The Evolution of Small Flares Observed with Hinode/EIS and SDO (AIA and EVE)

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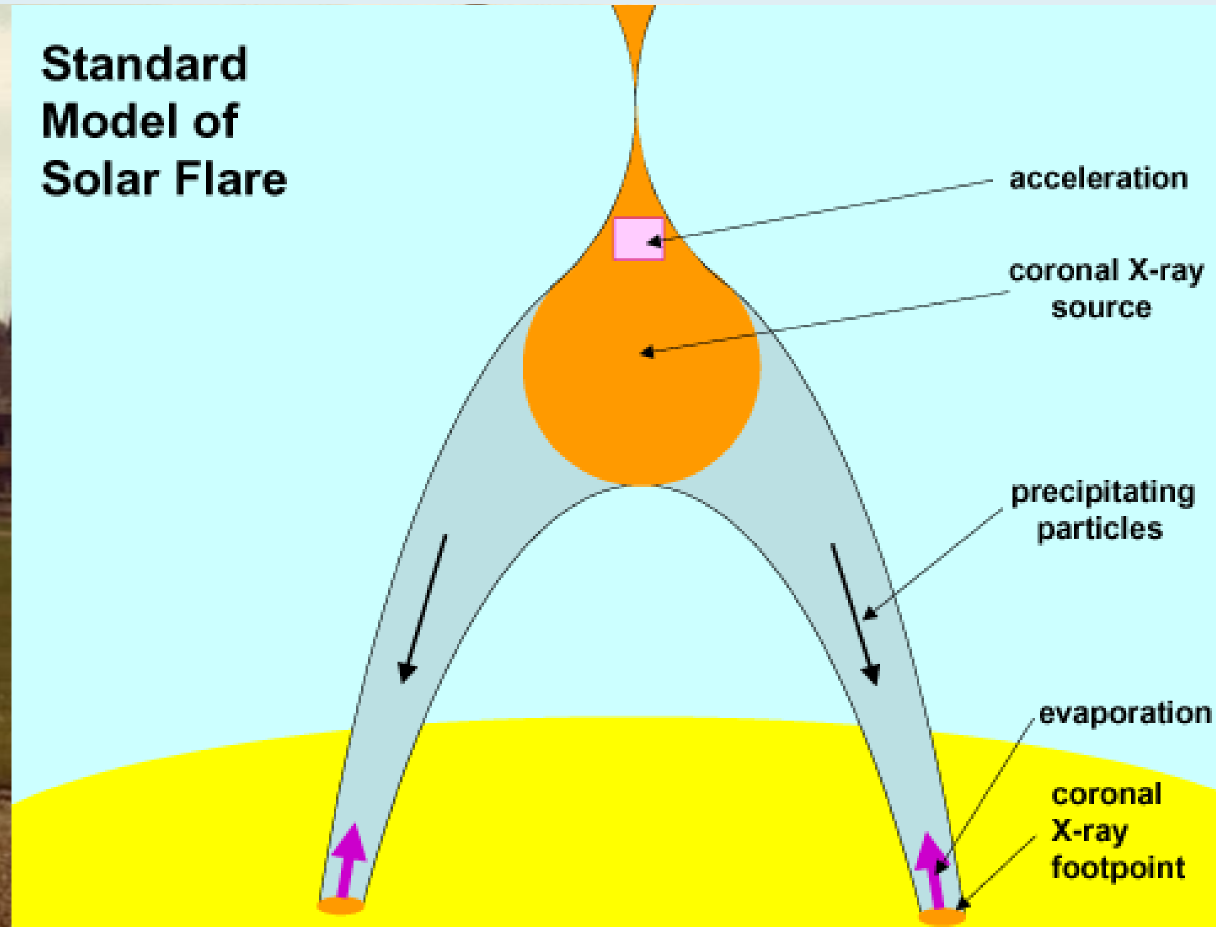
Plan of Talk

- Consider small (confined) flares
- Classes C, B and M
- Standard flare model
- Some early (pre-Hinode) results
- Spectroscopic results - Hinode/EIS
- + TRACE, SDO/EVE, HMI, AIA
- + RHESSI
- Comparisons with theoretical models
- Further work
- Summary

Solar Flares – the Skylab Era – 1970's

Doschek-san and I not only worked on solar flares, we actually wore flares!



Flares in the 1970's

Benz, 2008, Living Rev. Sol. Phys

Dere, Mason, Widing &Bhatia (1979) Skylab NRLA

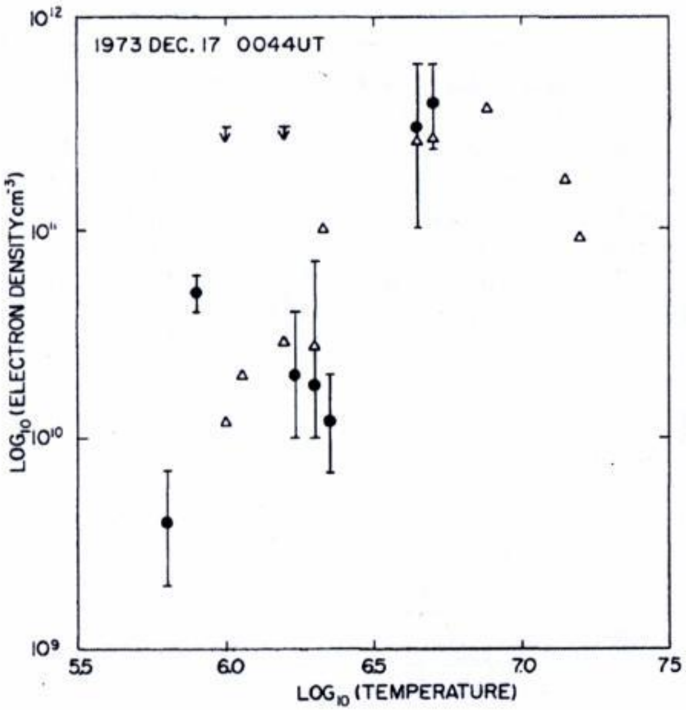


FIG. 13.—Electron density as a function of electron temperature for the 1973 December 17 flare. For meaning of symbols, see Fig. 12.

Skylab – NRL S082A
Overlap-ogram, up to 1" spatial resoluton
Excellent spectra for a small compact flares eg 1973 Dec 17
Electron density – diagnostic ratios (filled circles) and EM/volume (triangles)

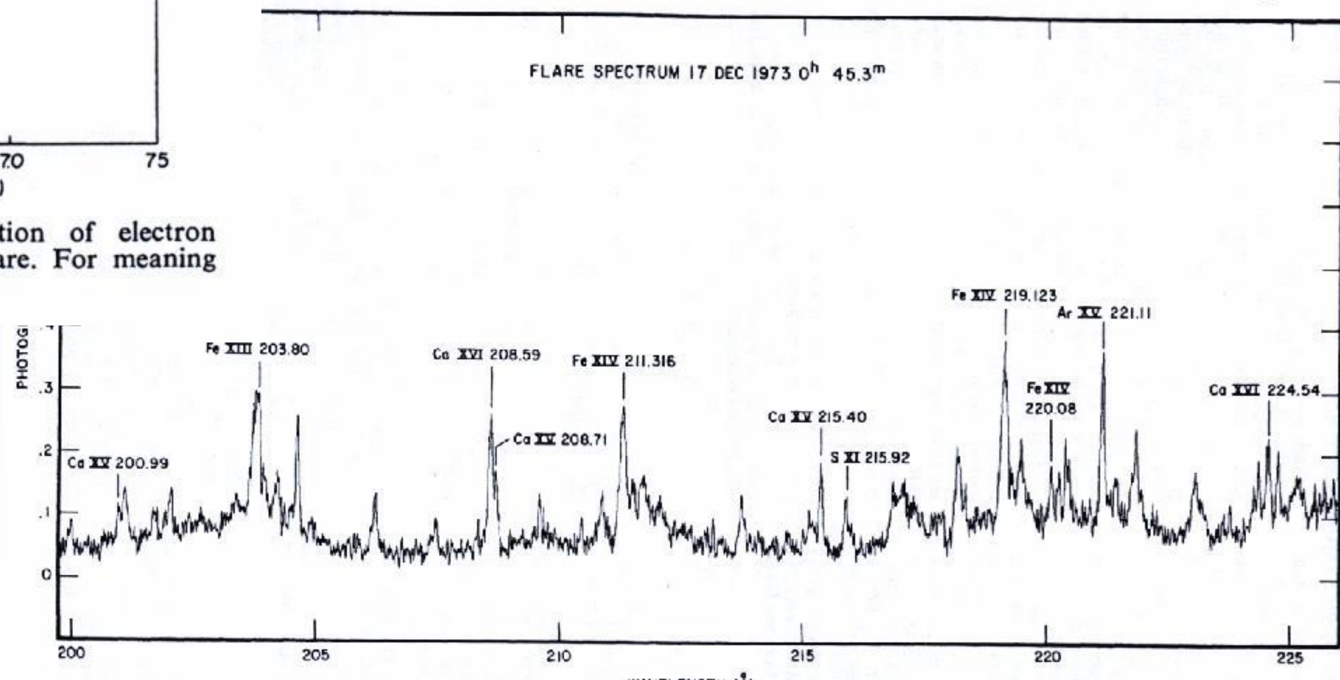


FIG. 3.—A portion of a microdensitometer tracing from a solar XUV spectroheliogram of the 1973 December 17 flare for the wavelength region 200–225 Å

Feldman, Doschek, Behring and Phillips (1996)

YOHKOH – 868 flares - Peak Temperature versus X-ray class

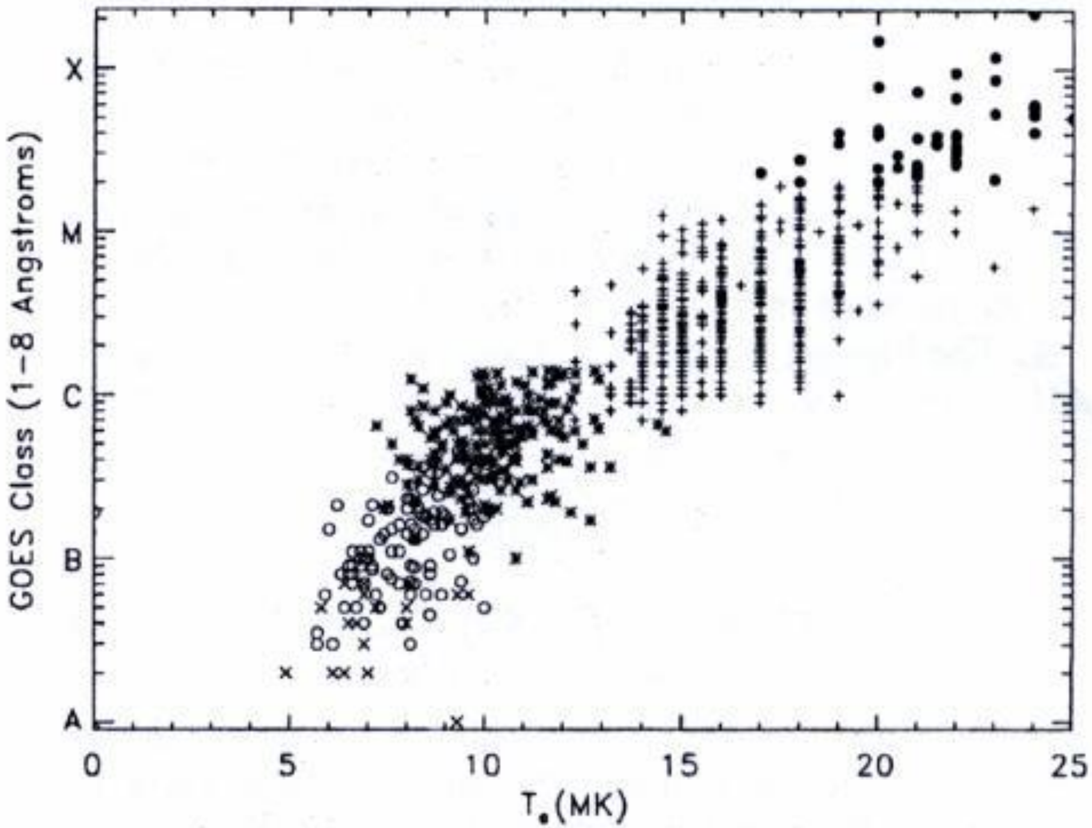
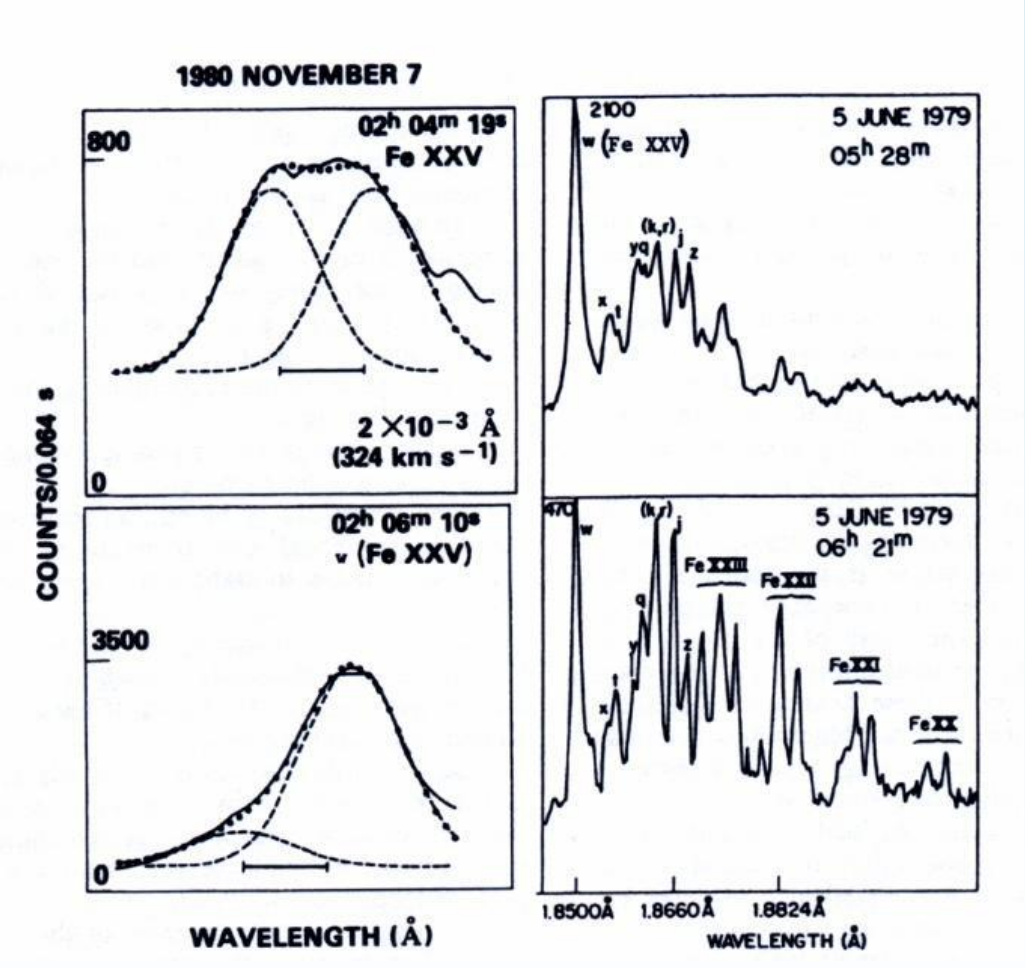
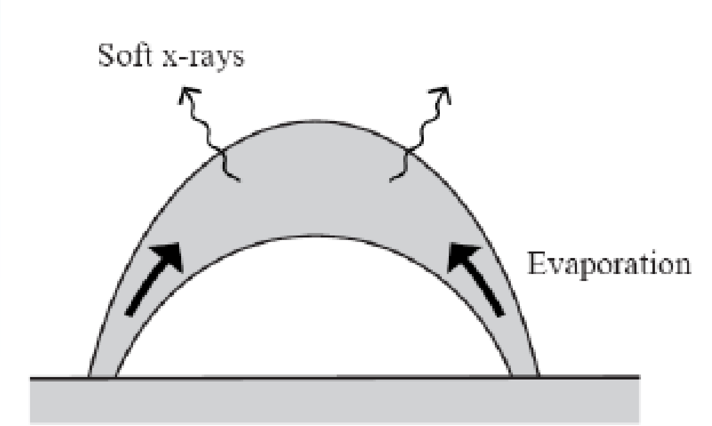


FIG. 6.—A display of the X-ray class from the *GOES* 1–8 Å detector vs. peak electron temperature. (The associations between X-ray classes and fluxes are as follows: A1 ⇒ 1×10^{-8} W m^{-2}, B1 ⇒ 1×10^{-7} W m^{-2}, C1 ⇒ 1×10^{-6} W m^{-2}, M1 ⇒ 1×10^{-5} W m^{-2}, X1 ⇒ 1×10^{-4} W m^{-2}, X10 ⇒ 1×10^{-3} W m^{-2}. Flares marked by filled circles have X-ray magnitudes of M2 or larger. They are from the study by Feldman et al. (1995b). During peak emission such flares saturate the BCS detectors. For the rest of the symbols see Fig. 5.)

Doschek (1990) – Chromospheric Evaporation ?

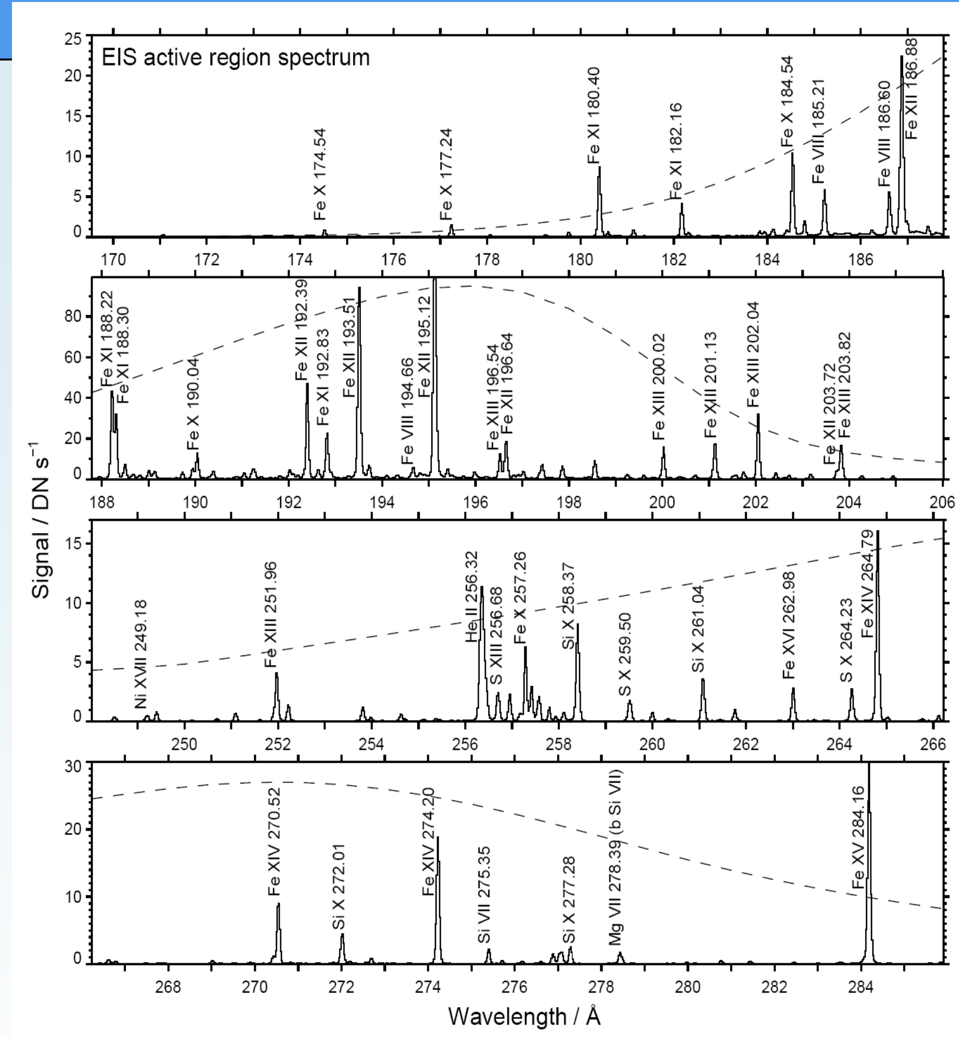
- Blue-shifts in high temperature flare lines were seen with X-ray spectrometers
- However, it was not possible to know where this blue-shifted emission came from.
- SMM/UVSP – FeXXI - Mason, Shine, Gurman and Harrison (1986) spatially located during impulsive phase of flares.
- SoHO/CDS – FeXIX, several authors
- Chromosphere heated by non-thermal particles/ conduction fronts
- 'gentle' evaporation
- 'explosive' evaporation

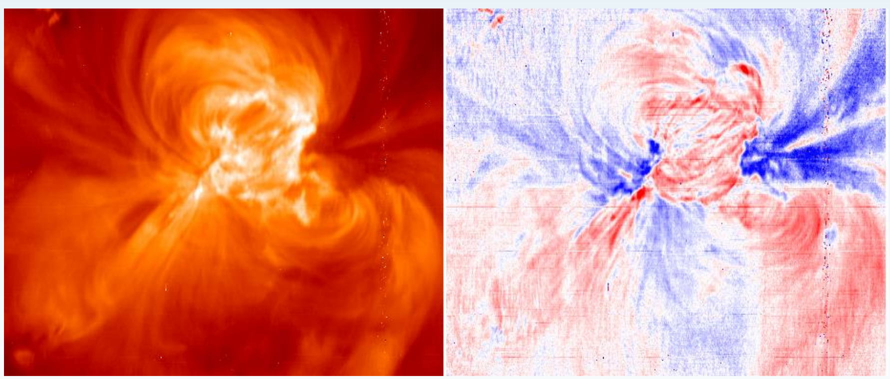




Hinode/EIS

Hinode/EIS is rich in spectral lines and diagnostics
- Complex raster modes
Need: atomic data calculations
CHIANTI – Ken Dere, Peter Young, Enrico Landi, Giulio Del Zanna, Helen Mason

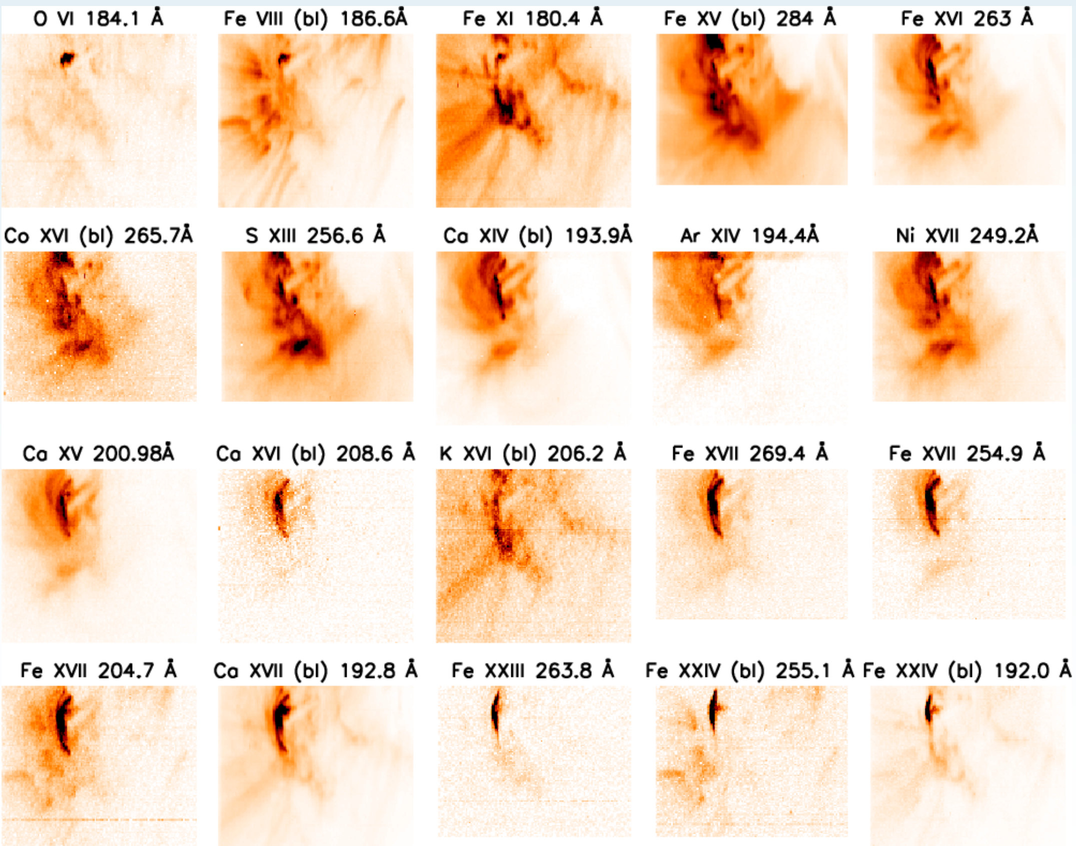


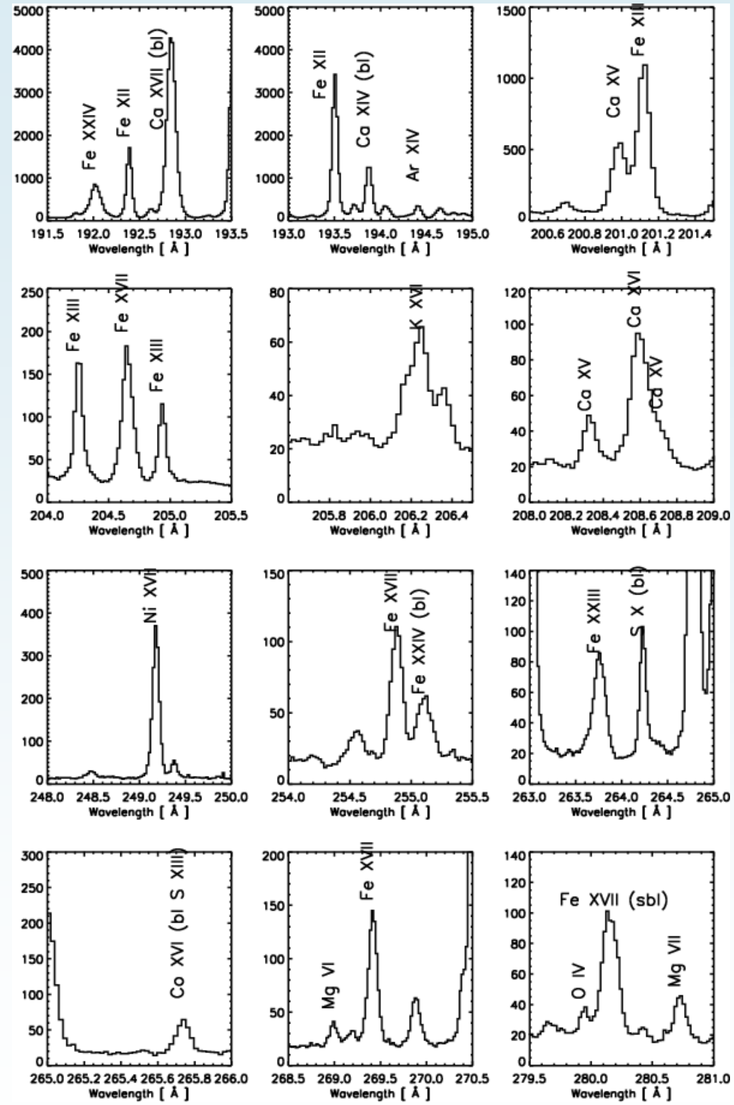


Intensity and flows (Doppler shifts) in Fe XII emission at 1MK

Small solar flare - Del Zanna, 2008

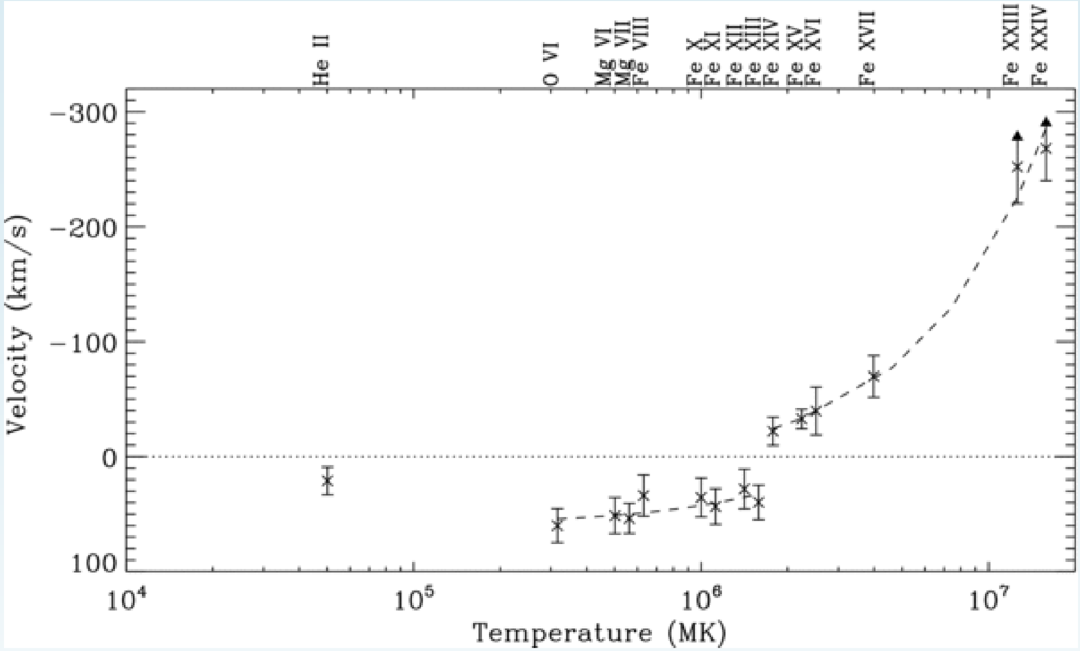
- **2007 June 2, Flare Class – B2**
- **EIS, Full spectral atlas**
- **Hot flare lines: FeXVII – Fe XXIV**
- **CaXV - CaXVII**

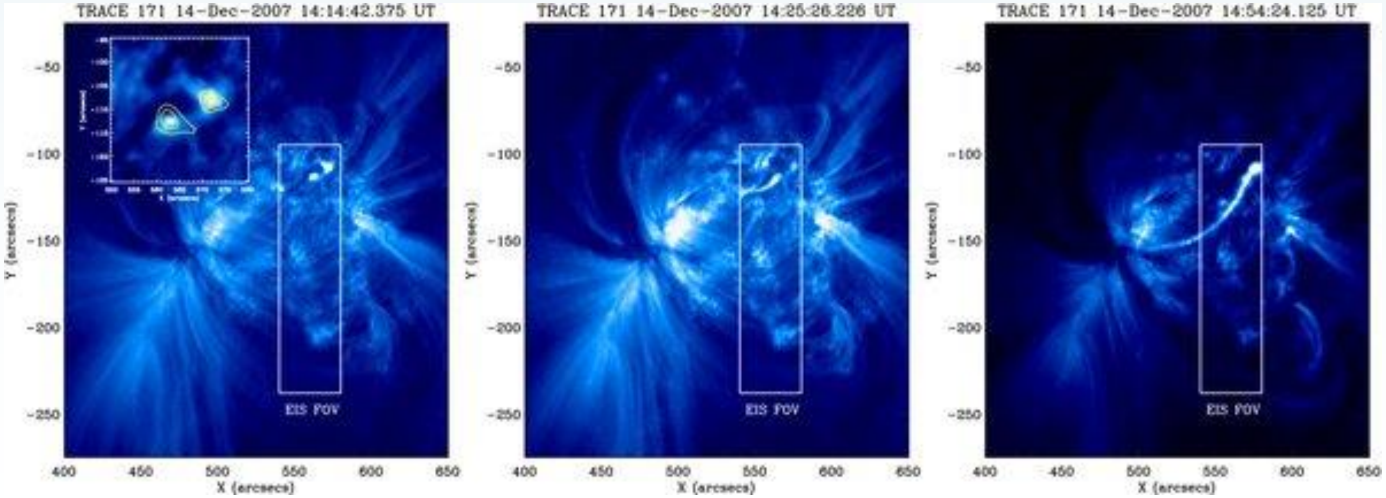




Milligan and Dennis (2009) – EIS with RHESSI

- 2007 December 14, Class C1.1
- EIS, 2” slit, 40” raster, about 4min to raster, several rasters
- Hinode + RHESSI
- Blue-shifts component up to 200km/s FeXIV-XXIV (2-16 MK) in flare ‘kernals’
- Red-shifts at lower temps
- Evidence for ‘explosive’ evaporation

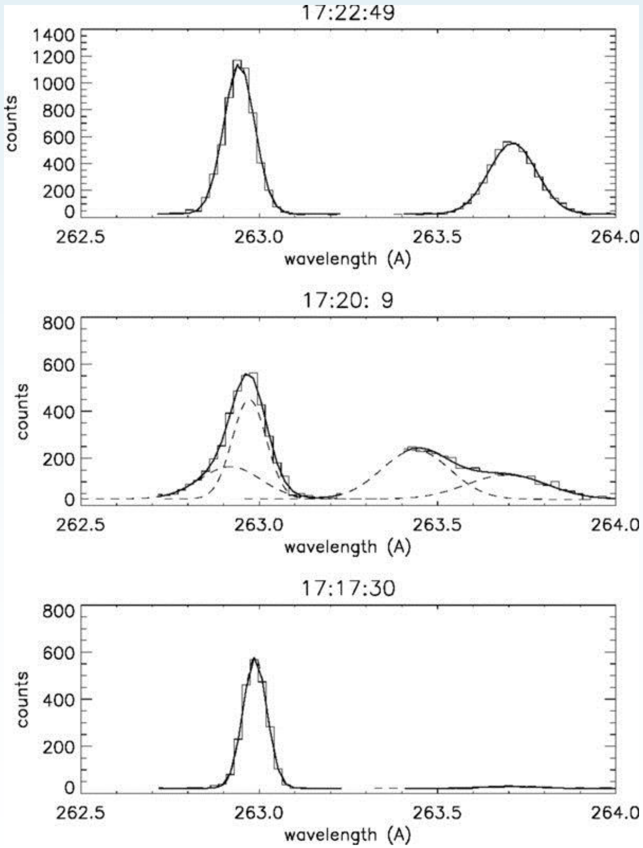


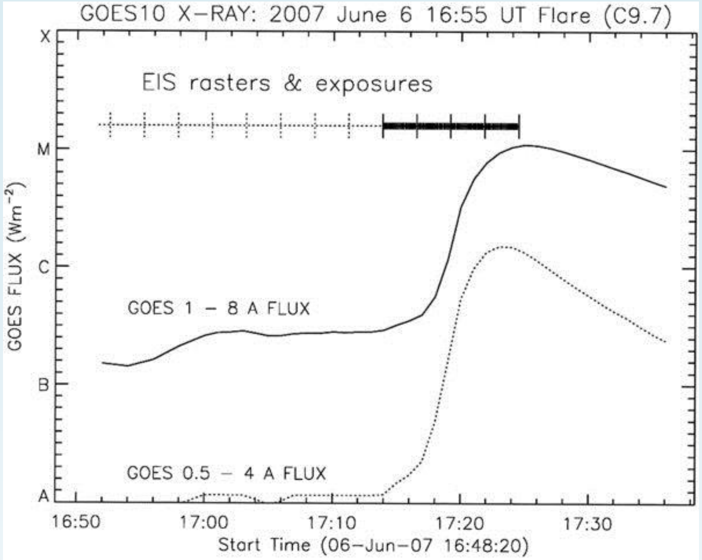


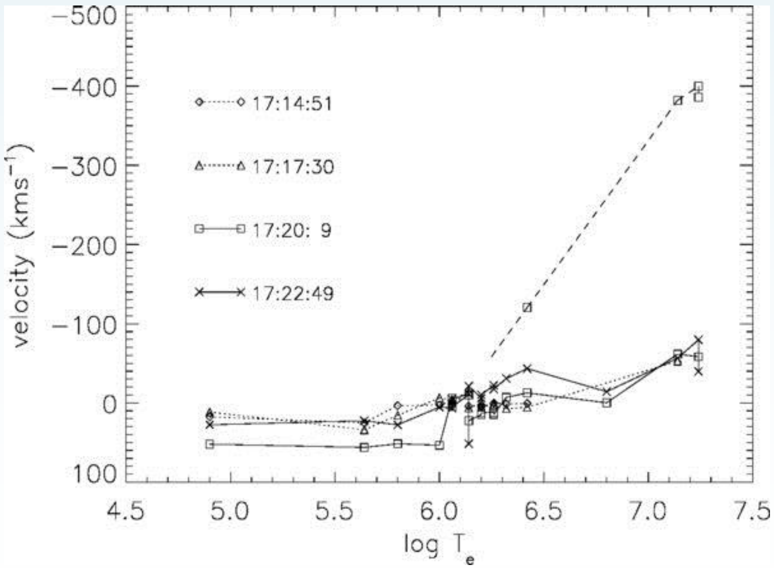
Watanabe, Hara, Sterling, Hara, 2010 - EIS

- **2007 June 6, C9.7/M1**
- **EIS, 1” slit, 240” raster, 160s to raster, sparse raster (10” steps)**
- **Caught rise phase**

Rise phase **FeXVI** **FeXXIII**





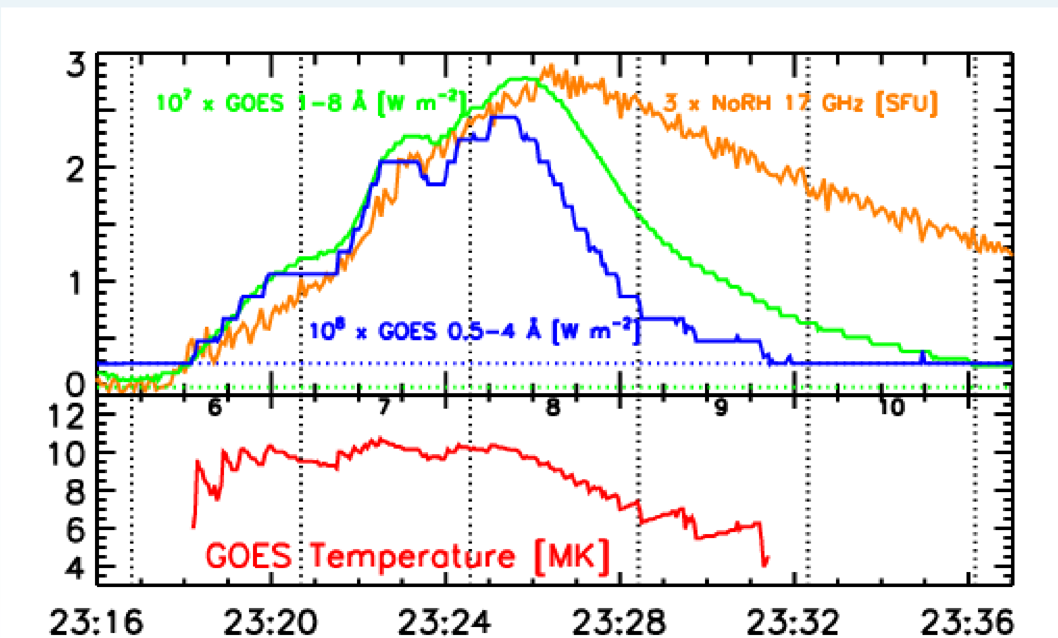


Blue-shifted component at high Te, FeXXIII – 380 km/s

Evidence for ‘explosive’ evaporation

Del Zanna, Mitra-Kraev, Bradshaw, Mason, Asai, 2011

- **2007 May 22**
- **Giulio's Birthday Flare!**
- **Flare Class –B2**
- **EIS, 2" slit, 40" raster, about 4min to raster, several rasters**
- **Hinode, TRACE, Nobeyama/radio**



3 MK Intensity

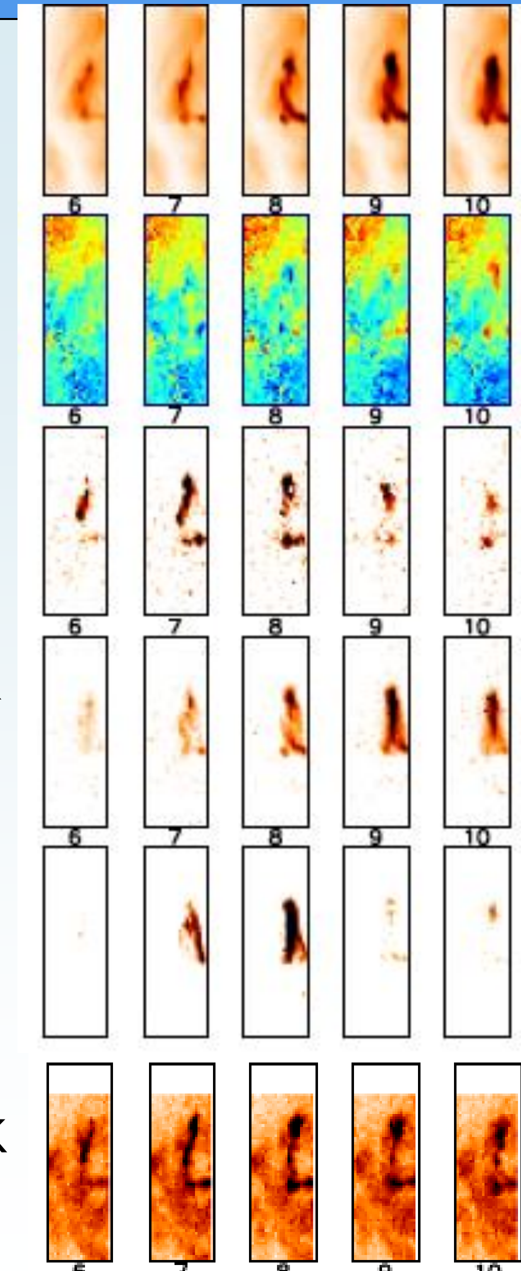
Doppler shift

Blue-wing intensity

5 MK

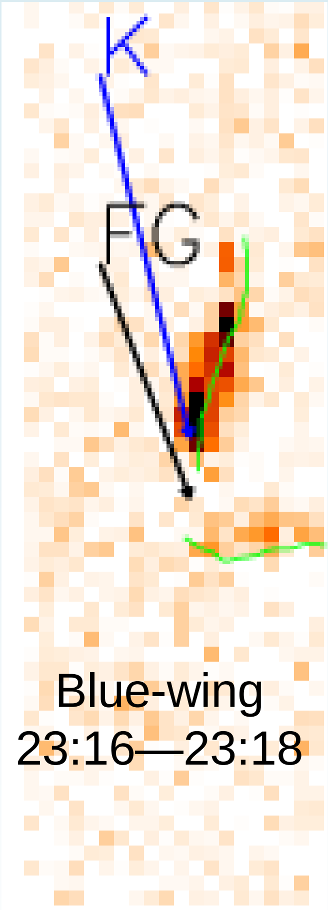
10 MK

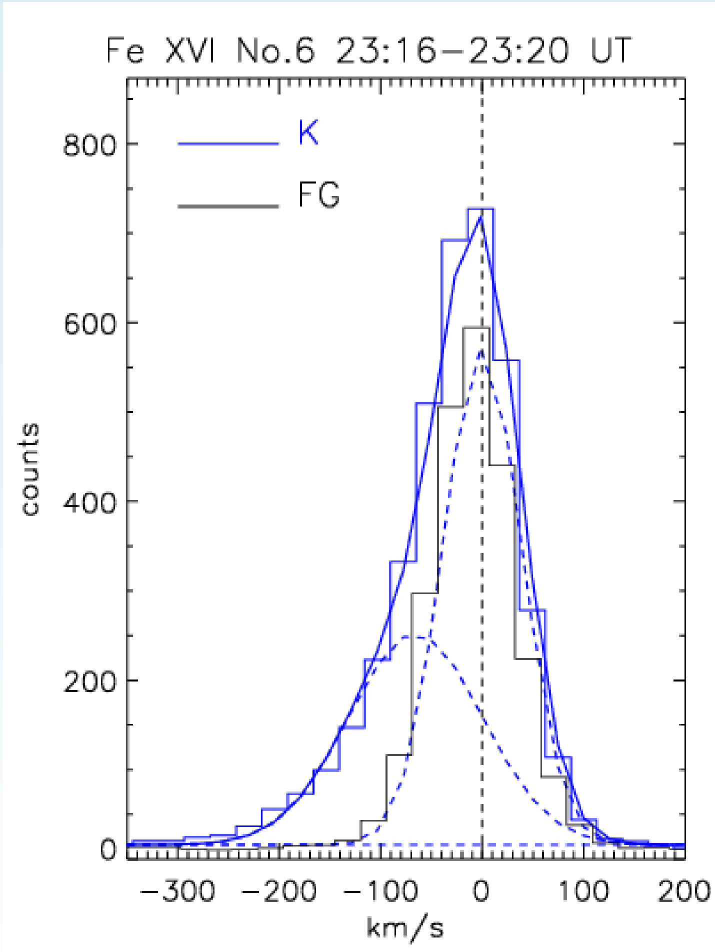
<1 MK



rise **peak** **decay**

Site of chromospheric evaporation



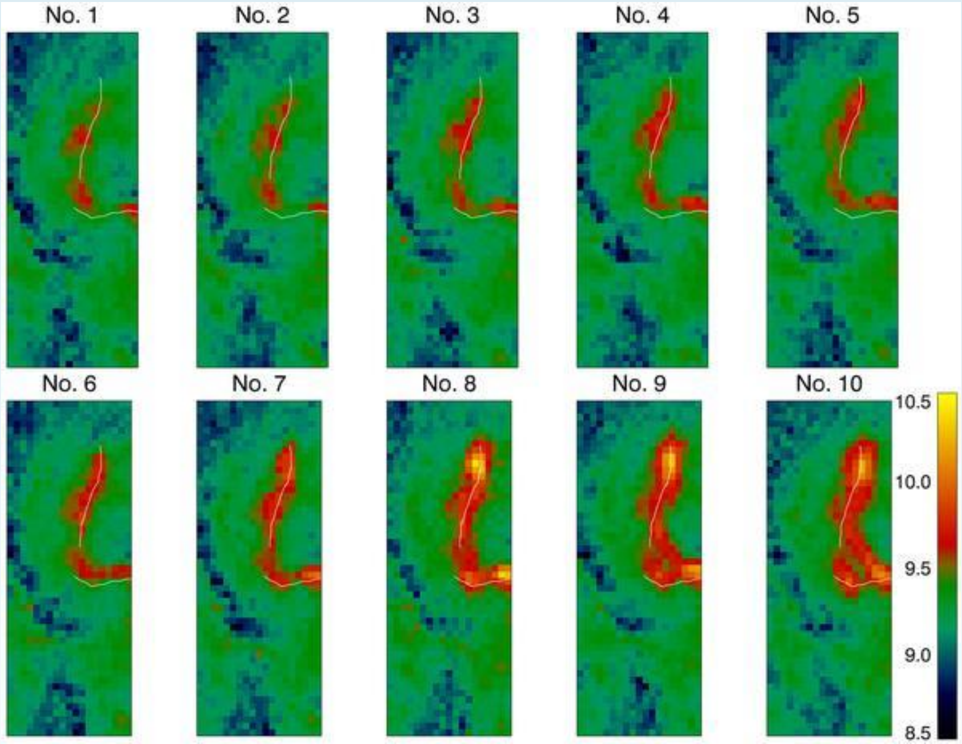


The profile in the kernel region K is a superposition of a stationary component equal to the foreground spectrum at FG, and a strongly blue-shifted component, seen only in lines formed at 2-3 MK.

NO asymmetries

Simply a blue-shifted profile as 1-D hydrodynamic simulations predict.

Electron Densities from FeXIV



Electron Densities , $N_{e,}$ in the kernals are high, almost 10^{11} cm^{-3}

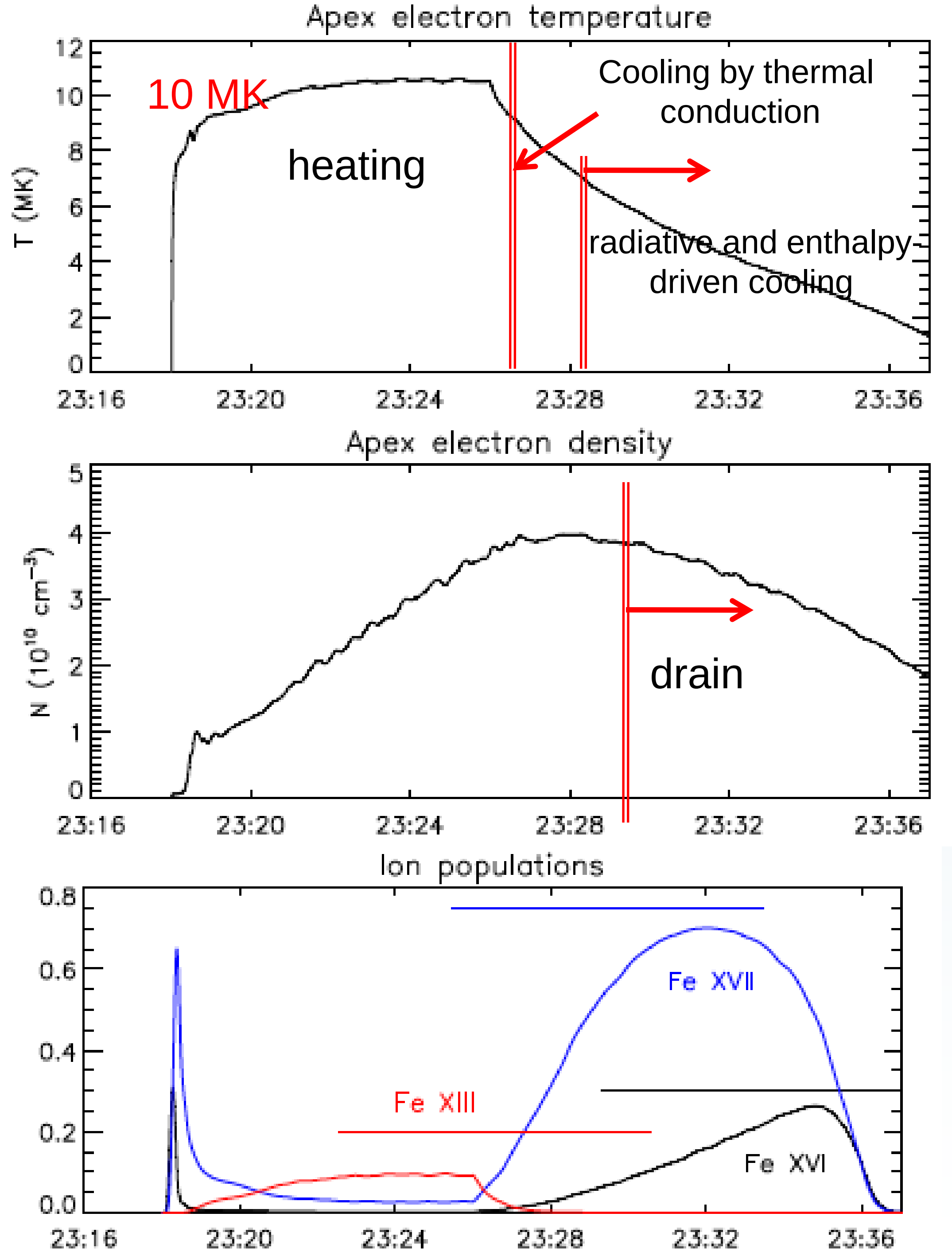
From the measured densities (from Fe XIV) of the blue-shifted plasma 10^{10} cm^{-3} , and the EM, we obtained an estimate of the depth of the chromospheric evaporation site: 200 km

HYDRAD

Steve Bradshaw's code:
1-D hydrodynamic with
time-dependent ionization

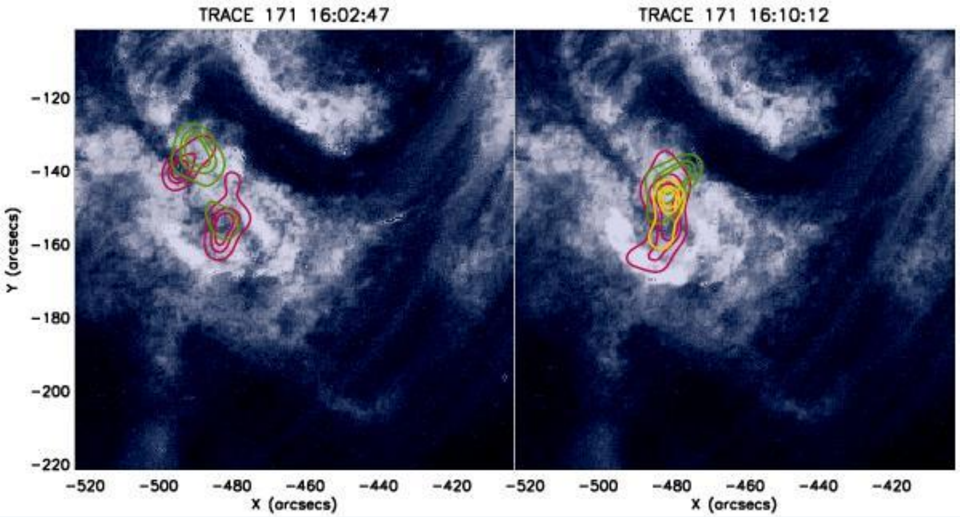
Hydrostatic loop - 40 Mm long
Ne = 1.5 10^9
8 min - uniform heating.
Results:
1)Ne good agreement with obs.
2)Ionization equilibrium holds.
3)Ion populations in broad agreement with EIS obs.

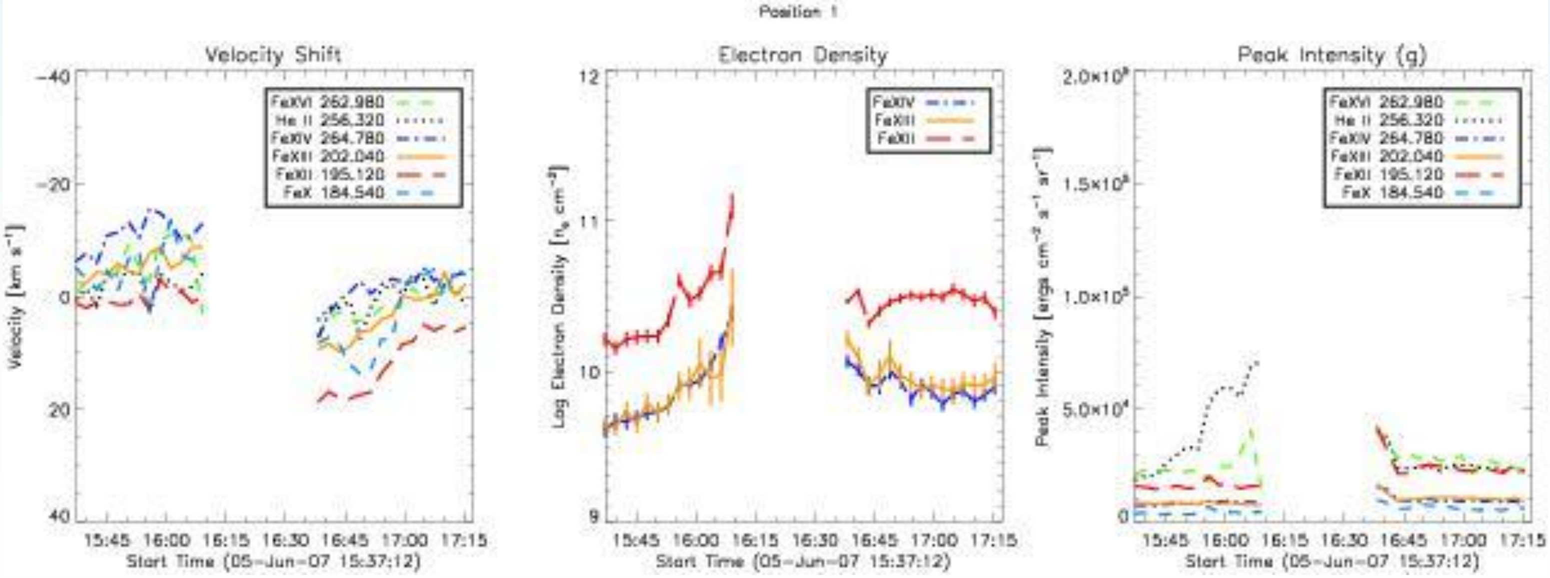
The evaporation (heating) is driven by thermal conduction.



Graham, Fletcher and Hannah, 2011

- 2007 June 5, C6.6 flare
- Hinode/EIS/SOT/XRT +RHESSI
- Flare footpoints > 7MK
- Upflows at high temps
- Ne few x 10^{10} cm^{-3}
- Heat deposition relatively high in the chromosphere drives chromopsheric evaporation

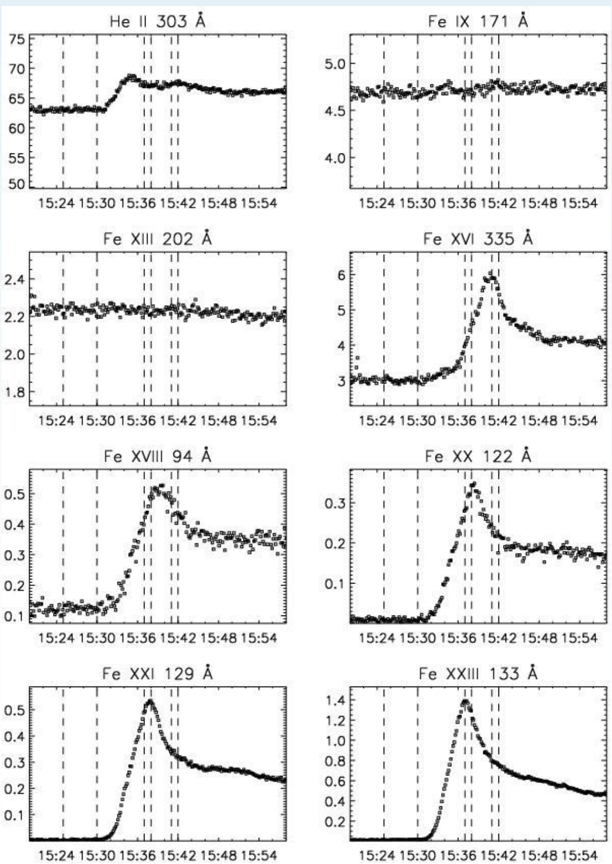


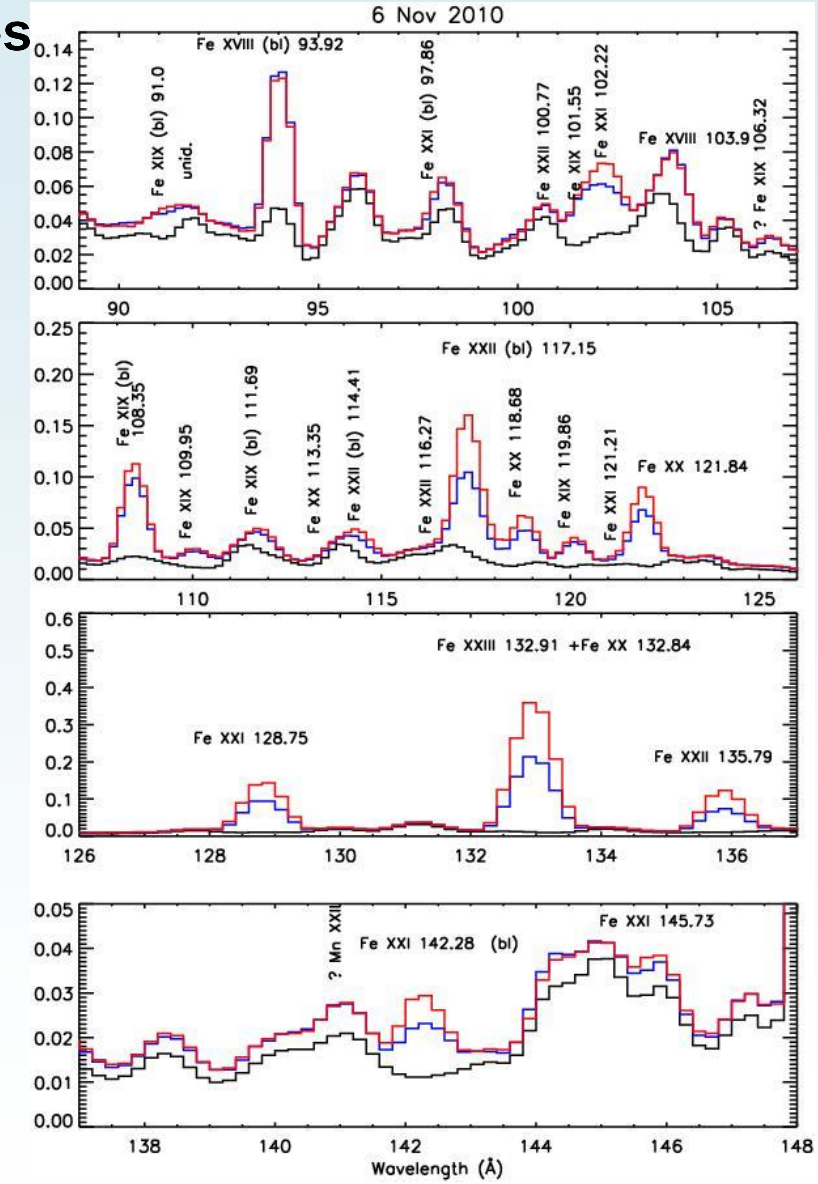


Further studies, EM of impulsive phase flare footprints, Graham et al (2013)

Del Zanna and Woods (2013) – SDO/EVE

- **Benchmark study (4 flares**
- **80-640A, Fe XVIII-XXIV**
- **2010, Nov. 6, M5.4**
- **Temperature 12MK**





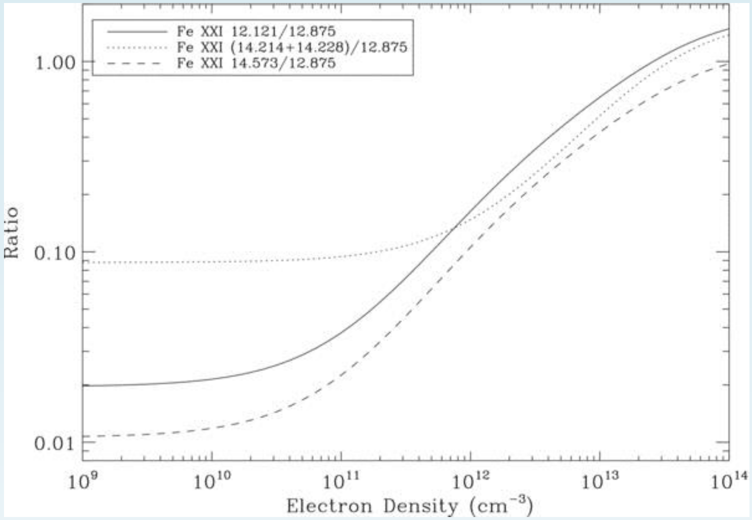
Pre-flare (black), peak gradual phase (red)
Decline gradual phase (blue)

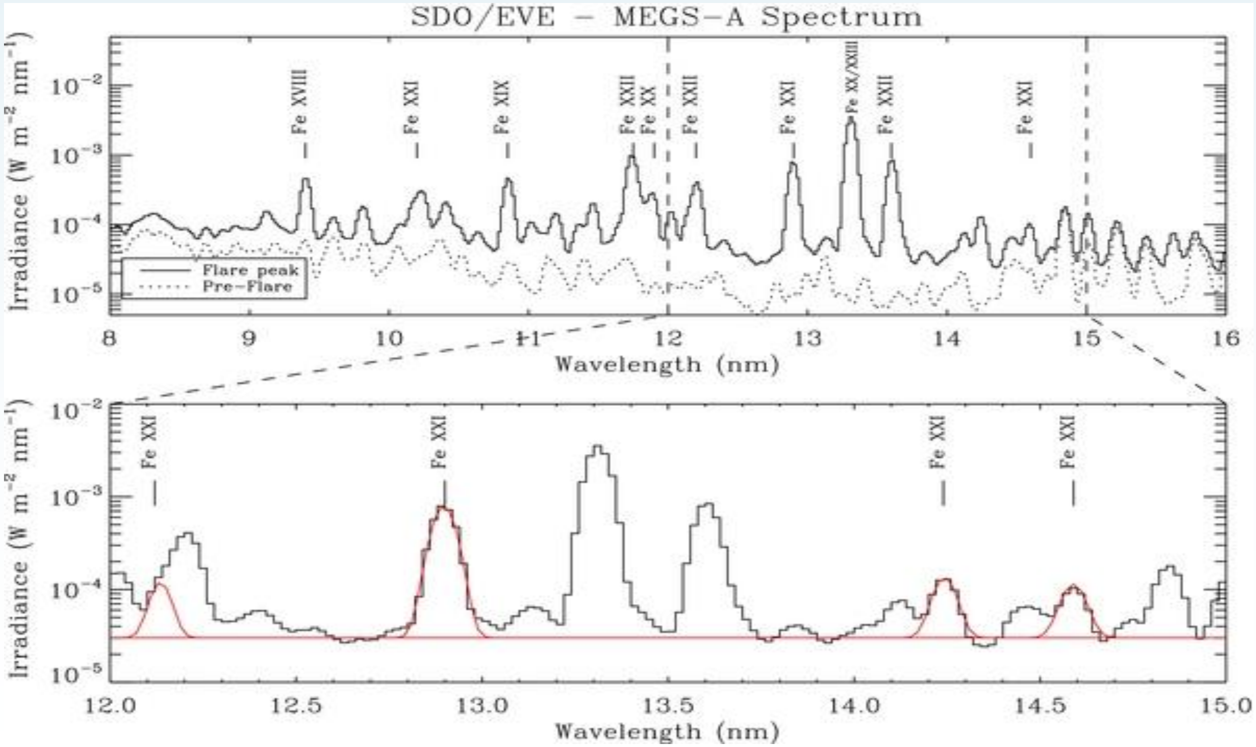
Milligan, Kennedy, Mathioudakis, Keenan, 2012

- **Ne difficult to measure with EVE lines.**
- **Can use FeXXI lines**
- **Values for X-class flares: Log Ne = 11.2-12.1**

Consistent with Mason et al (1984)

Note: SDO/EVE: 80-160A



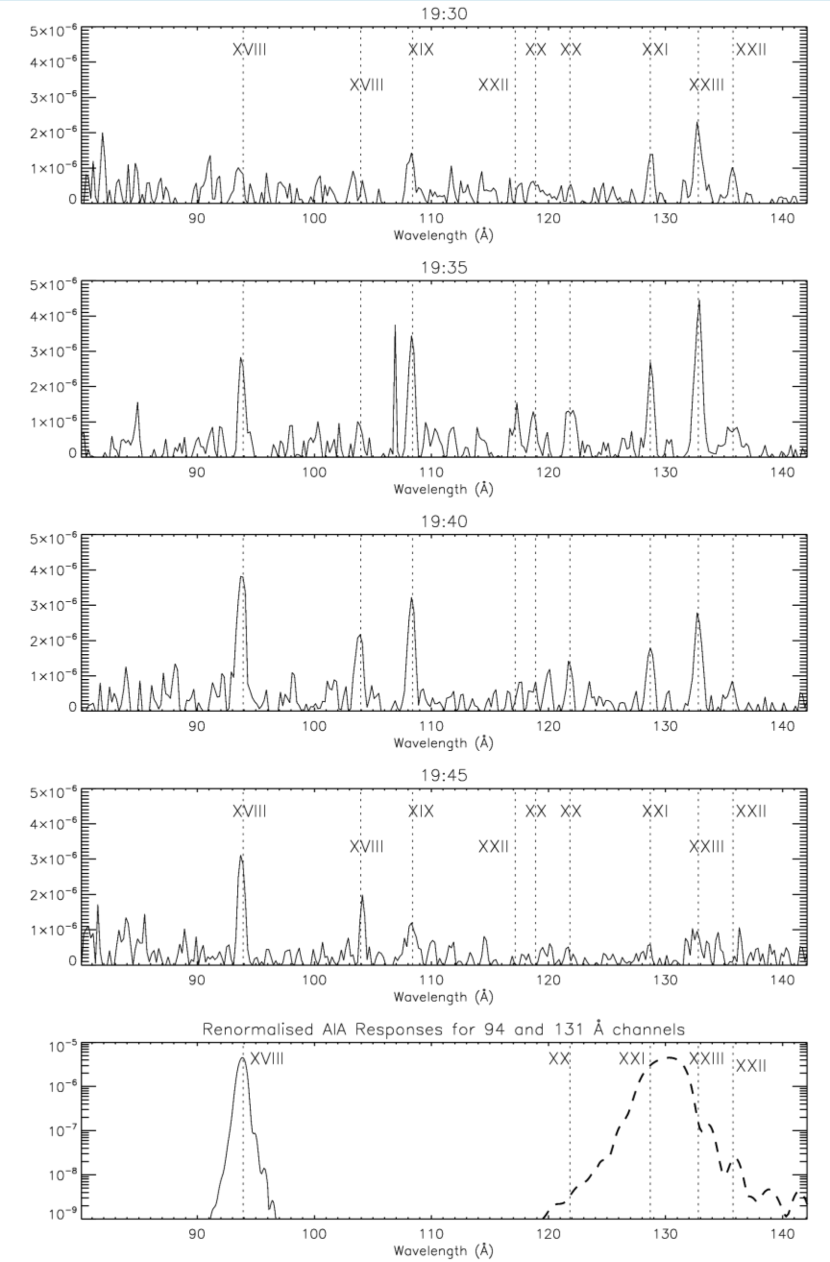


Many other EVE papers

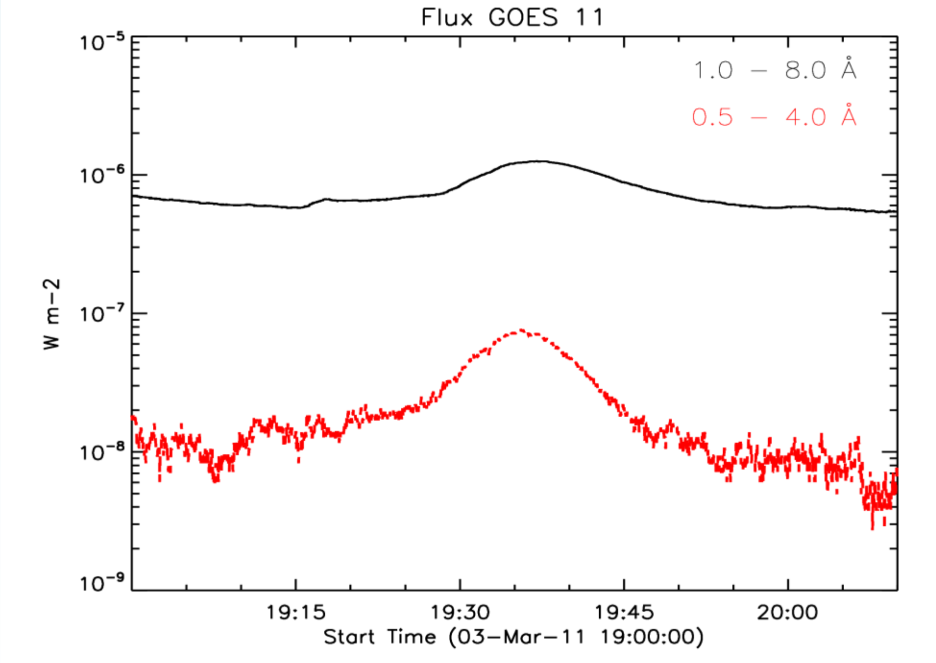
Chamberlin, Milligan and Woods (2012)
Thermal evolution of Flares by EVE

Warren et al (2013)
X-class flare –
Study of thermal phase

Petkaki, Del Zanna, Mason, Bradshaw, 2012



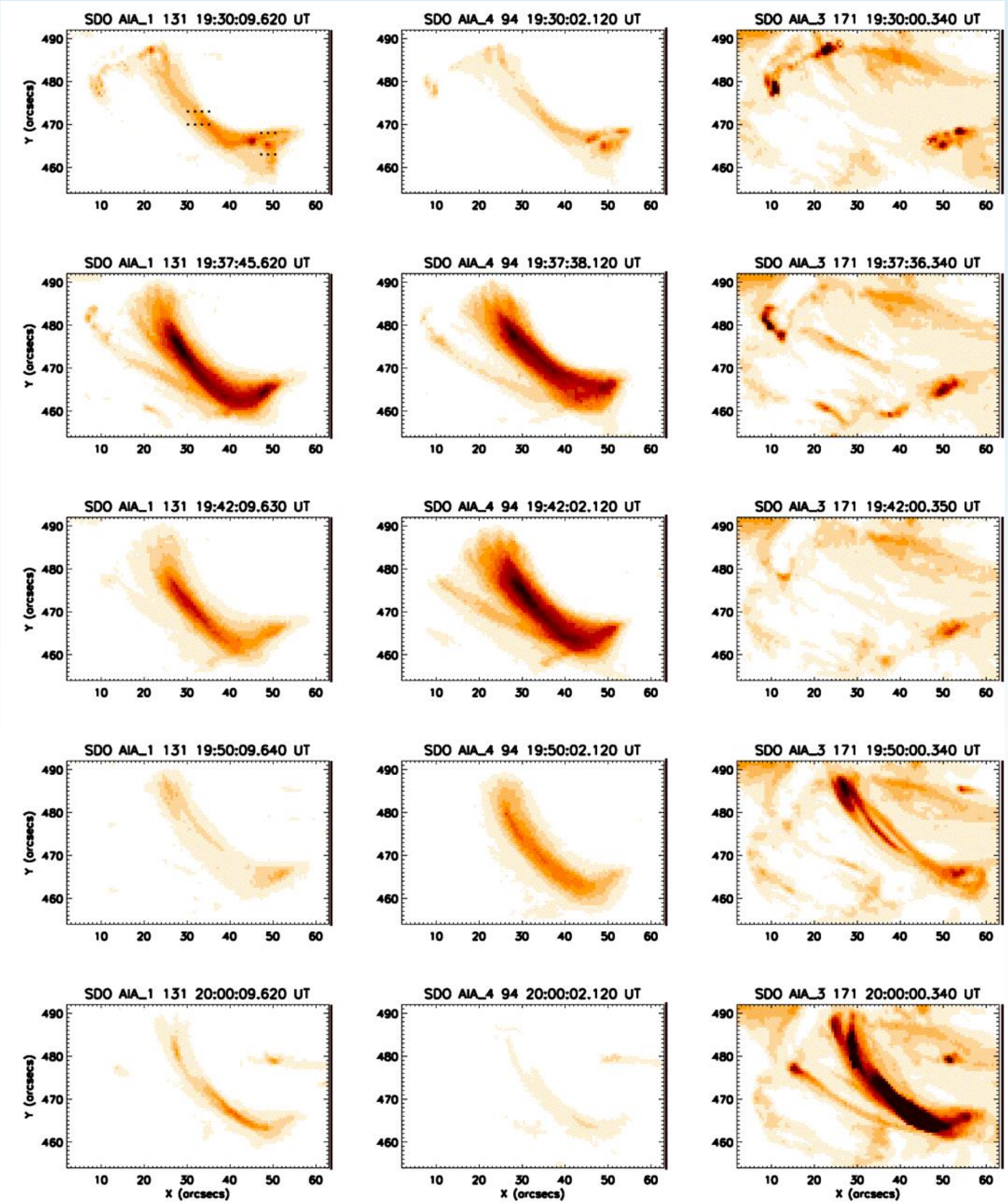
- 2011 March 3,19:25 – 20:10 UT
- C1 flare
- GOES, SDO/AIA + EVE
- Temperature estimate, **Log T = 7**



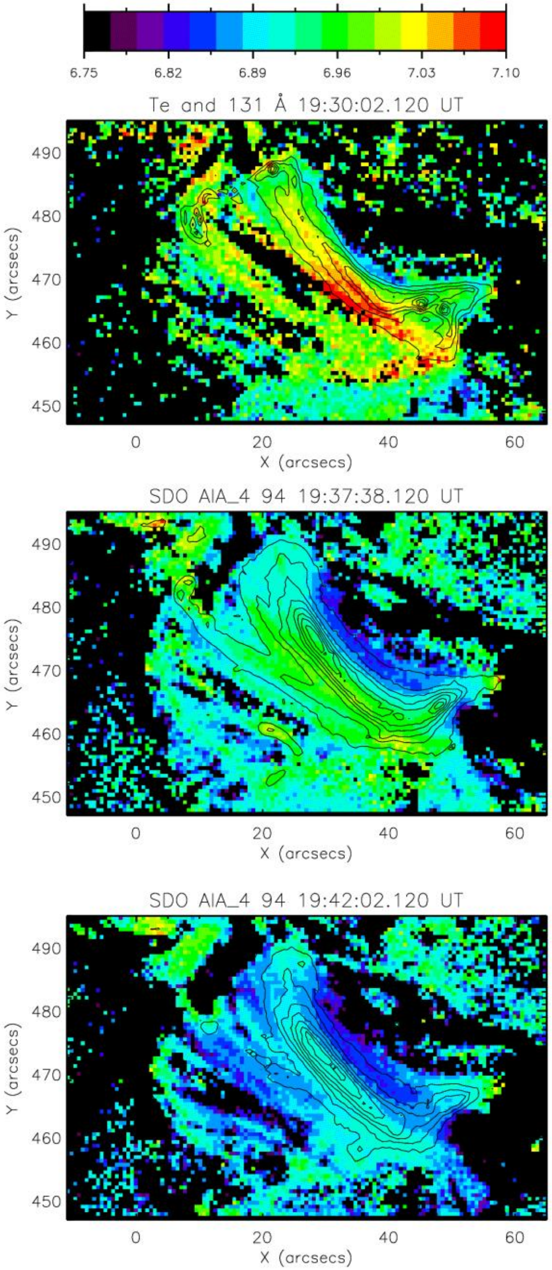
SDO/AIA emission

Time

131 94 171

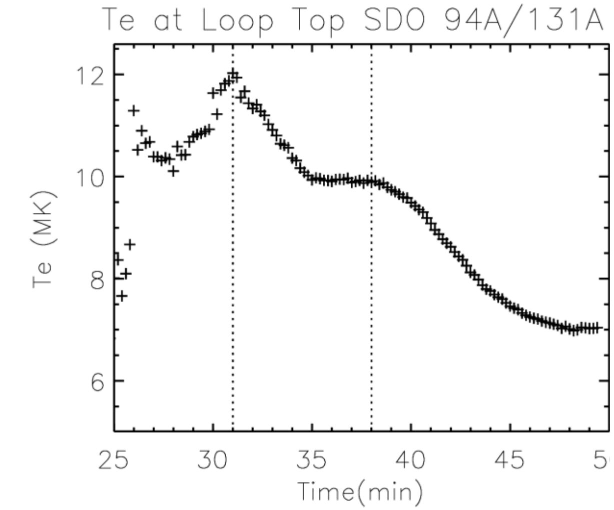


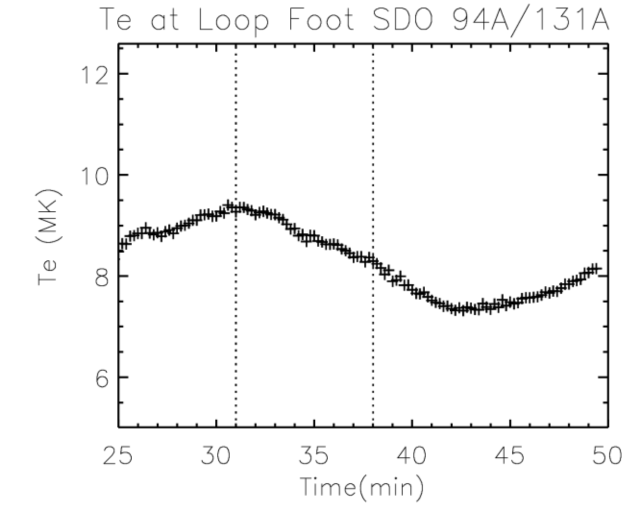
Temperature Maps from AIA 94 to 131 Å

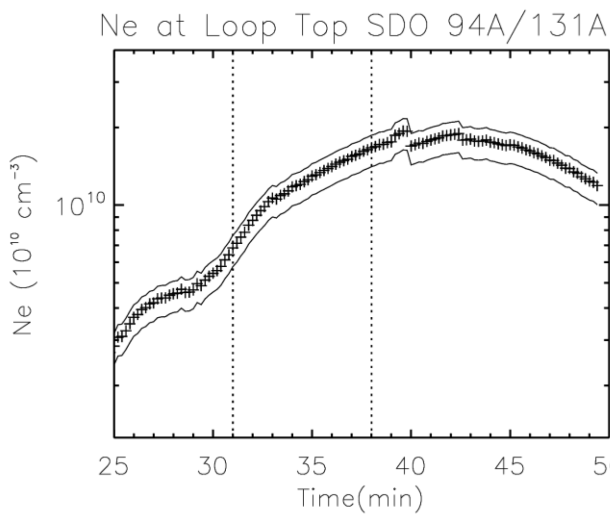


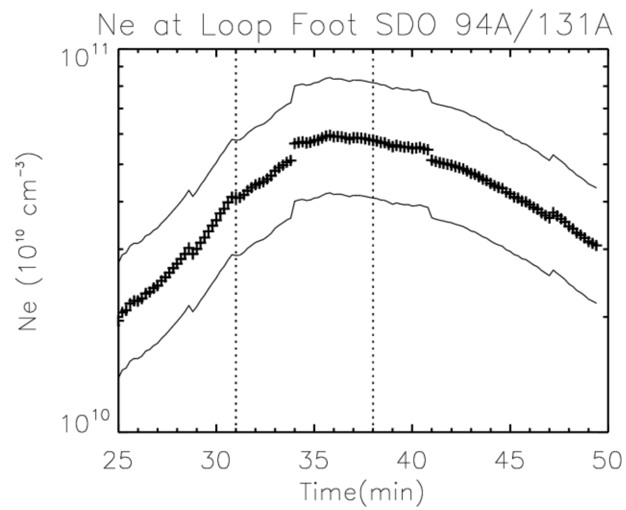
SDO AIA Te and Ne of Main Loop

Loop Top **Loop Footpoint**

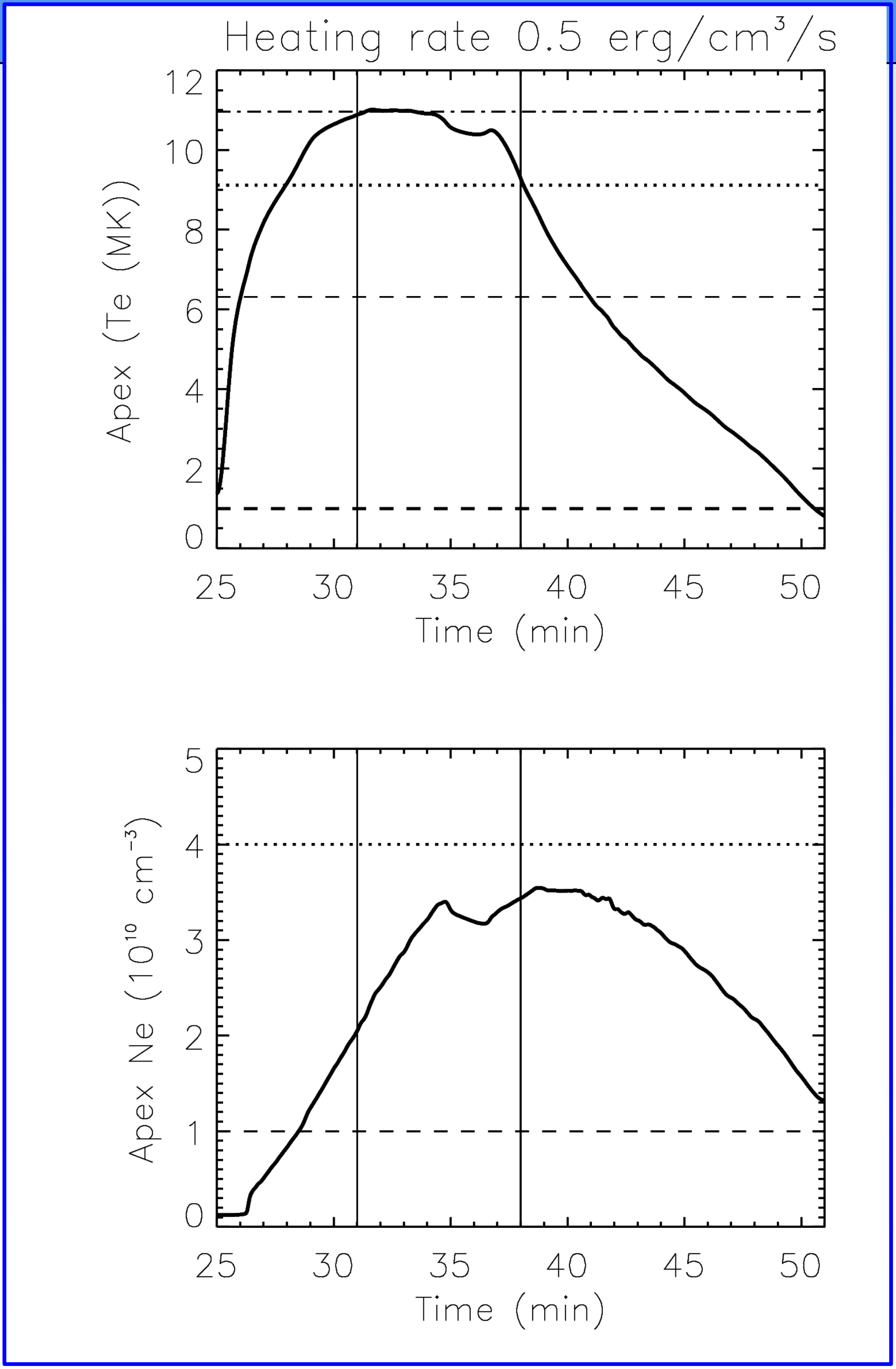








HYDRAD Run



Heating rate 0.5 ergs/cm^3/s

- **Duration of heating event 13 min**
- **Rise Phase 4 min**
- **Decay Phase 80 sec**
- **Loop length 4 10^9 cm**
- **Uniform Heating**
- **Event starts on 19:25 UT**

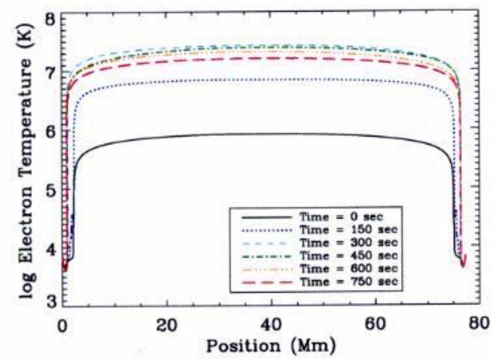
The theory (HYDRAD) agrees very well with the parameters derived from GOES, SDO/EVE and SDO/AIA

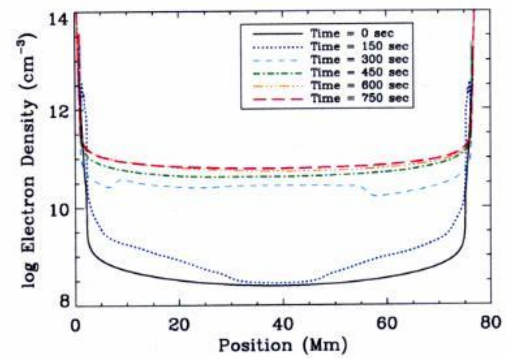
Reep, Bradshaw, McAteer, 2013

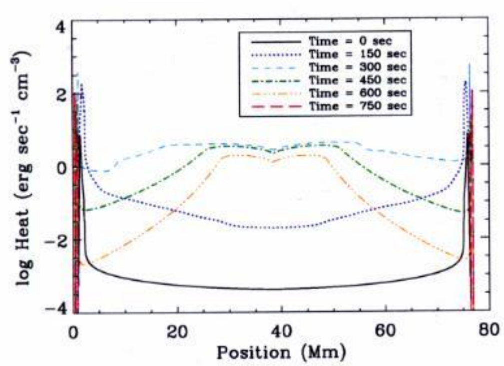
- Extension of HYDRAD
- Chromosphere
- Electron Beam

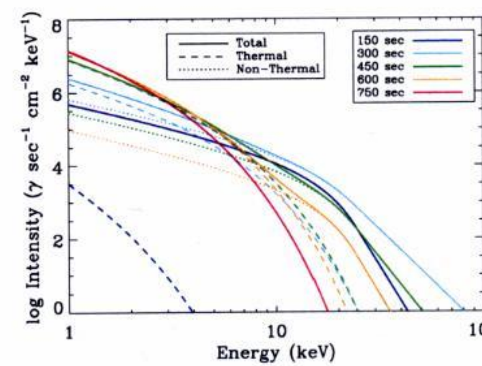
Results:

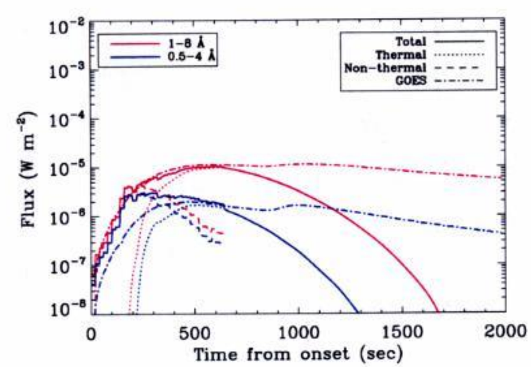
- parameters from RHESSI
- GOES class proportional to non-thermal energy
- $E^{1.7}$ for 1-8A passband





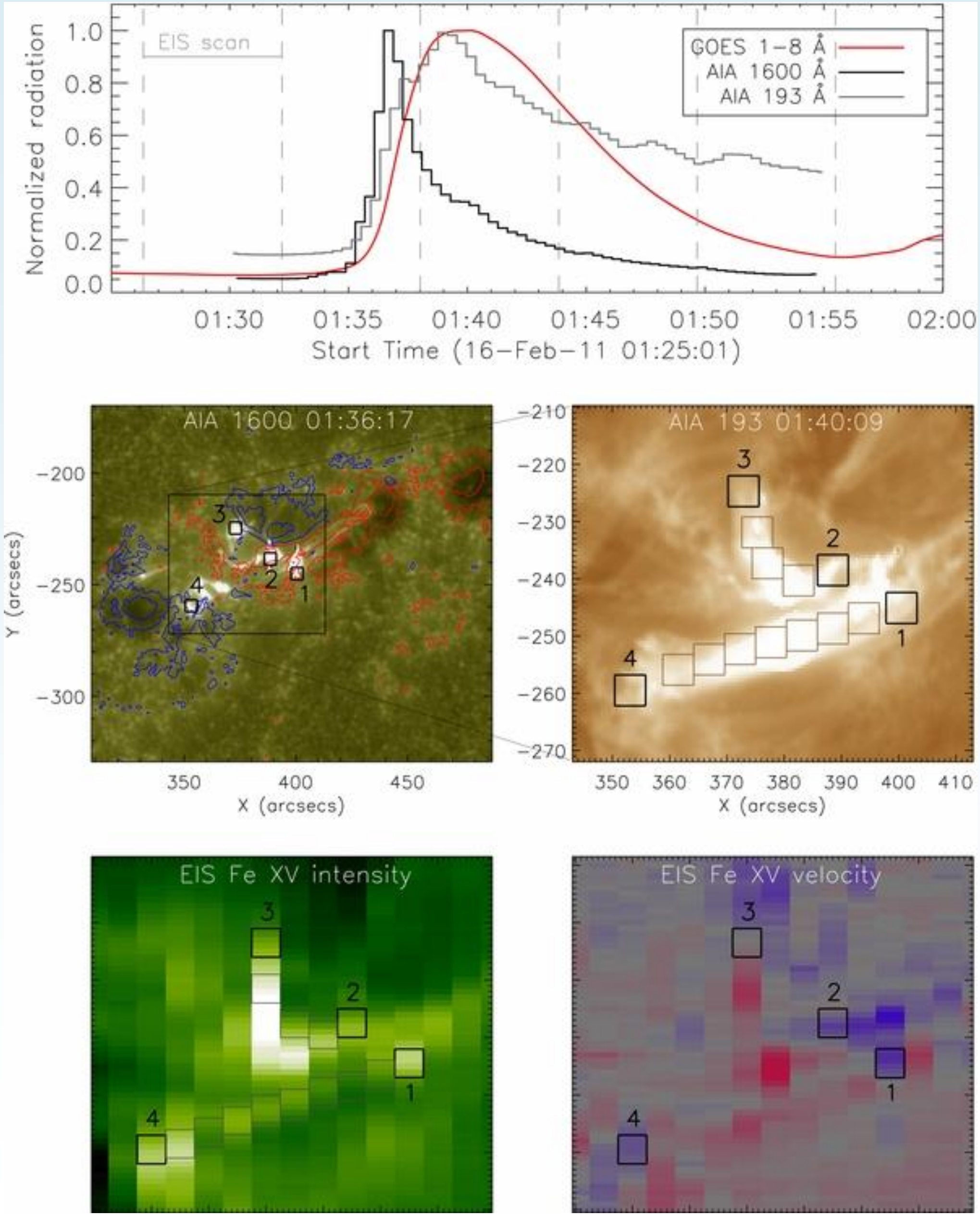






Li, Qui and Ding (2012) - AIA and EIS

- **M1.0 flare 2011 Feb 16**
- **2 distinct loops**
- **EIS, 2” slit, 5” steps, about 6min to raster**
- **EIS raster in FeXV at peak of X-ray flux**
- **EIS missed impulsive phase**

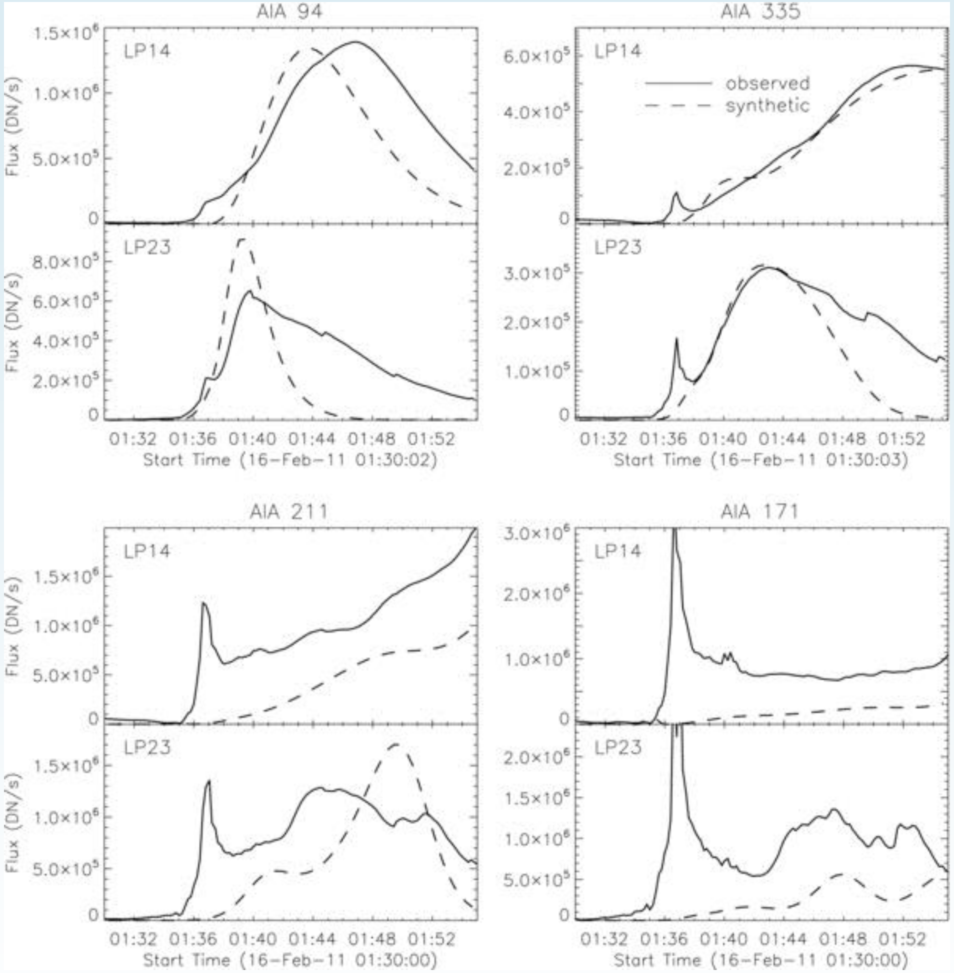


Li, Qui and Ding (2012) – AIA and EIS

- **Qualitative agreement between model (EBTEL- Klimchuk, 2008) and EIS (intensities and flows)**
- **Heating function inferred from UV (1600A) light curves**
- **Temperature reaches 10-15MK**
- **Ne reaches 1-4 x 10^9 cm^{-3}**

The figure shows the response of AIA channels.

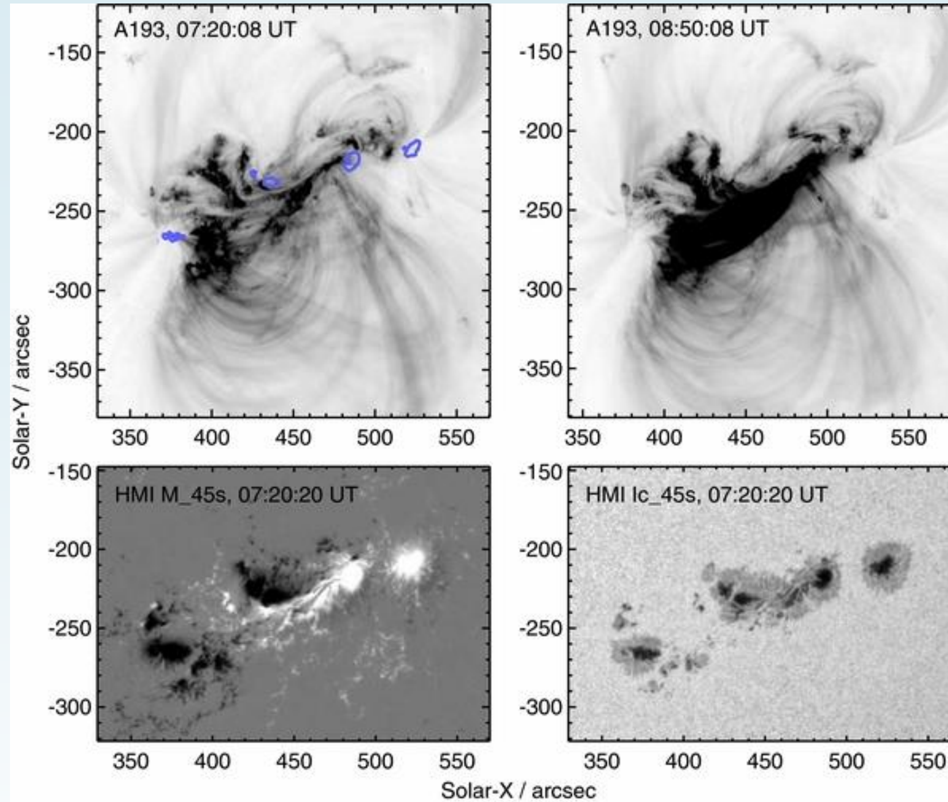
The impulsive peak is likely low temperature (<1MK) emission.

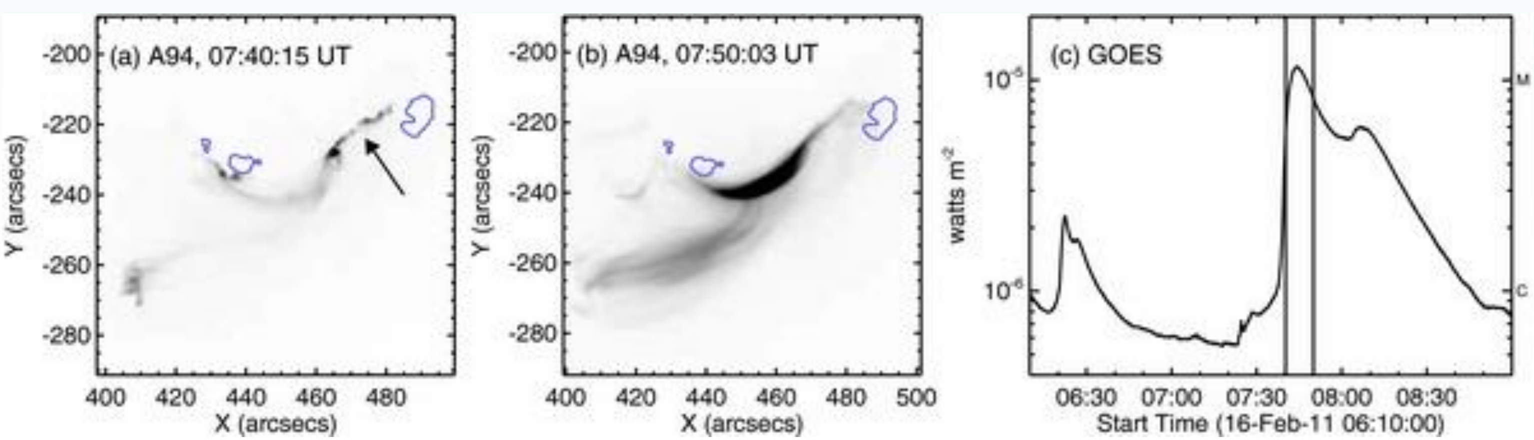


The comparison is made between synthetic (dashed lines) and observed (solid lines) EUV fluxes of the two full loops in 335 Å, 94 Å, 211 Å,171 Å

Young, Doschek, Warren, Hara, 2013 – SDO/EIS

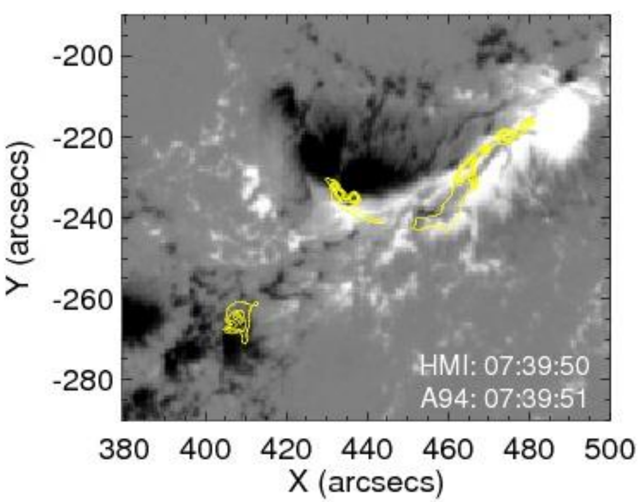
- 2011 February 10, 17:30
- M1.1 flare
- Hinode/EIS + SDO/AIA, HMI
- The figure shows AIA 171 before and after the flare
- The arrow on 94A indicates group of flare kernals





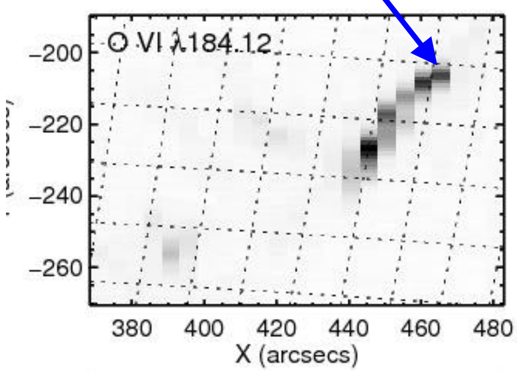
Young, Doschek, Warren, Hara, 2013 – SDO/EIS

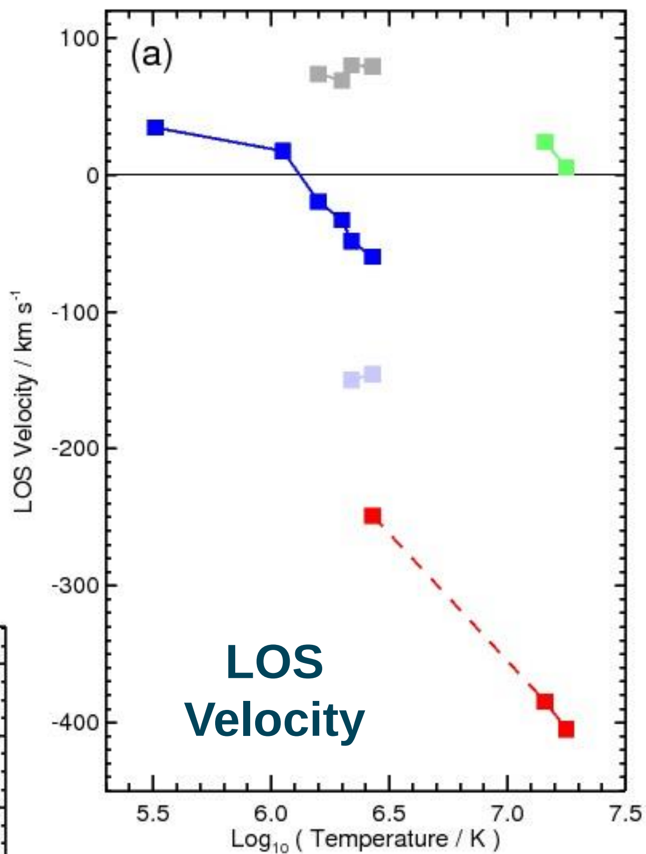
- Compact (<400 km) kernel emits from chromospheric temperatures to 30 MK
- Magnetic field: 1000 G
- 400 km/s blue-shift at 30 MK (Fe XXIII-XXIV)
- Multiple flows at 1-3 MK (blue and redshift)
- Density: 3.4 x 10^{10} cm^{-3} (2 MK, Fe XIV)



Kernels: yellow (AIA 94)

Kernel



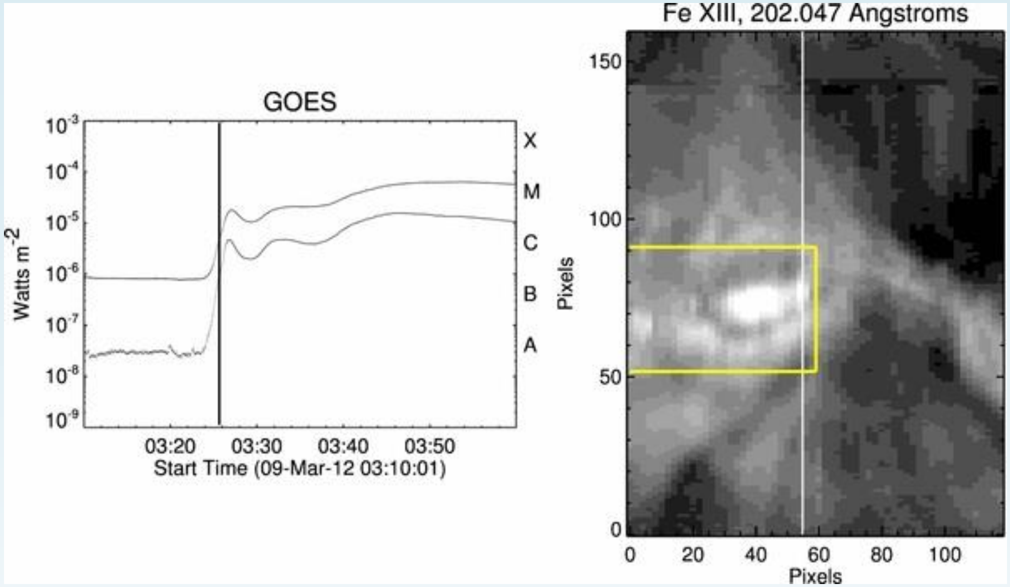


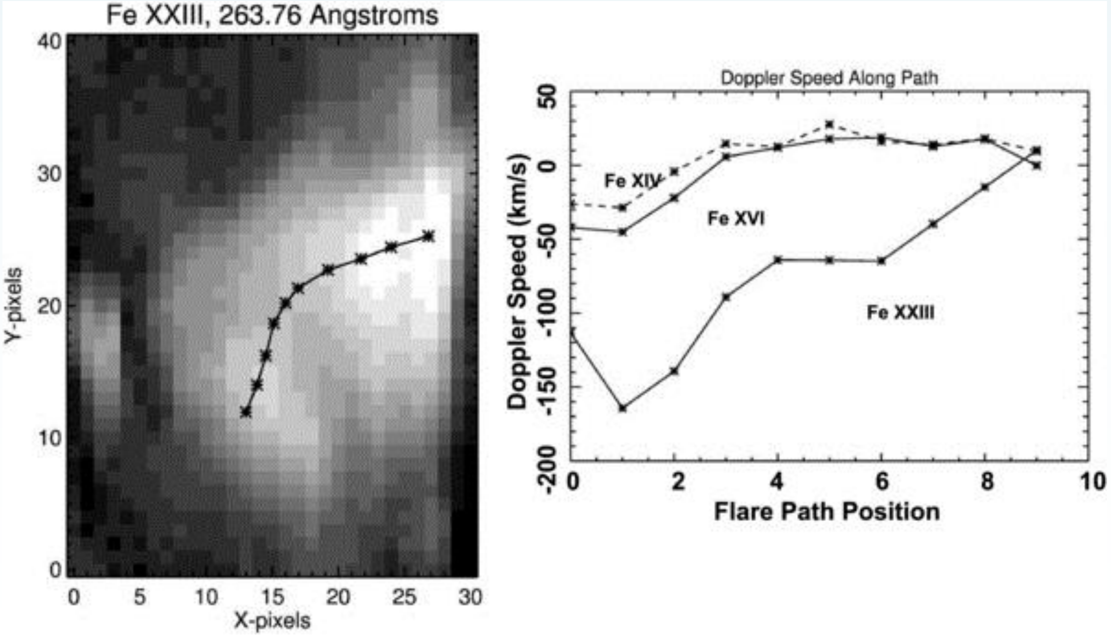
LOS Velocity

Flows from EIS

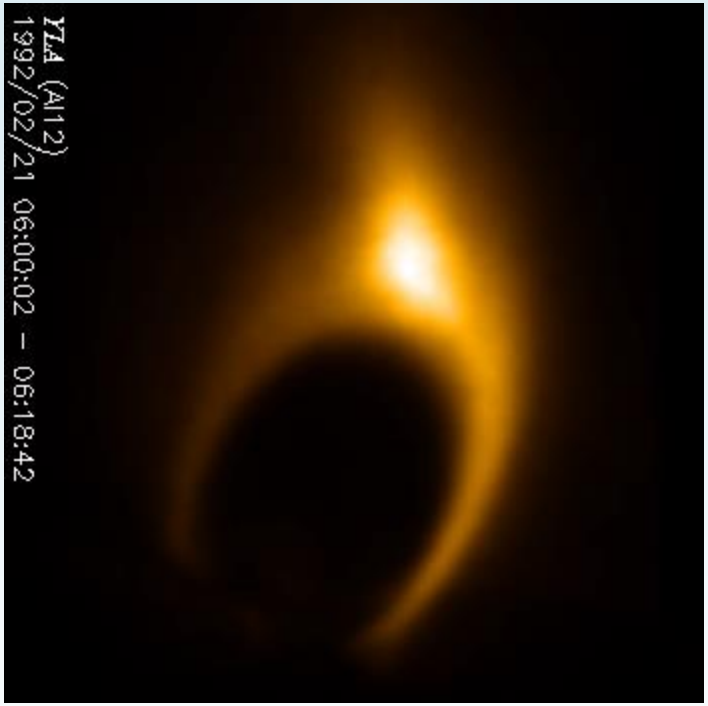
Doschek, Warren and Young, 2013

- 2012 March 9
- M1.8 flare
- Full CCD EIS spectrum
- Evidence for chromospheric evaporation
- 150-200 km/s FeXXII-FeXXIV
- Isothermal source – 14MK
- SEE SP- 4 - 18





What about the ‘acceleration’ region?



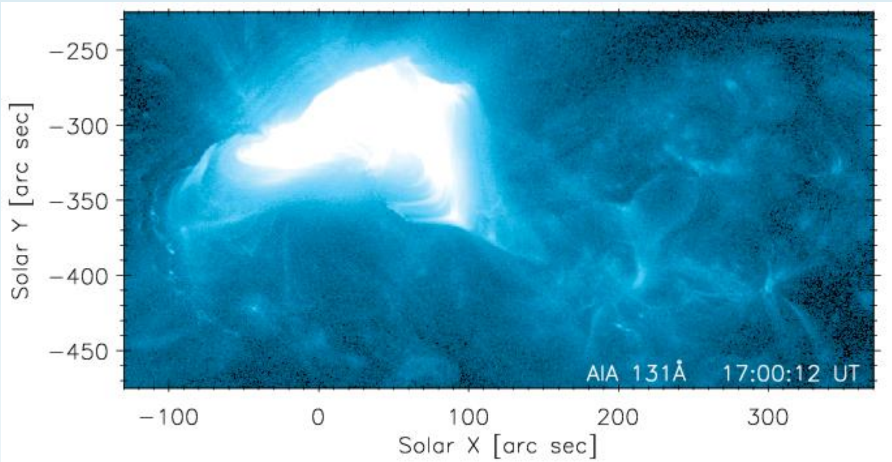
Tsuneta-san solar flare

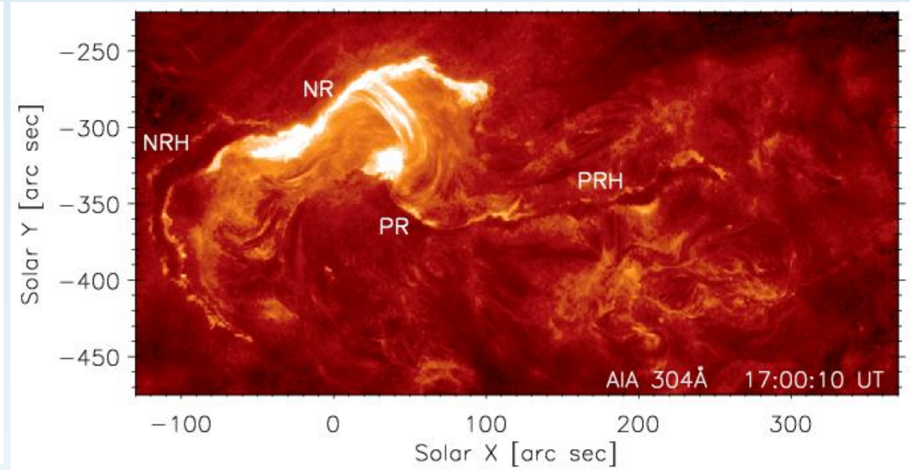
SP-P-20:
Matsui and Yokoyama, 2013
- C-class flare
- High temperature cusps, 10MK, seen with AIA and EIS
- Bi-directional flows
- FeXXIV outflows – 300km/s

S4-P-21:
Watanabe, T., Hara, H., Watanabe, K.
Hot reconnection outflows associated with an X1.4-class flare seen with EIS, AIA, RHESSI
- Hot, 10MK, FeXXIII, FeXXIV
- Upflows in flare lines exceeds 600km/s
- Downflows in coronal lines
- FeXIV, Ne = 10^{11} cm^{-3}

Dudik, Janvier, Aulanier, Del Zanna, Karlicky, Mason and Schmieder, 2013

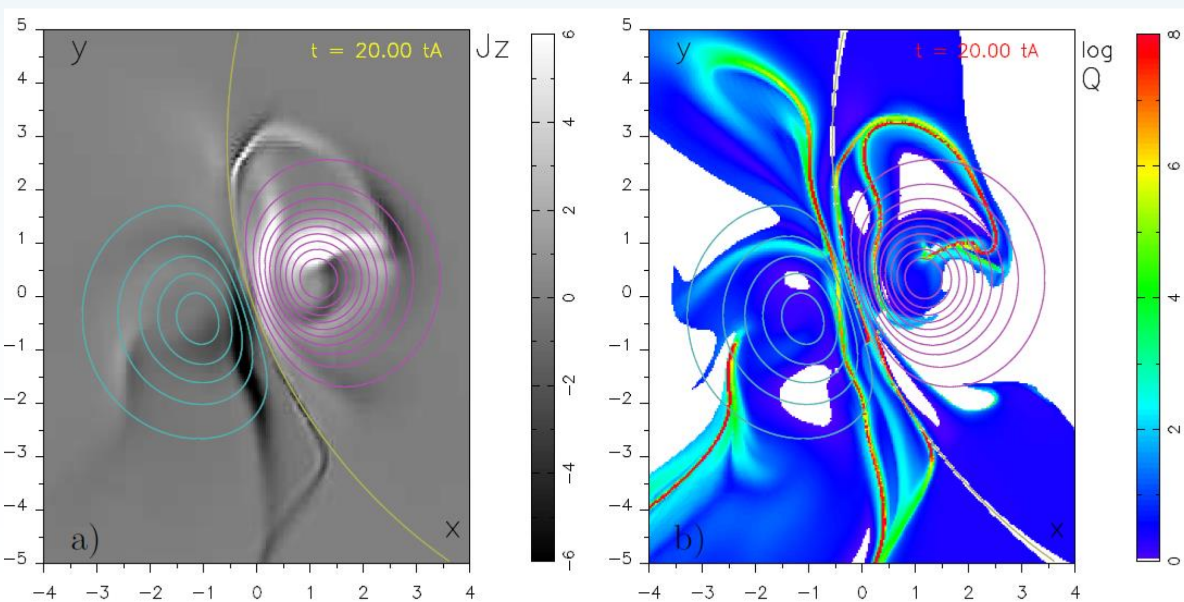
S4-P-26: Slipping Magnetic Reconnection: Theory and Observations





Flux imbalance and hooked QSLs

Aulanier et al. (2012); Janvier et al. (2013)



Summary

- A combination of EUV spectroscopy and imaging has given us a powerful tool
- Combined with RHESSI, even better
- We have clearly identified the sites of chromospheric evaporation
- Various aspects of the impulsive and gradual phases are well predicted by hydrodynamic modeling
- EIS, EVE and AIA provide excellent temperature measurements up to 12 MK
- Flows in the reconnection region have been observed with EIS
- High-resolution X-ray imaging spectroscopy would be really useful
- Non-equilibrium (ionisation, non-Maxwellian)
- Really looking forward to new observations with SolarC!!

COSPAR 2014

- **2 -10 August 2014**
- **Session on ‘Flows in solar flares’**
- **Giulio Del Zanna and Sergey Bogachev**

My thanks to the Hinode and SDO teams, and especially to the organisers of Hinode7!