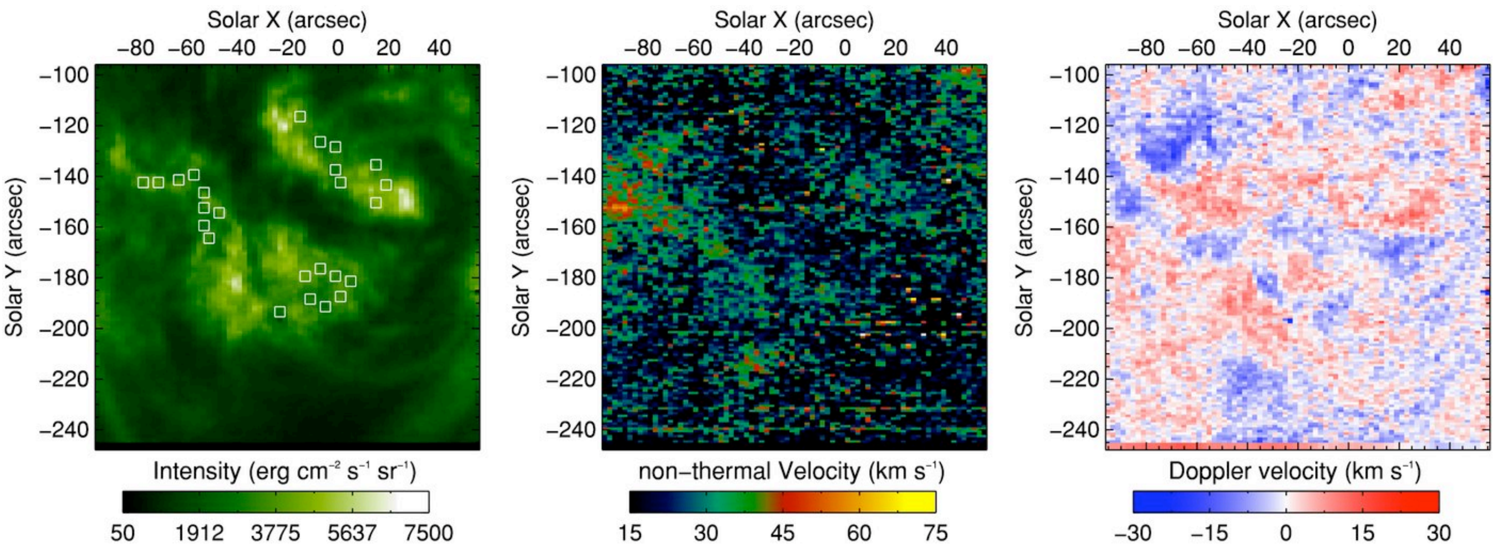
1. Evaporation phase: fast, faint upflows
2. Draining / condensation phase: slow, bright downflows



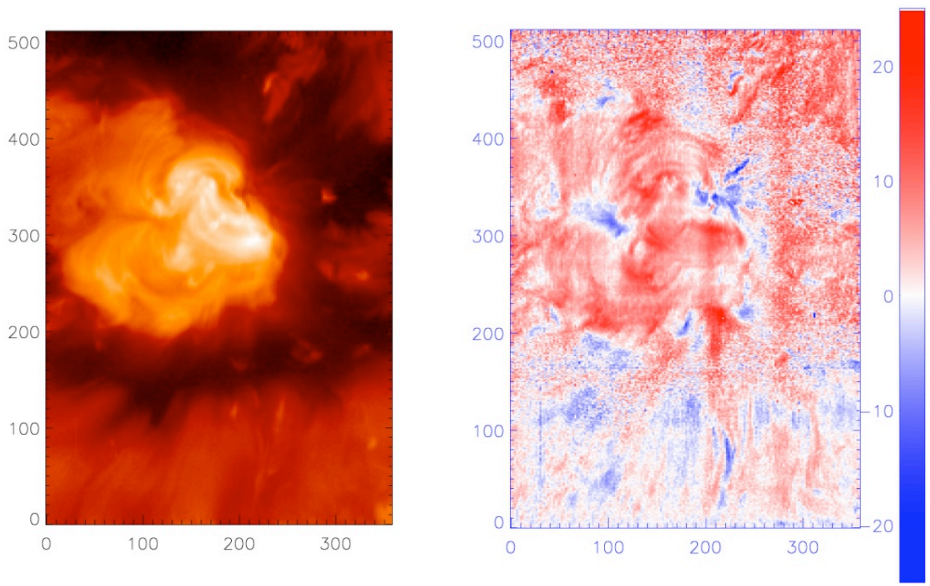


Line core Doppler shifts and blue wing enhancements are temperature (line) dependent

Fe XII (195) Doppler Shifts



Brooks & Warren (2009)



Tripathi & Mason
(preliminary results)

also Del Zanna (2008)

C IV (1548) Doppler Shifts

C IV
Lt. -- red
Dk.-- blue

Mag.

H_α

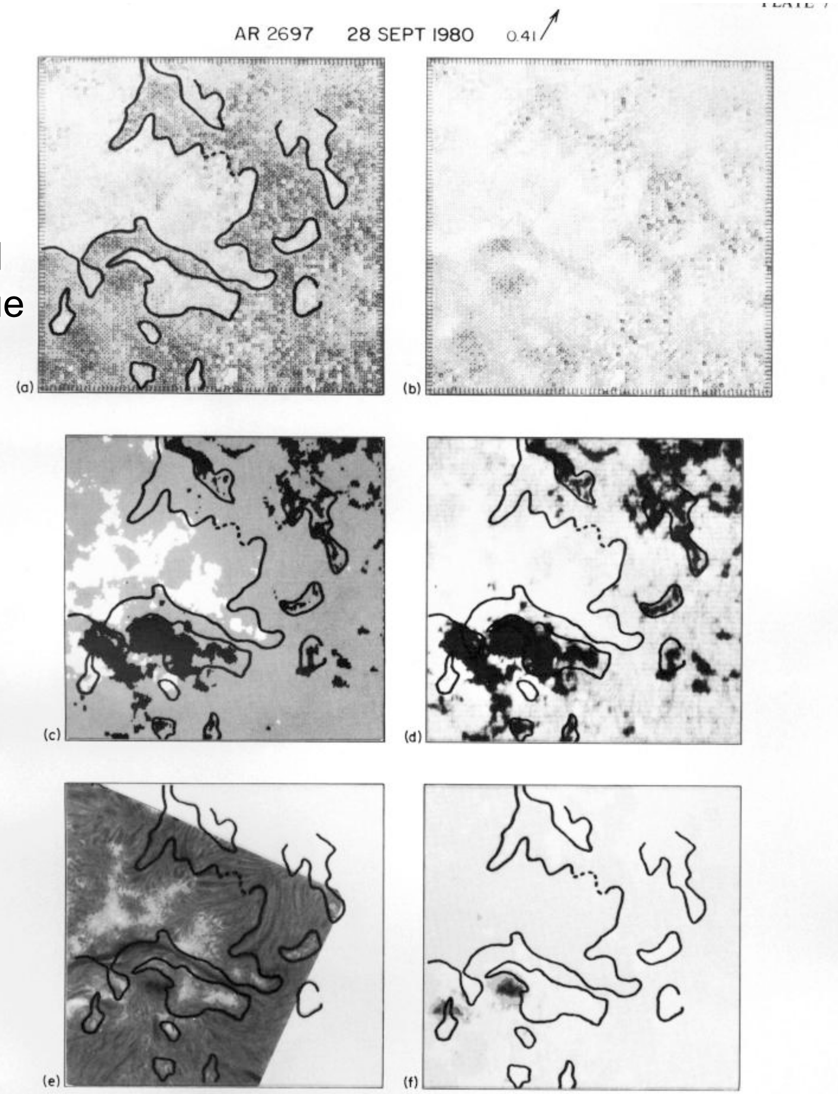


FIG. 5.—As in Fig. 1, but for Active Region No. 2697, observed on 1980 September 28. Times of the observations are as follows: (*a*) and (*b*), 16:10 UT; (*c*), (*d*), and (*f*), 15:46 UT; (*e*) 17:30 UT.

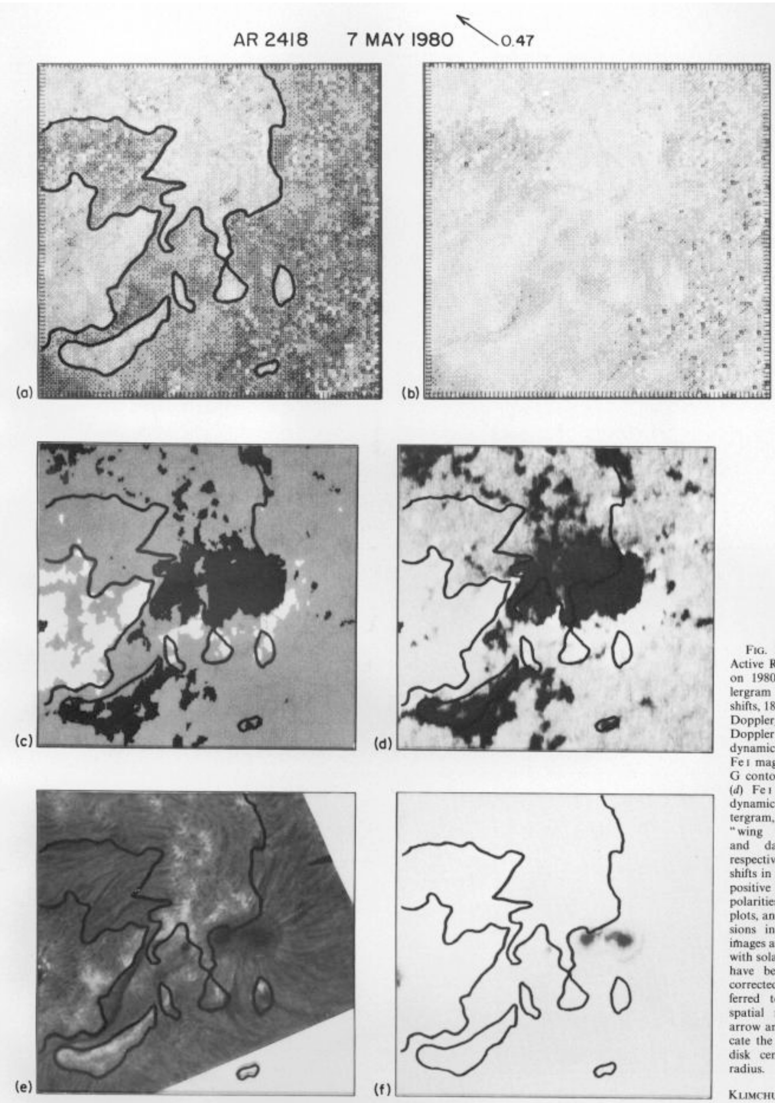


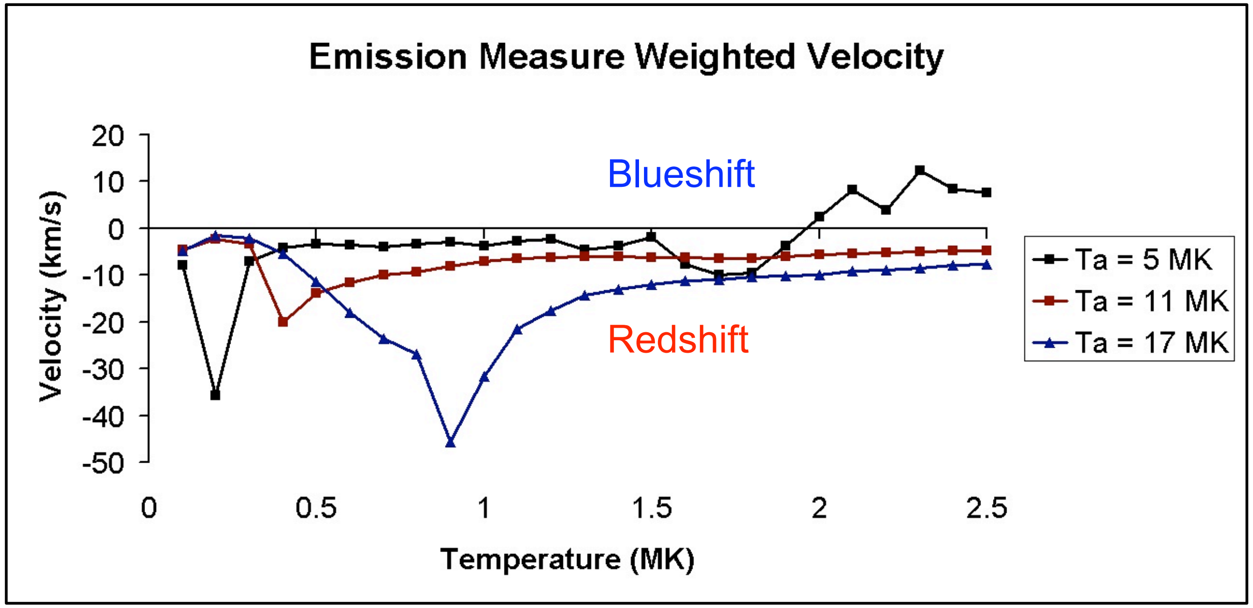
FIG. 1.—Six coaligned images of Active Region No. 2418, observed on 1980 May 7: (*a*) C IV Dopplergram showing relative Doppler shifts, 18:02 UT; (*b*) calibrated C IV Dopplergram showing absolute Doppler shifts (±30 km s^{-1} dynamic range, black to white); (*c*) Fe I magnetic contour plot (±100 G contours indicated), 16:01 UT; (*d*) Fe I magnetogram (±100 G dynamic range); (*e*) on-band Hα filtergram, 19:04 UT; and (*f*) Fe I "wing spectroheliogram." Light and dark shades correspond, respectively, to redshifts and blueshifts in the Dopplergram plots, to positive and negative line-of-sight polarities in the magnetogram plots, and to bright and faint emissions in the intensity plots. All images are 4′ on a side and oriented with solar north to the top. V_0 lines have been traced on the time-corrected Dopplergram and transferred to the other images for spatial reference (see text). The arrow and number at the top indicate the direction and distance to disk center in units of a solar radius.

KLIMCHUK (*see* **323**, 369)

Relative Doppler shift ~ 20 km/s

Klimchuk (1987)

Nanoflare "Doppler Shifts"

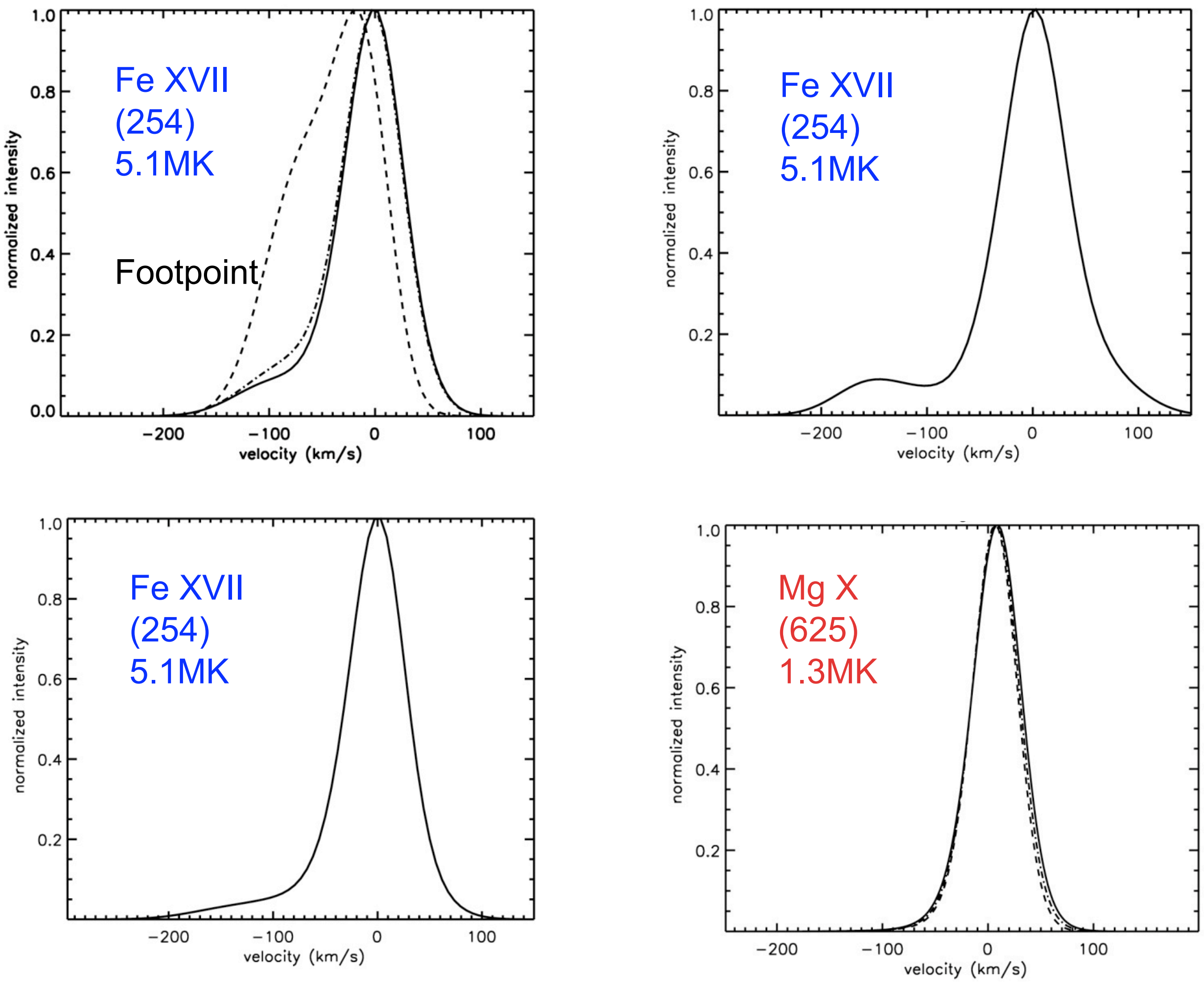


Nanoflares

Weak
Intermediate
Strong

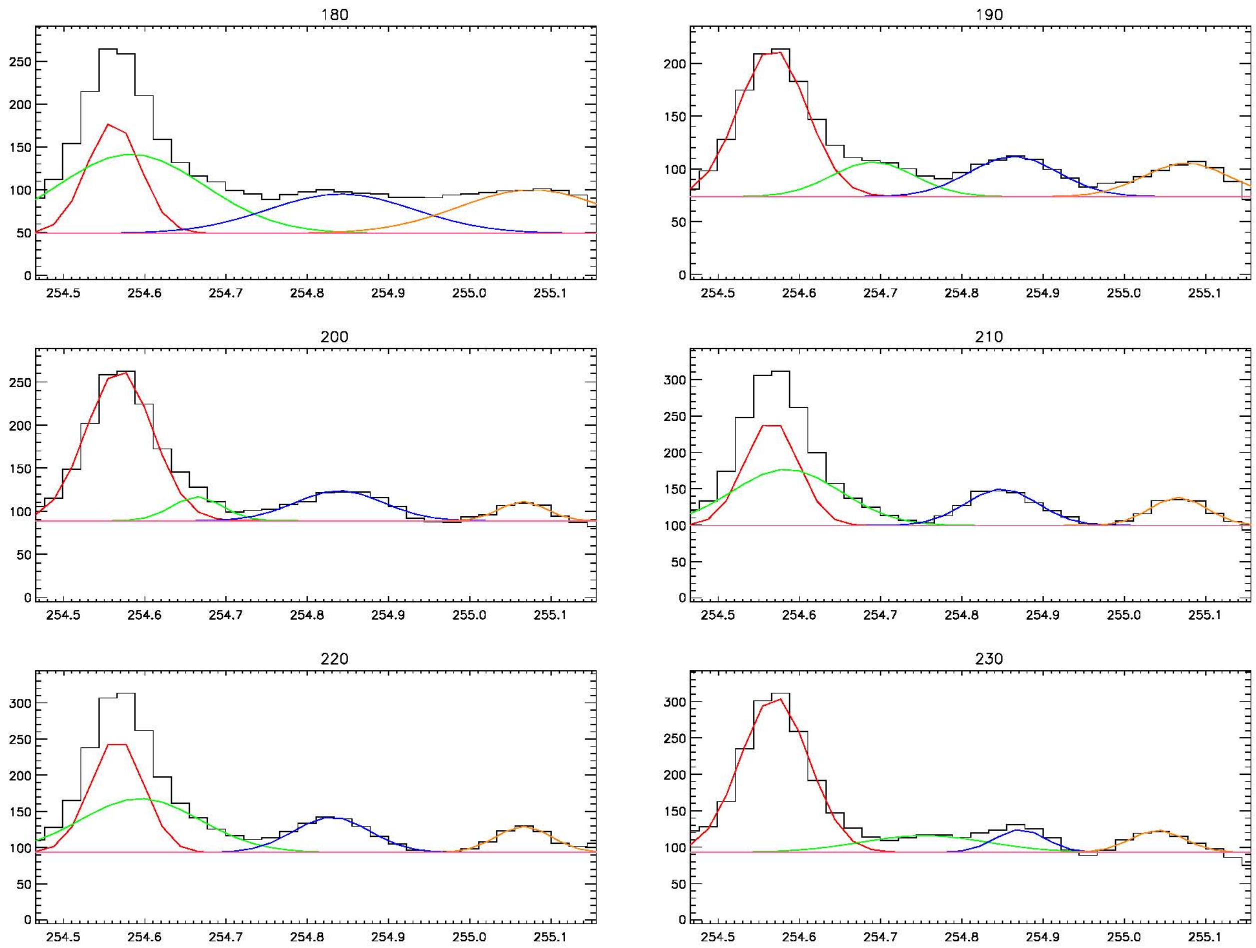
Steve Bradshaw's HYDRAD simulations

Simulated Line Profiles

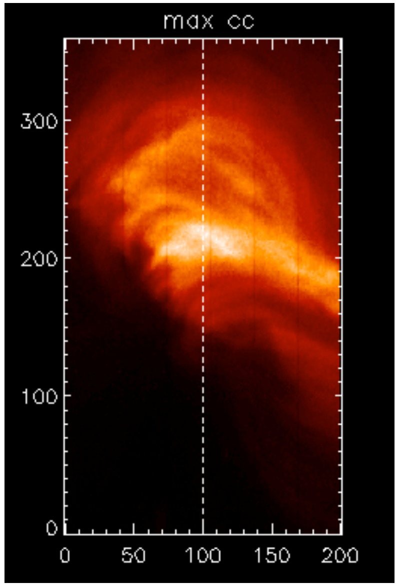


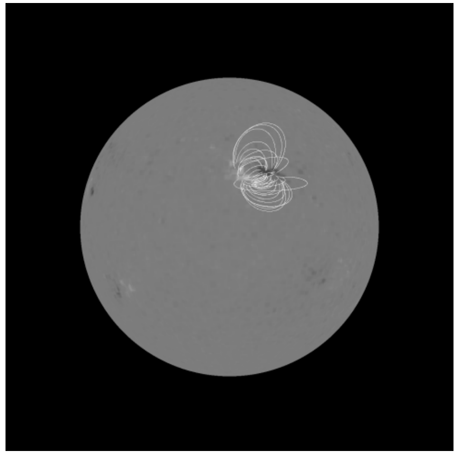
Patsourakos & Klimchuk (2006)

Fe XVII 254 (Hinode EIS)



2010 April 26

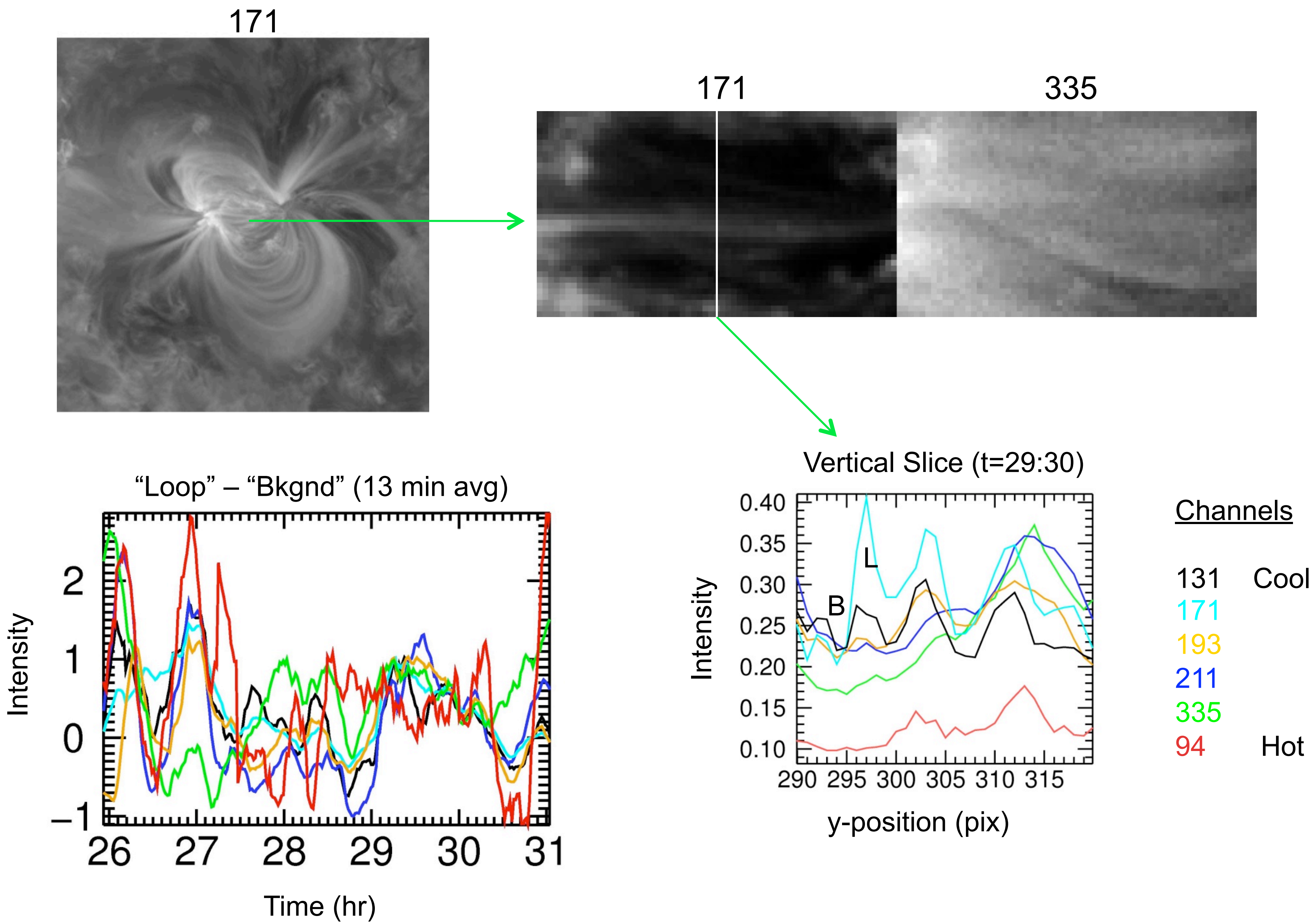




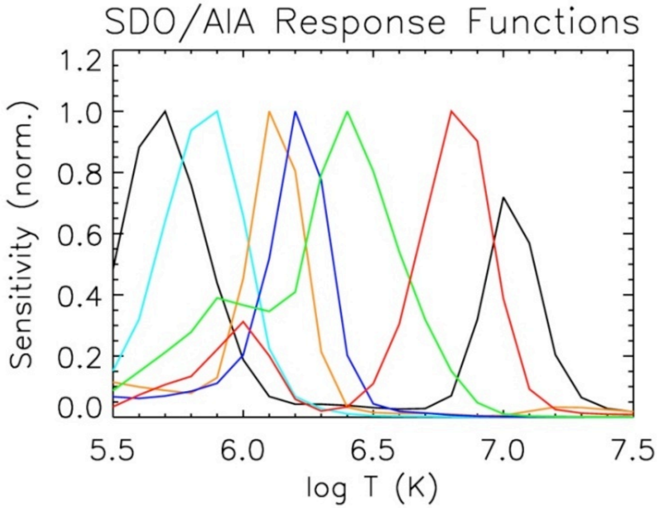
254.59 possibly Fe XI
254.71 ? (possibly cooler)
254.87 Fe XVII
255.06 S X

Study with S. Patsourakos and P. Young

Observed Light Curves

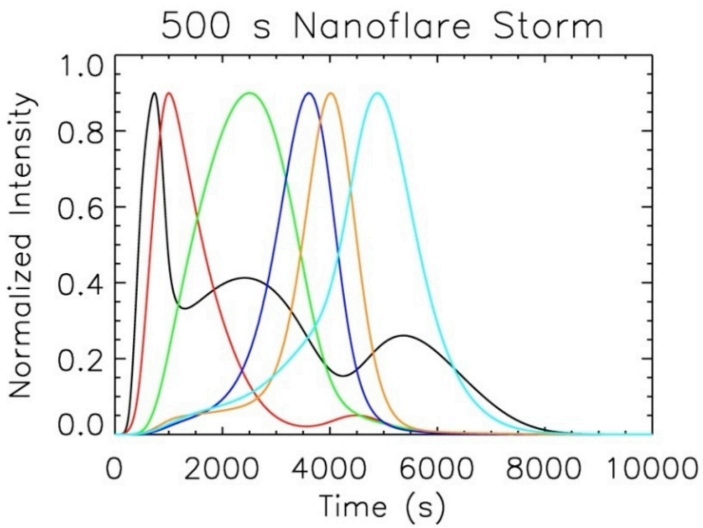


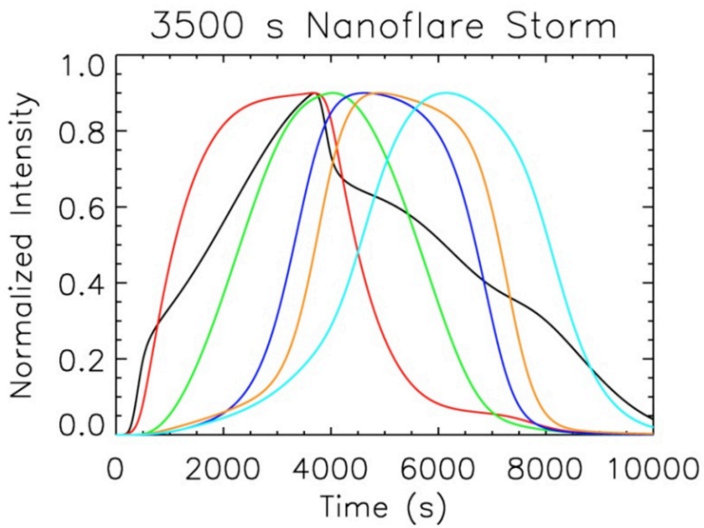
Simulated Light Curves



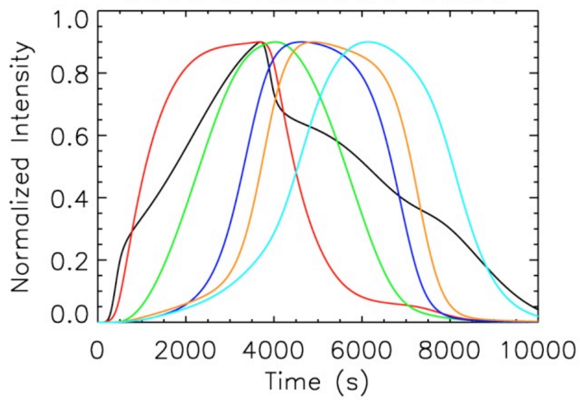
<u>Channels</u>

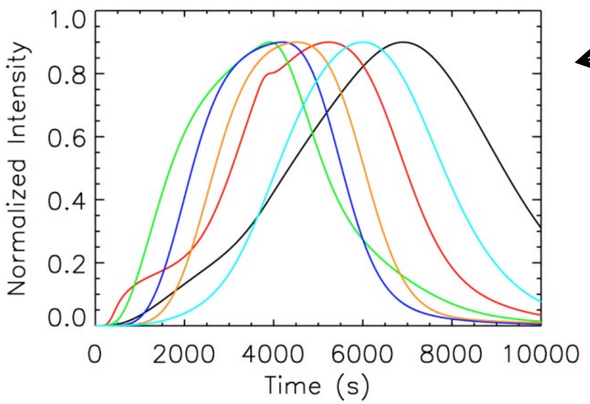
131 Cool
171
193
211
335
94 Hot

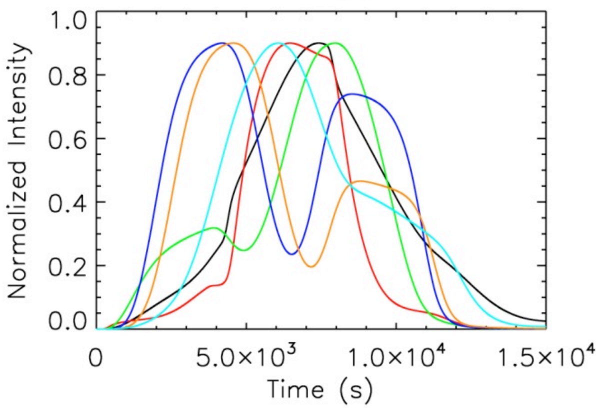




Simulated Light Curves

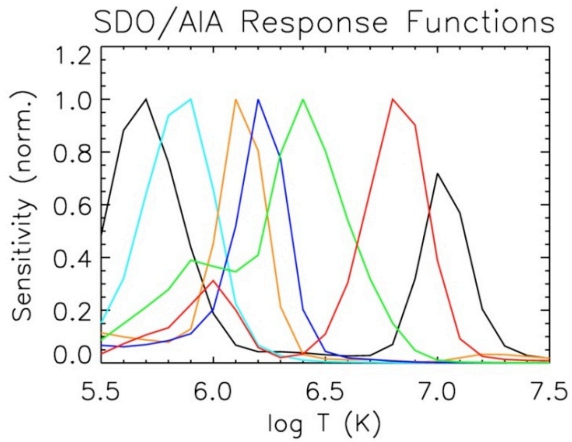






<u>Nanoflare Storms</u>

Strong nanoflares	94	131	335	211	193	171
Weak nanoflares	335	211	193	94	171	131
Weak, then strong	211	193	171	94	131	335



Summary

- Most emission comes from a diffuse component, not distinct loops
- Spectroscopy is crucial for diagnosing unresolved structure and understanding coronal heating
- Active region cores may be heated by nanoflares
    - Some observations suggest this is likely

Summary

- Most emission comes from a diffuse component, not distinct loops
- Spectroscopy is crucial for diagnosing unresolved structure and understanding coronal heating
- Active region cores may be heated by nanoflares
  - Some observations suggest this is likely
- Helen Mason has made enormous contributions to solar physics, both in her research and in the scientists she has trained