Elementary Atmospheric Structures and Coronal Properties

by
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Some Plan B Observation and Science Goals

- *Fundamental observation goal*: trace the flow of energy that powers solar activity and the solar wind as it propagates from the photosphere, through the chromosphere and transition region, and into the corona with objectives such as:
  - Determine unambiguously the source(s) of coronal heating
  - Understand the physics of the initiation mechanism of coronal mass ejections
  - Observe in detail the physics of magnetic reconnection in initiating solar flares and its importance in active region heating
  - Observe the propagation of energy via waves and transient phenomena from the chromosphere/transition region into the corona and its role in determining coronal heating and structure
  - Determine the origin of the slow and fast solar wind
- *Science approach*: High spatial (0.1-0.3”), spectral (40-60 mÅ), and temporal (<10s) resolution imaging and spectroscopic observations, covering a temperature range from about $1x10^4$ K (e.g., O I, He I) to $20x10^6$ K (e.g., Fe XXIV, Fe XXV).

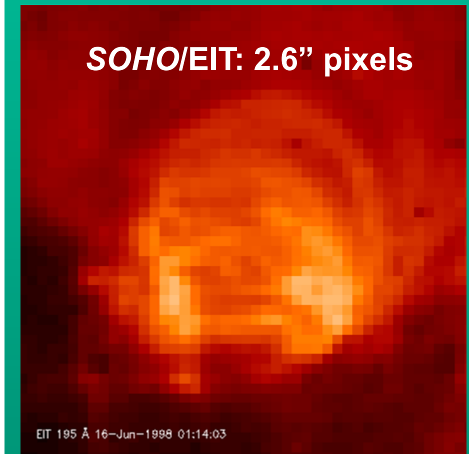
Key Instrument Characteristics for Tracing the Flow of Energy

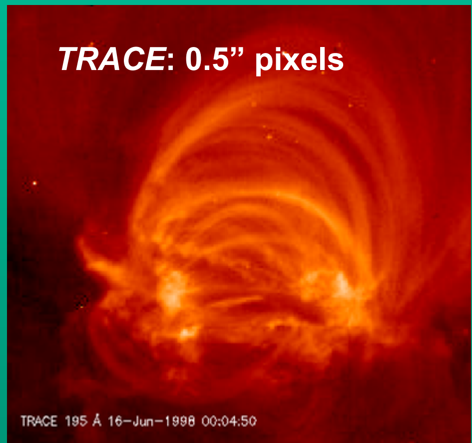
- **Matched spatial resolution from the photosphere into the corona**
  - **Structures and activity in the corona cannot be *unambiguously* traced from the corona to possible origins in the photosphere without matched spatial resolution.**
- **Continuous temperature coverage (no missing temperatures!) from the photosphere into the corona, including flare temperatures**
  - **Plasma must not be allowed to "escape" observation by heating or cooling into an unobservable temperature range.**
  - **There must be no ambiguity in temperature determinations (high temperature resolution is necessary).**
- **Ability to measure dynamical properties of plasma (flows, turbulence) over a wide temperature range**
  - **Plasma energetics cannot be unambiguously determined without dynamical measurements.**
- **No current mission or combination of current missions has all of the above characteristics**

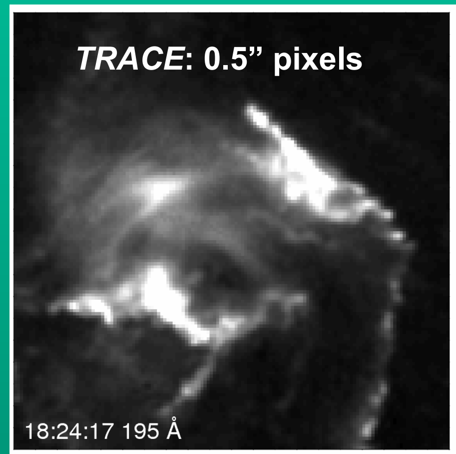
Unveiling the Microphysics of the Solar Corona

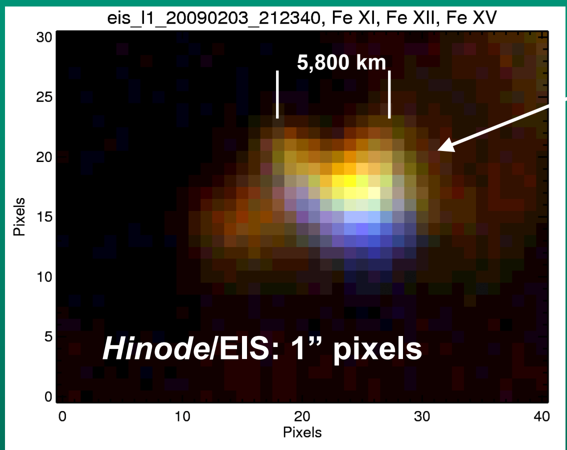
- Particle acceleration
- Magnetic reconnection
- Ion-cyclotron wave heating
- Turbulent cascades
- Non-Maxwellian distributions

Seeing the microphysics requires high spatial and spectral resolution coupled observations from the photosphere into the corona



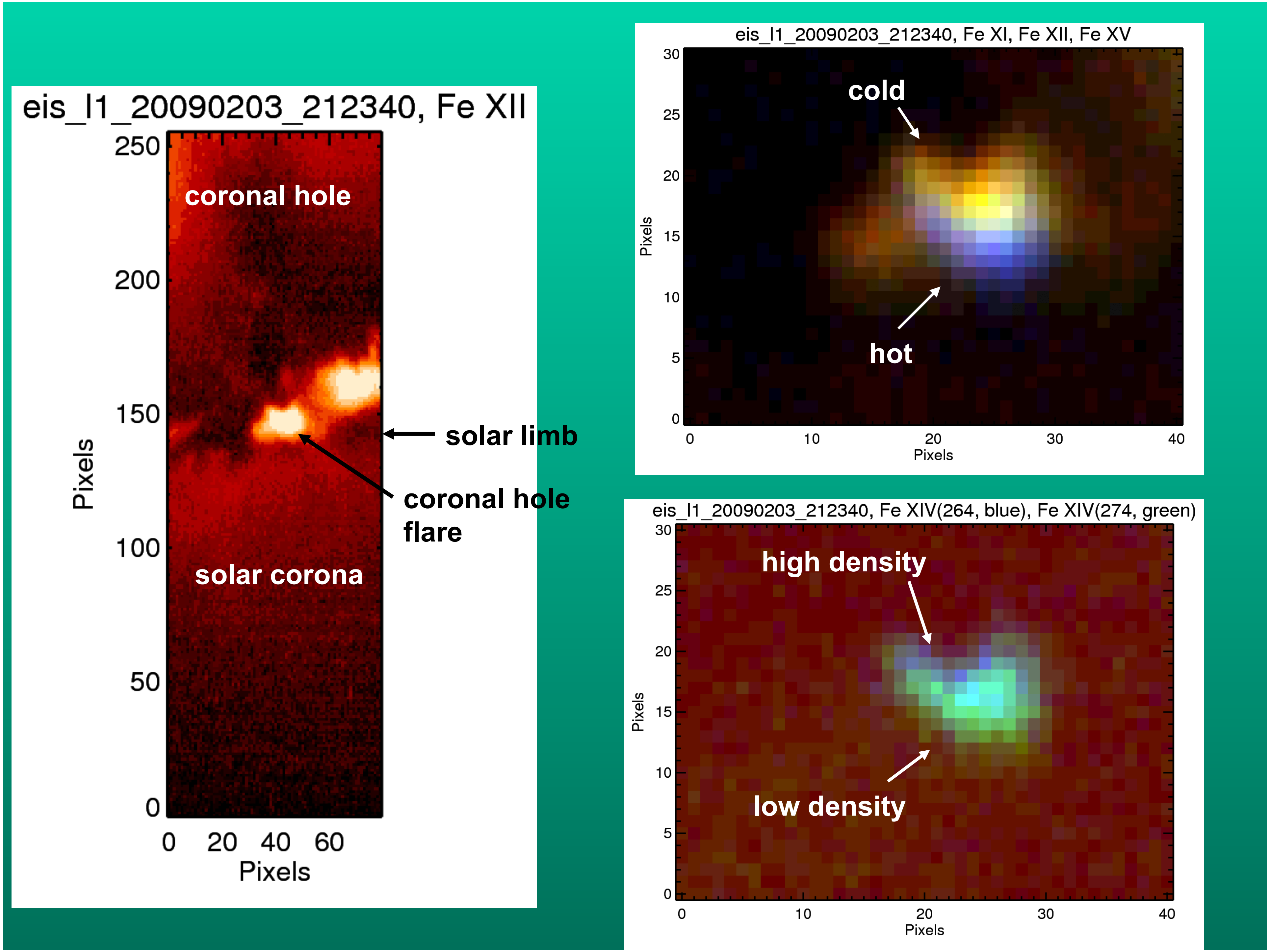






Elementary heating event in a polar coronal hole. This event is clearly unresolved at ~EIS/TRACE spatial resolution.

***Plan B Solar-C*: 0.1” – 0.3” spatial resolution will provide an exact match from the photosphere into the corona, thus allowing resolution of elementary heating events and traceability of footpoint mechanical energy into the coronal magnetic field and into consequent plasma heating.**

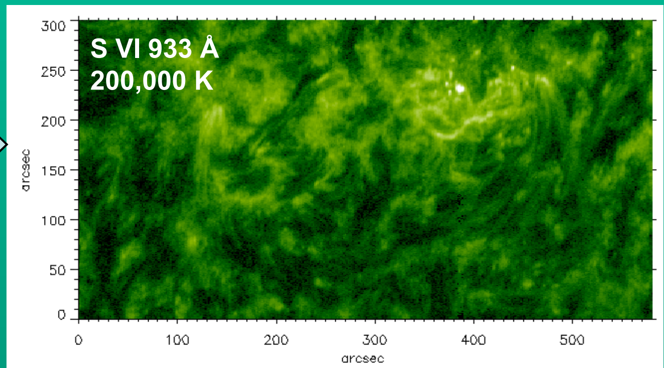


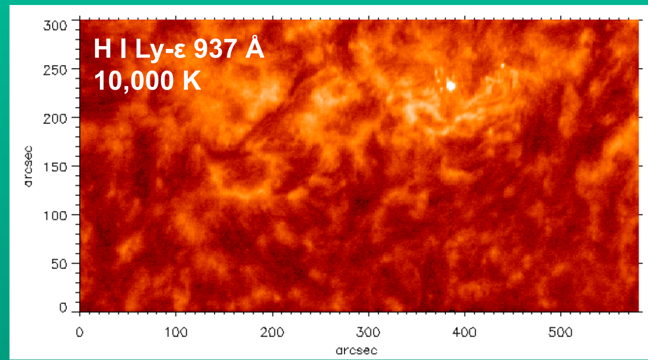
eis_l1_20090203_212340, Fe XII
coronal hole
solar limb
coronal hole
flare
solar corona
Pixels
250
200
150
100
50
0
0
20
40
60
Pixels
eis_l1_20090203_212340, Fe XI, Fe XII, Fe XV
cold
hot
Pixels
30
25
20
15
10
5
0
0
10
20
30
40
Pixels
eis_l1_20090203_212340, Fe XIV(264, blue), Fe XIV(274, green)
high density
low density
Pixels
30
25
20
15
10
5
0
0
10
20
30
40
Pixels

Unveiling the Microphysics of the Solar Chromosphere/Transition Region

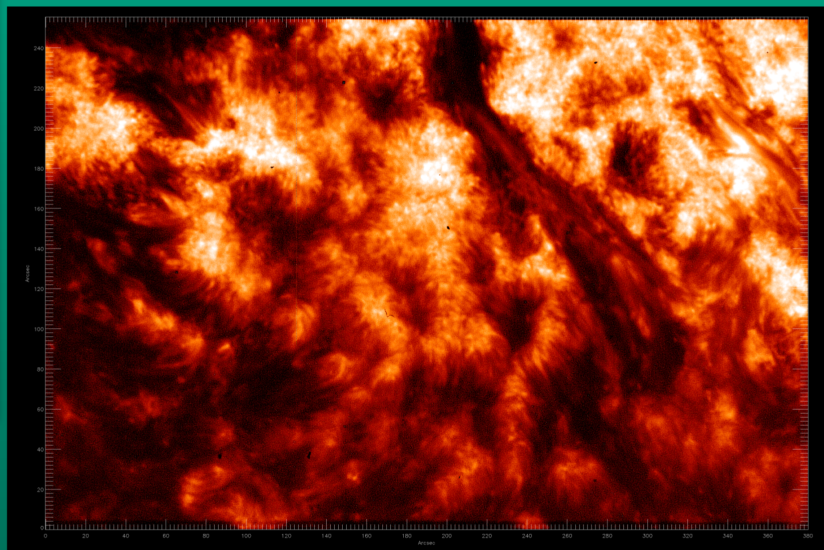
- The chromosphere/transition region (CTR) is the interface/connectivity between the corona and the source of its energy, i.e., the photosphere
- The CTR is spatially unresolved with present instrumentation (1.0” at best, with no spectroscopy
- The CTR is the site of complex dynamics including heating, waves, and bulk plasma motions
- Spectroscopy of the CTR (filling factors/opacity) indicate scale lengths of 70 – 200 km (0.1” – 0.3”)

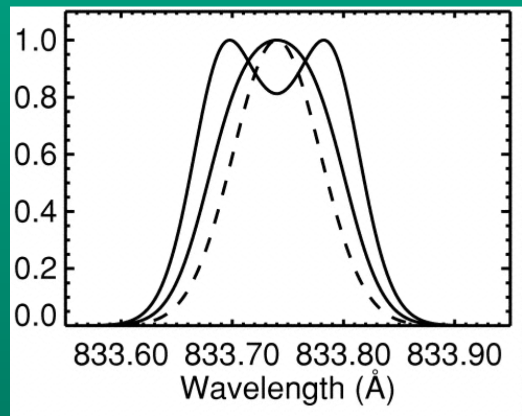
SUMER spectra showing that at 2” resolution different CTR regions are indistinguishable





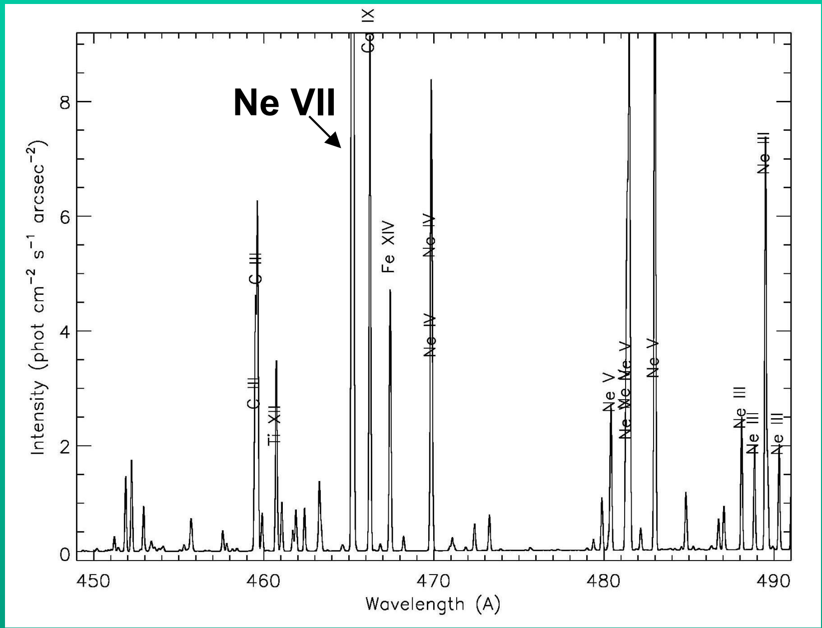
H I Lyman-α images from the VAULT rocket spectrometer with 0.3” spatial resolution. The X-axis is 380” long and the Y-axis is 250” long. The large tic marks are 20” intervals. Linking these structures seen in H I to the corona demands 0.1” – 0.3” spatial resolution.

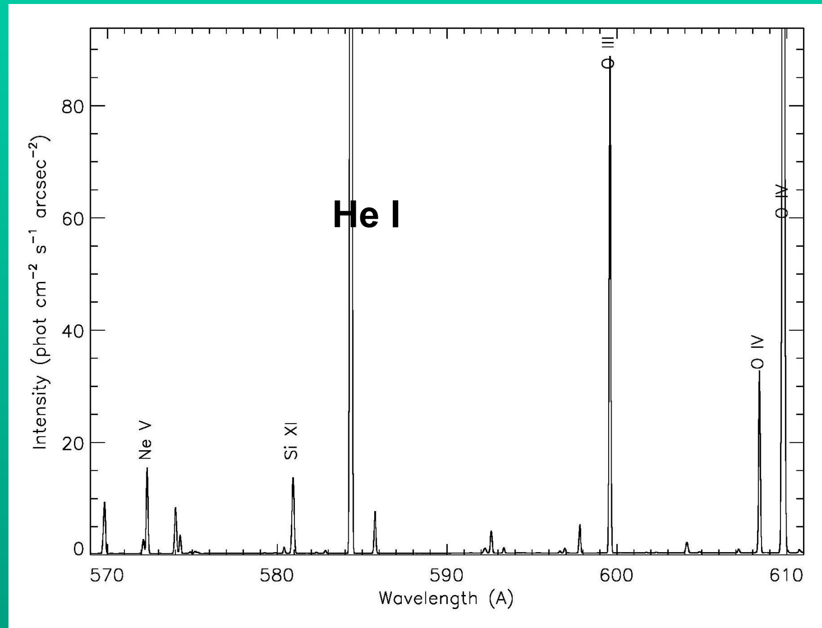


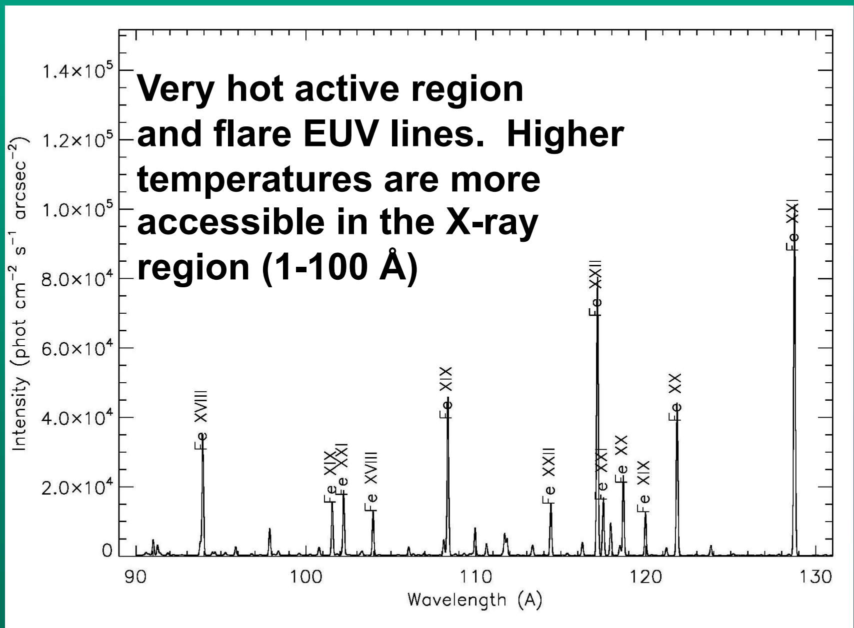


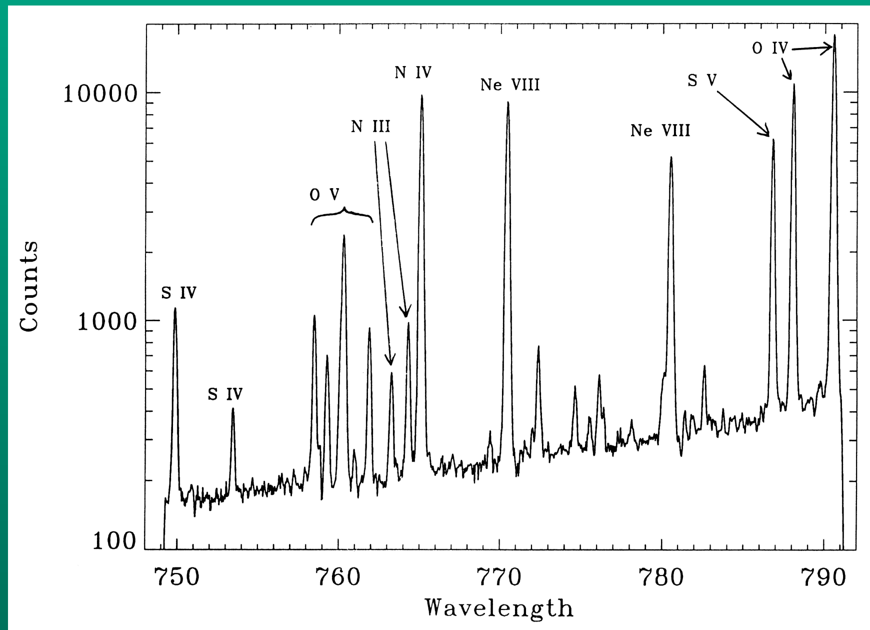
The shapes of CTR line profiles such as O III above show that CTR path lengths are 0.1” – 0.3”

Some Interesting Wavelength Regions for Consideration

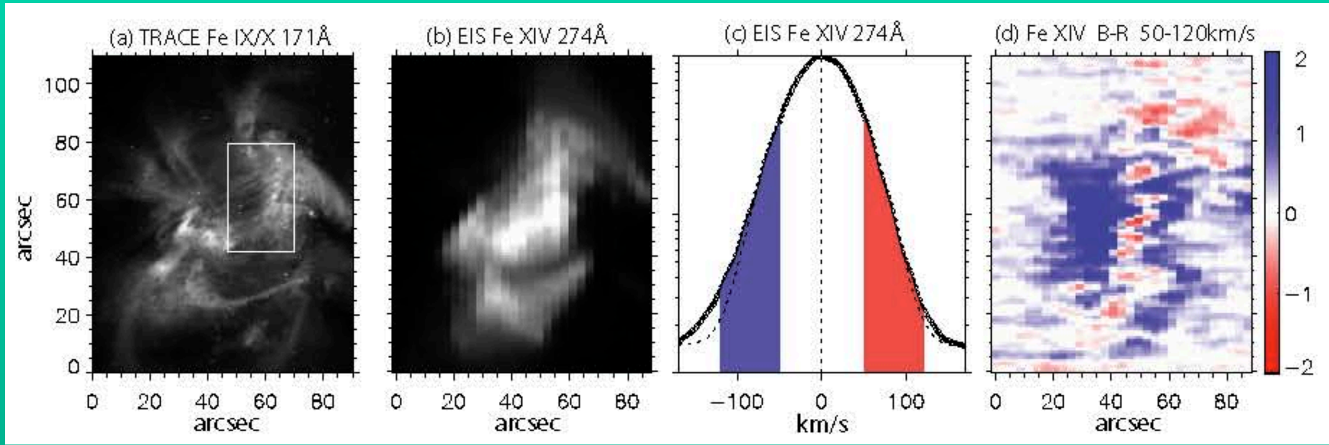




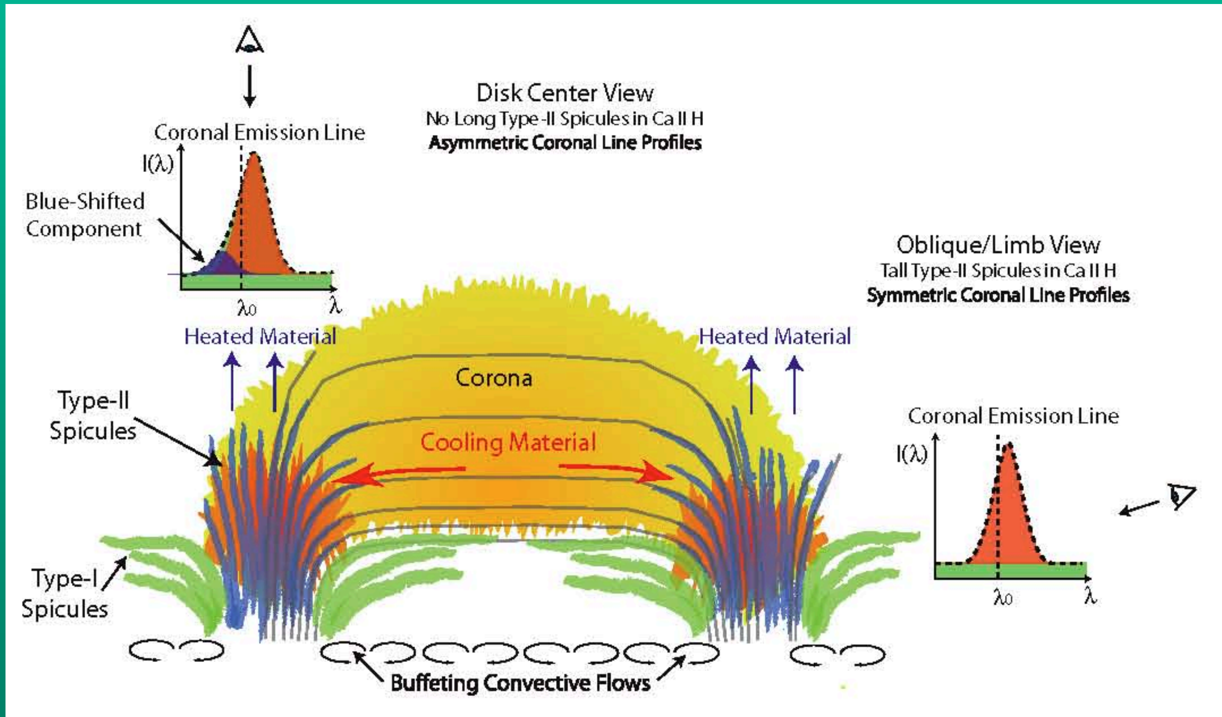




An *Hinode* discovery: a chromosphere & coronal loop heating connection.
De Pontieu et al., ApJ, 701, L1 (2009)

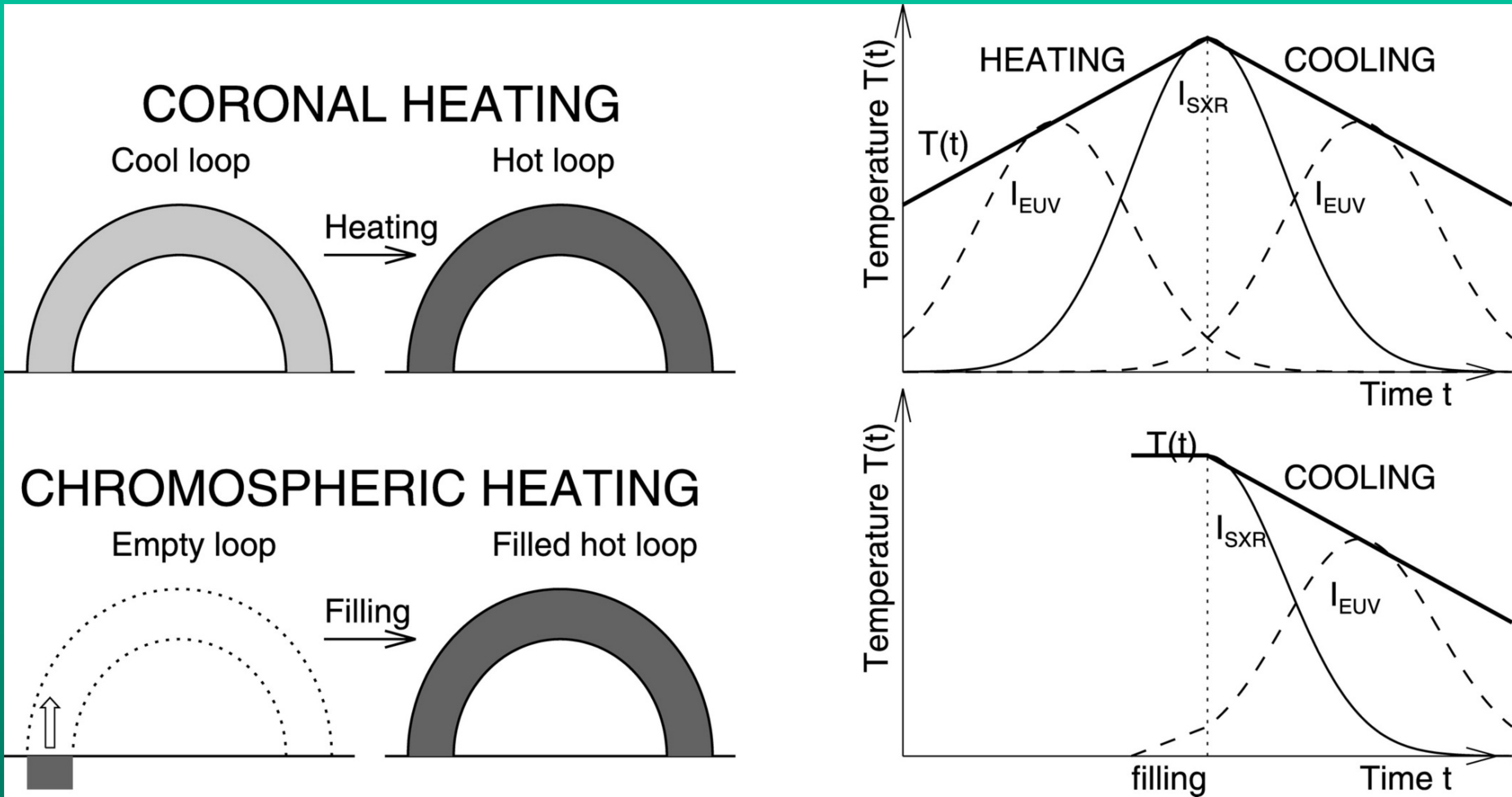


Tracking Type II spicules through the chromosphere/ transition region is highly desirable.



•Type II spicules – a source of heating and mass in the corona?
•What are the properties of the spicules between SOT and EIS Fe XIV temperatures?

How are coronal loops heated?
Plasma parameters are necessary to find out.
Current instrumentation cannot resolve multi-threaded coronal loops.

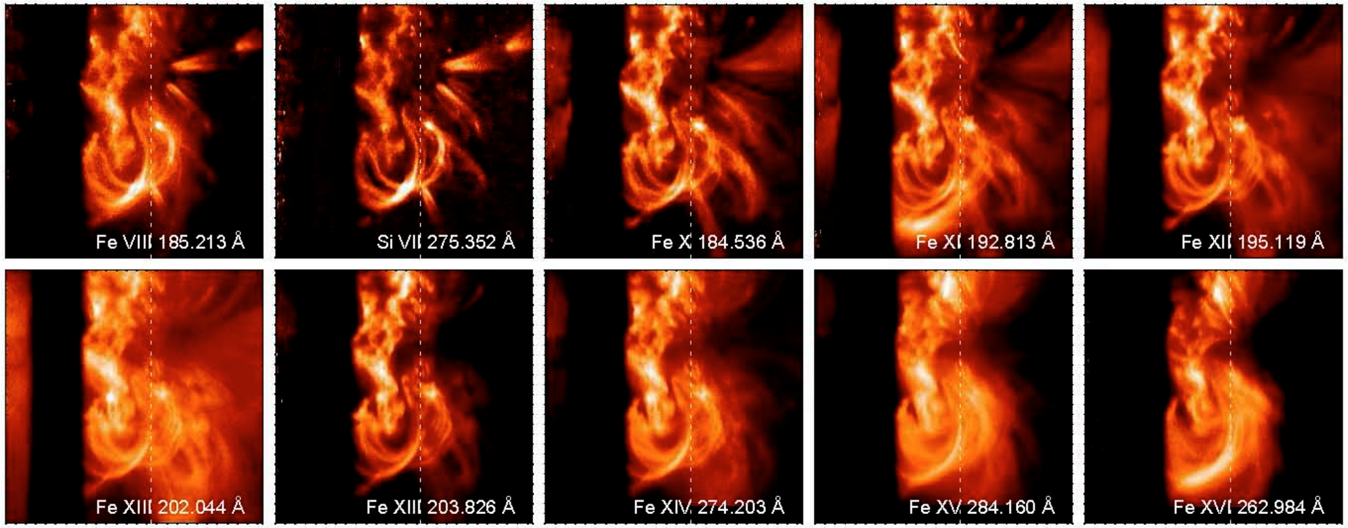


from Aschwanden et al., ApJ, 659, 1673 (2007)

A Multi-Thread Loop Model is Needed to Explain Many *Hinode* Loop Observations in Active Regions

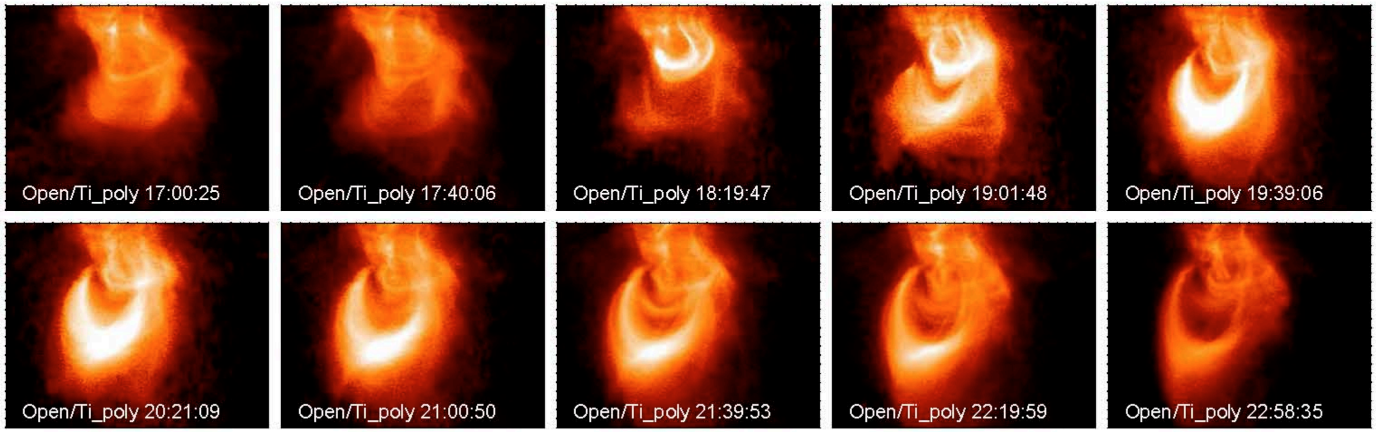
- The overall loop magnetic envelop is assumed to be composed of sub-resolution magnetic "threads".
- The threads are modeled as individual flare loops using a 1D solar flux tube model.
- Heating onset is modeled as a succession of independently heated threads.
- The length of the flare loop is determined by observations of the overall magnetic envelop.
- The energy in each successively heated thread is determined such that the total loop EUV flux matches the light curves such as generated by TRACE.

***Hinode*/EIS**

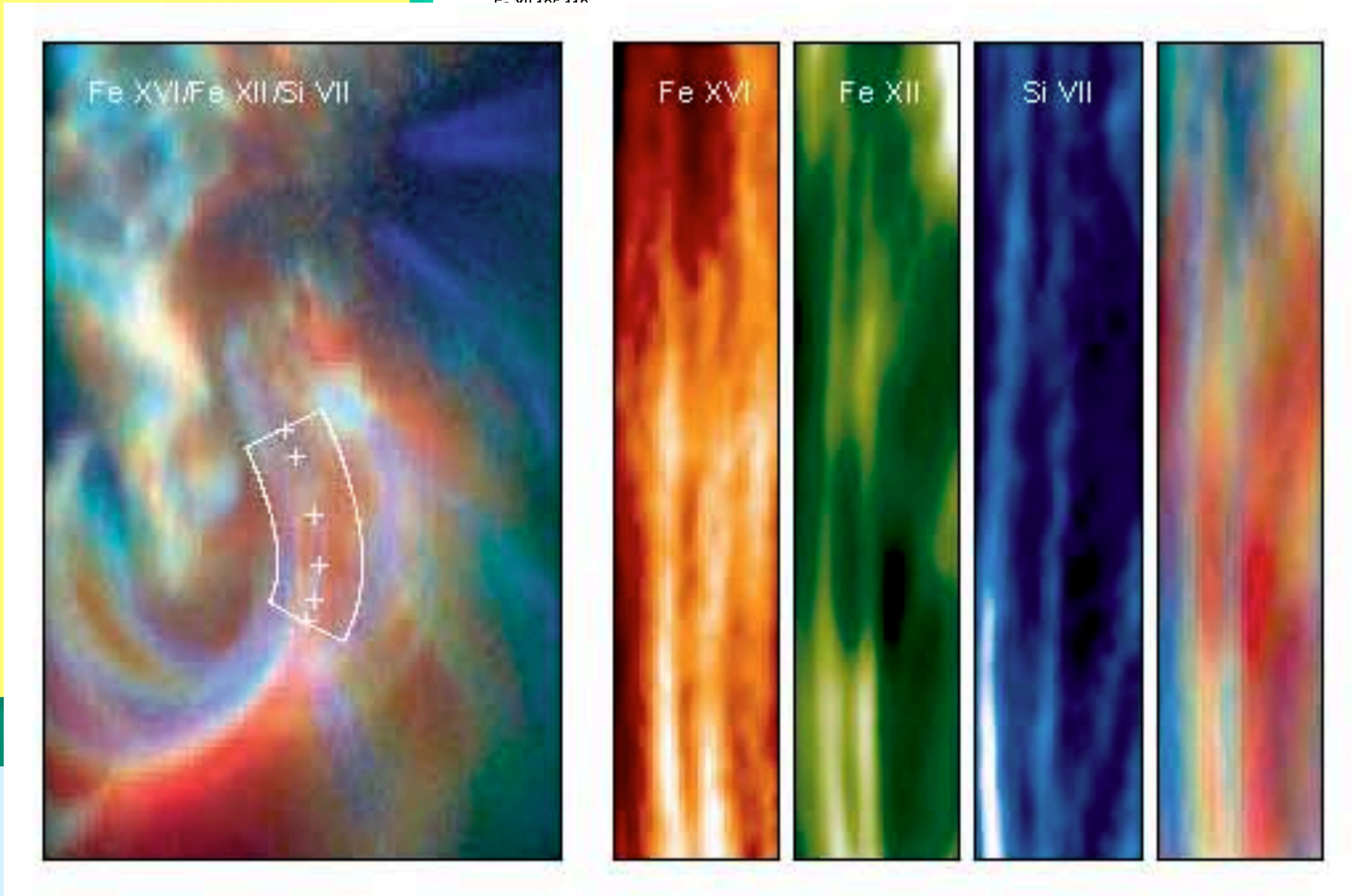


Flare loop, missing high temperatures complicates comparisons to models; models do not agree with observations at high temperatures

***Hinode*/XRT**

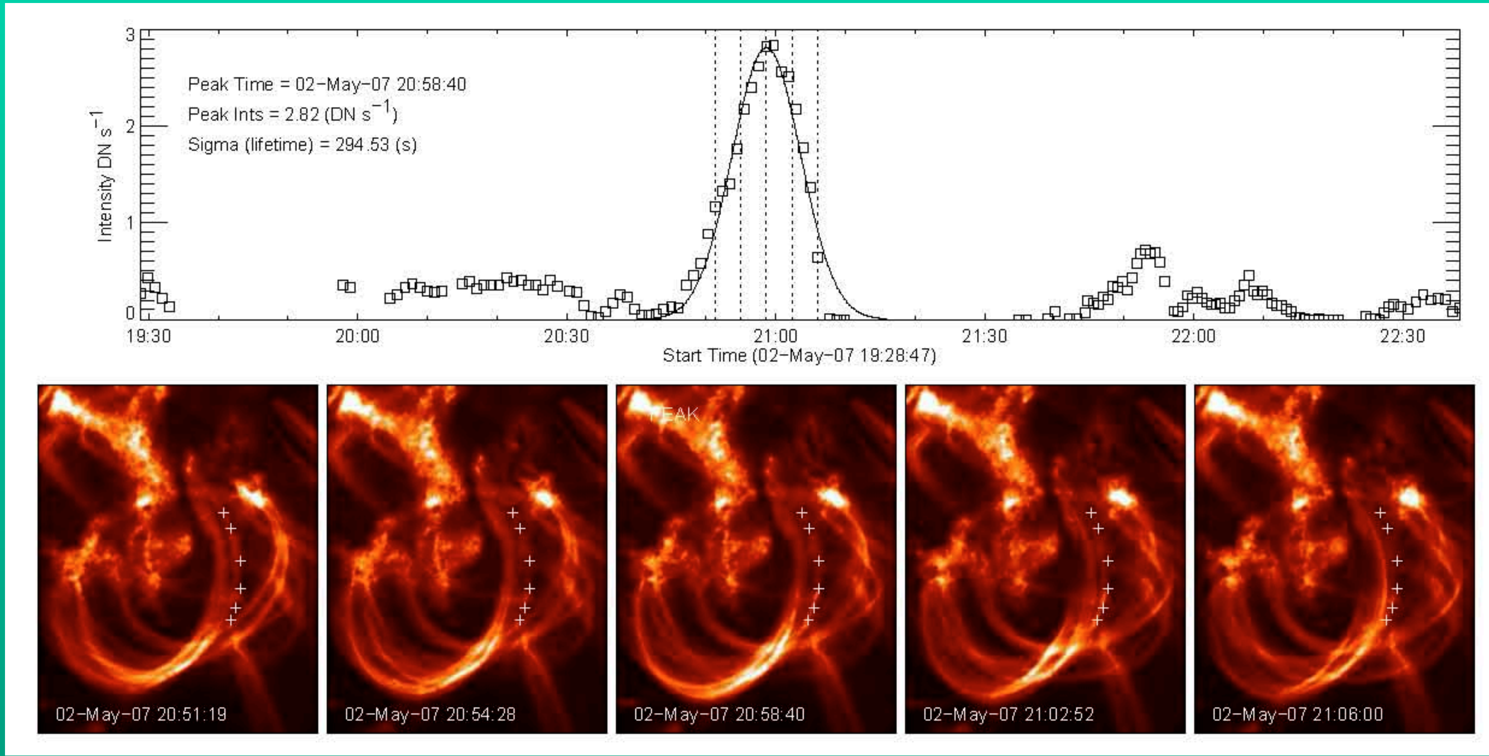


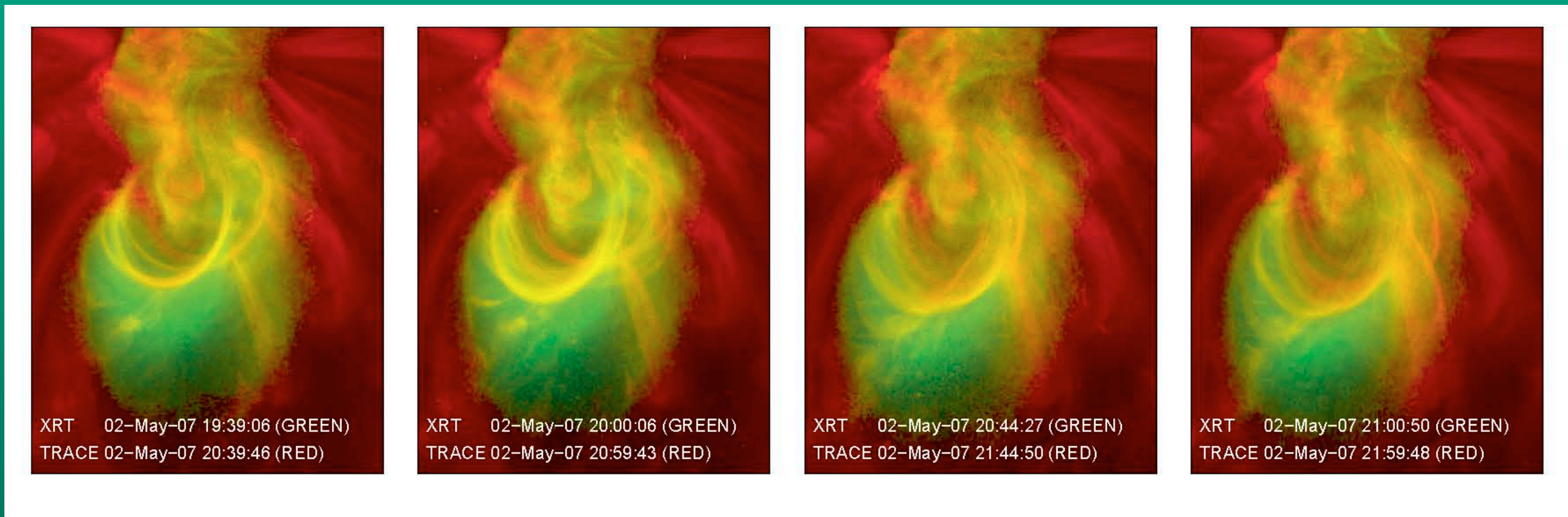
Warren, Kim, DeGiorgi, & Urgarte-Urra, ApJ, in press (2010)



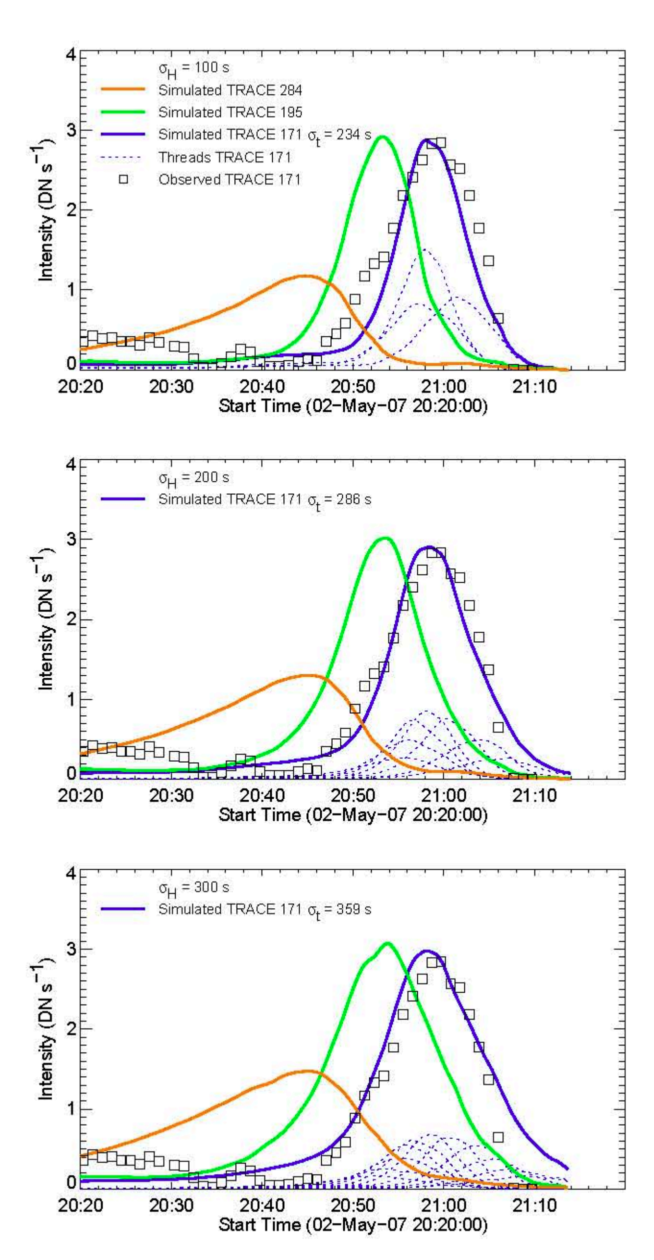
require impulsive heating models.

Warren, Kim, DeGiorgi, & Urgarte-Urra, ApJ, in press (2010)

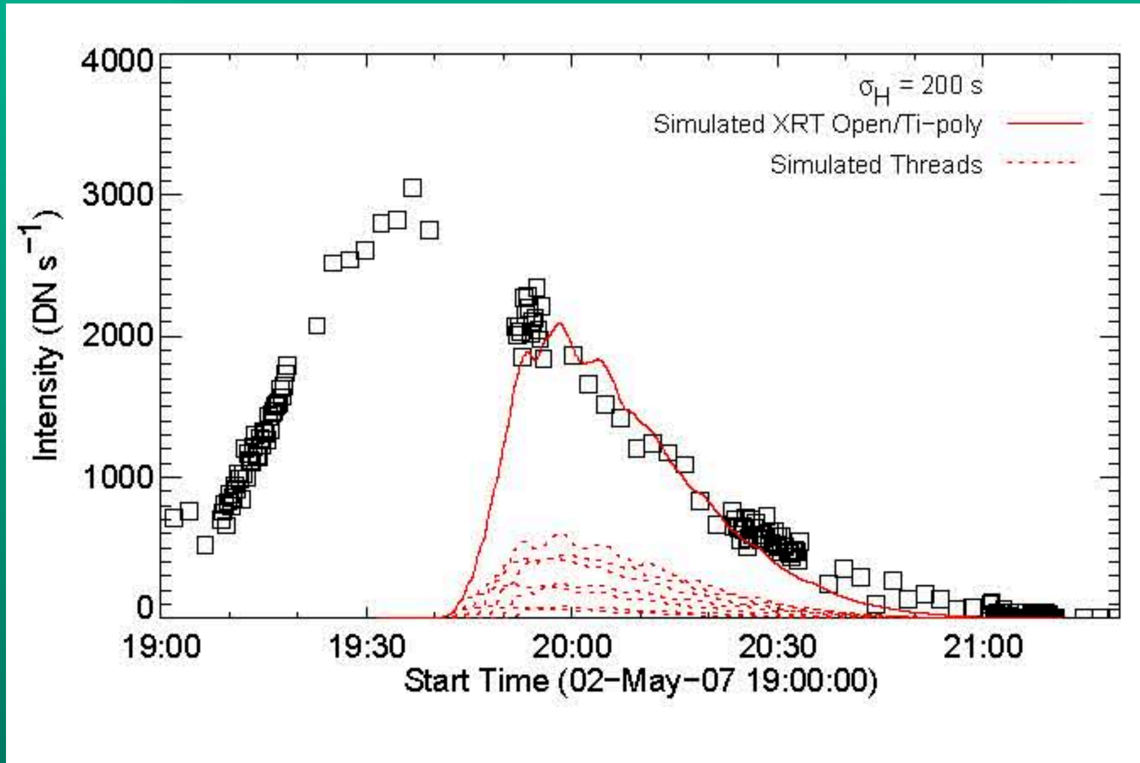




Warren, Kim, DeGiorgi, & Urgarte-Urra, ApJ, in press (2010)

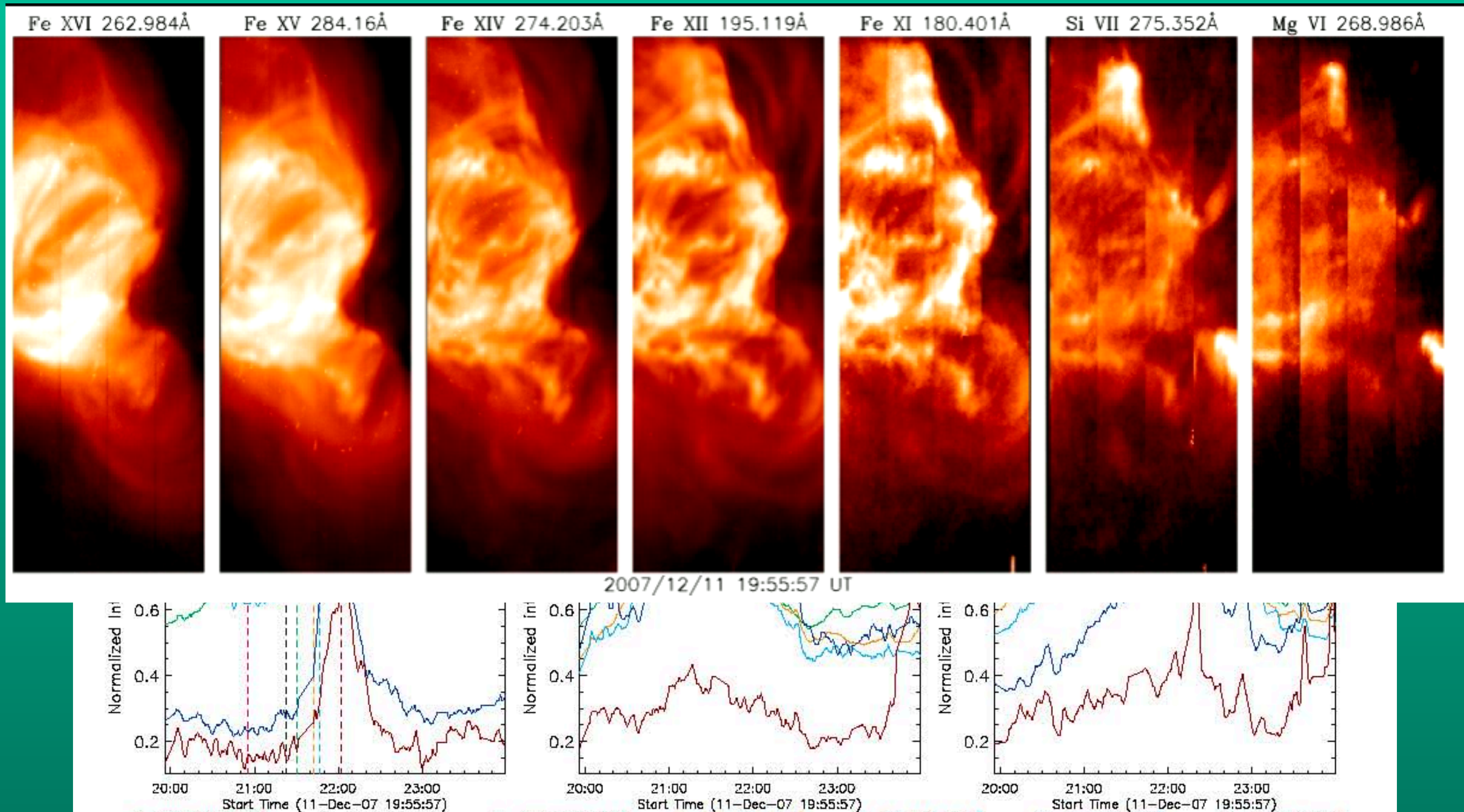


Multi-thread loop modeling of a post-flare loop. The models reproduce the "warm" emission well but fail to reproduce the "hot" emission observed by XRT. Temperature continuity is inadequate.



Warren, Kim, DeGiorgi, & Urgarte-Urra, ApJ, in press (2010)

***Hinode*/EIS 40” slot rasters of the “hot” (~3 MK) core of an active region. Light curves correspond to positions in the active region indicated by boxes. Loops cool from 3 MK or more to the lowest observable EIS temperatures. What happens when the temperatures reach lower transition region and chromospheric temperatures? Is the loop plasma visible as “coronal rain”? No one knows.**



Ugarte-Urra, Warren, & Brooks, ApJ, 695, 642 (2009)

Hinode Results

Hot 3 MK core active region loop cooling. Steady heating models can explain the emission. Impulsive heating models are needed to explain the "warm" loops outside the active region cores. (From Ugarte-Urra, Warren, & Brooks, ApJ, 695, 642 2009)

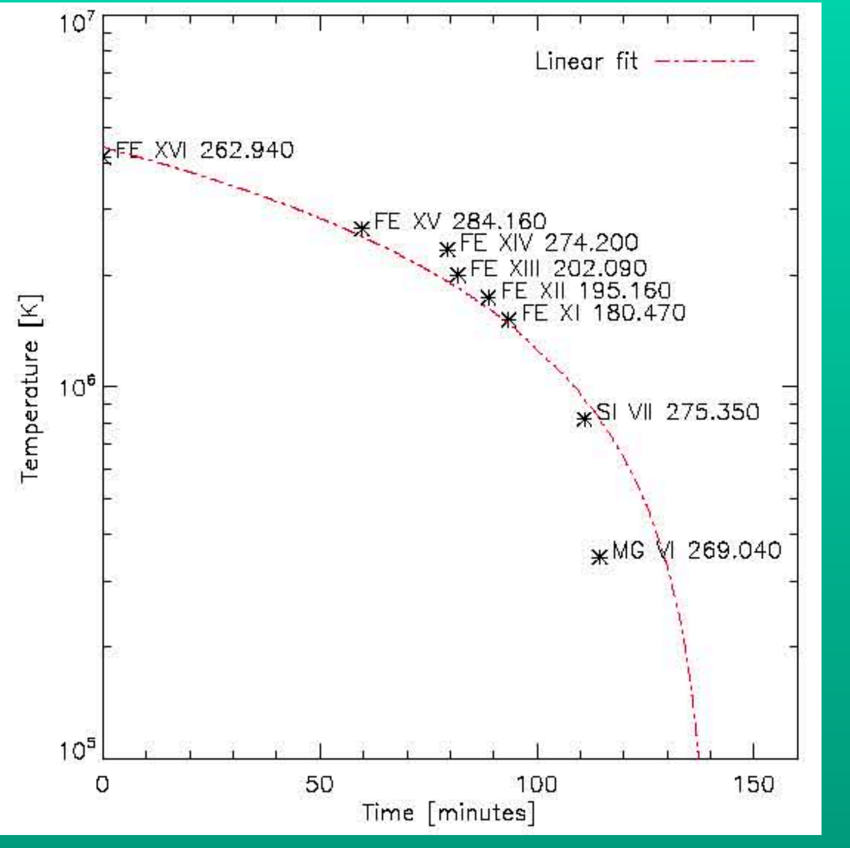
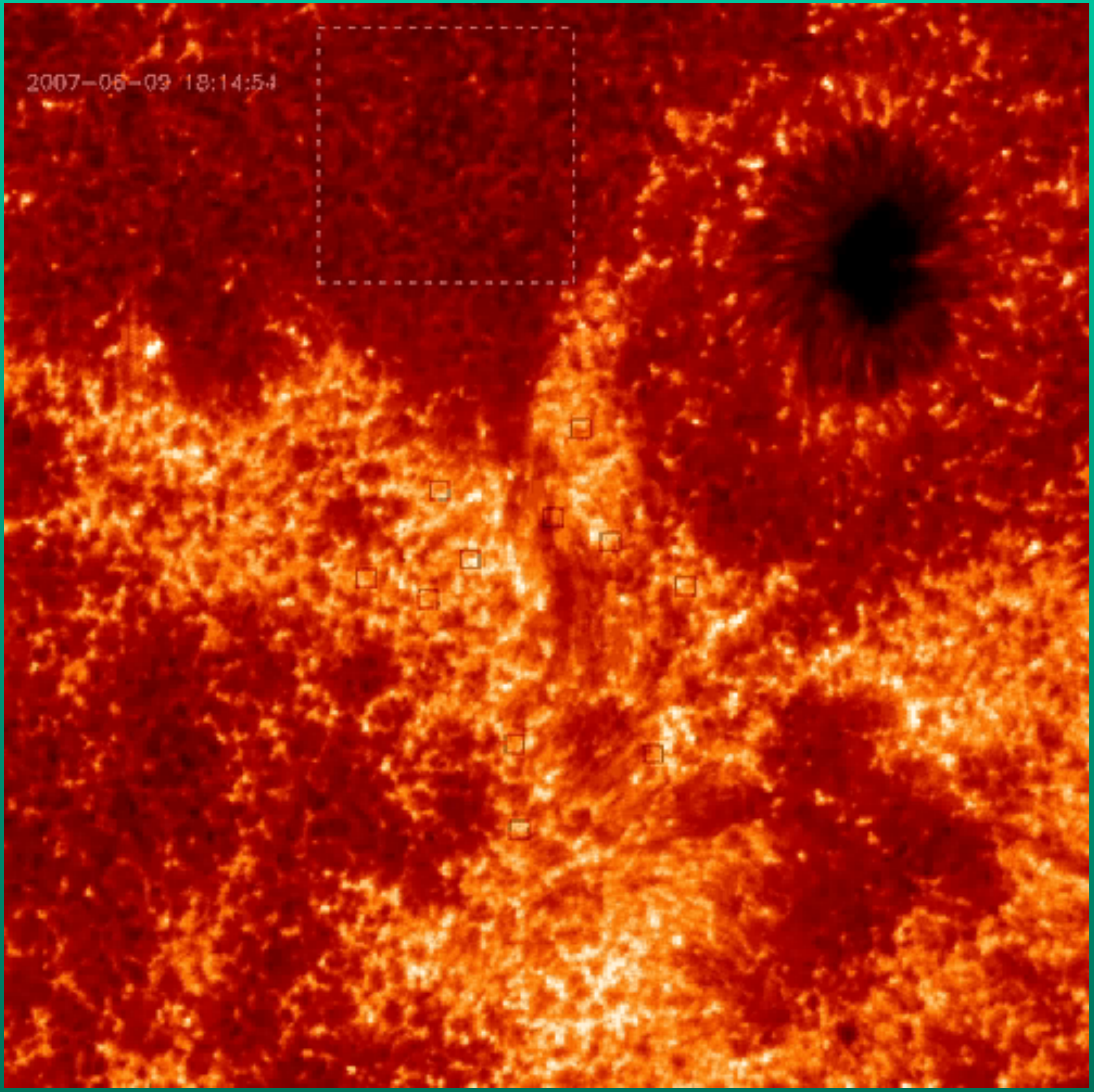
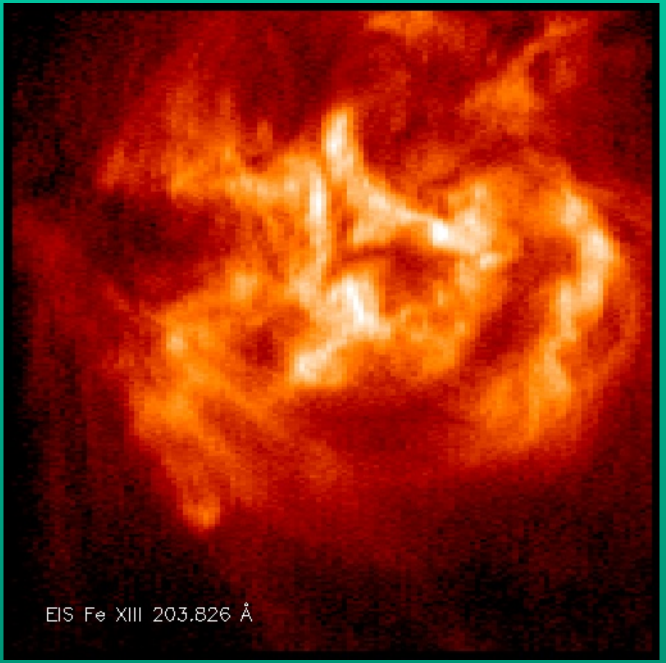


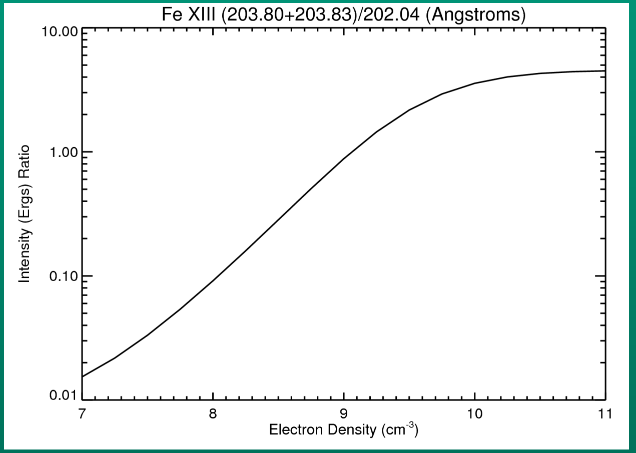
Table 2. Sample of loop lifetimes

No.	Date	Fe XV Start Time	Fe XV Lifetime	Fe XII Start Time	Fe XII Lifetime	Si VII Start Time	Si VII Lifetime	Mg VI Start Time	Mg VI Lifetime
1	2007/12/09	13:53:35	770s	14:06:24	630s	14:16:55	770s	14:18:05	770s
2	2007/12/09	14:36:45	770s	14:43:46	560s	14:44:55	560s	14:44:55	560s
3	2007/12/10	13:54:53	1820s	14:10:04	1050s	14:17:04	840s	14:19:23	770s
4	2007/12/10	13:56:02	1261s	14:05:23	980s	14:06:34	840s	14:07:43	770s
5	2007/12/11	07:23:45	1470s	07:38:55	840s	07:43:35	1121s	07:44:45	981s
6	2007/12/11	20:49:40	3431s	21:24:40	1540s	21:49:10	1121s	21:52:41	1190s
7	2007/12/12	19:51:51	1961s	20:18:41	1330s	20:28:01	1332s	20:29:12	1191s
8	2007/12/12	20:42:02	1786s	21:05:24	1226s	21:22:20	1190s	21:24:39	1120s
9	2007/12/13	21:04:13	4165s	21:39:16	1993s	22:27:40	1820s	-	-

•Spatial resolution and moss
•TRACE/XRT/EIS show steady heating (no intensity variations) in the moss at 1”+
•SOT reveals intensity variations within the moss at 0.2” resolution





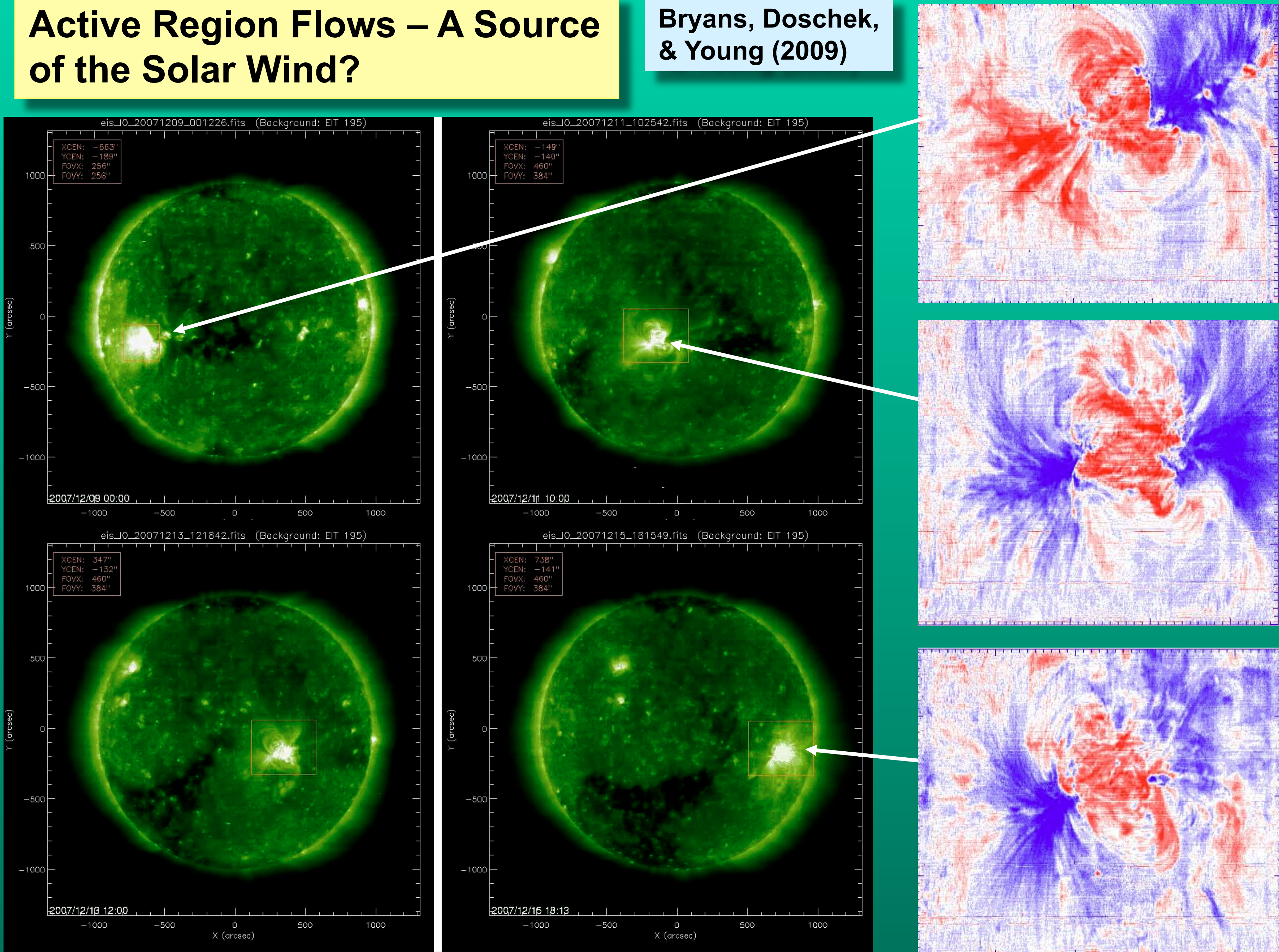


Active Regions as a Source of the Solar Wind

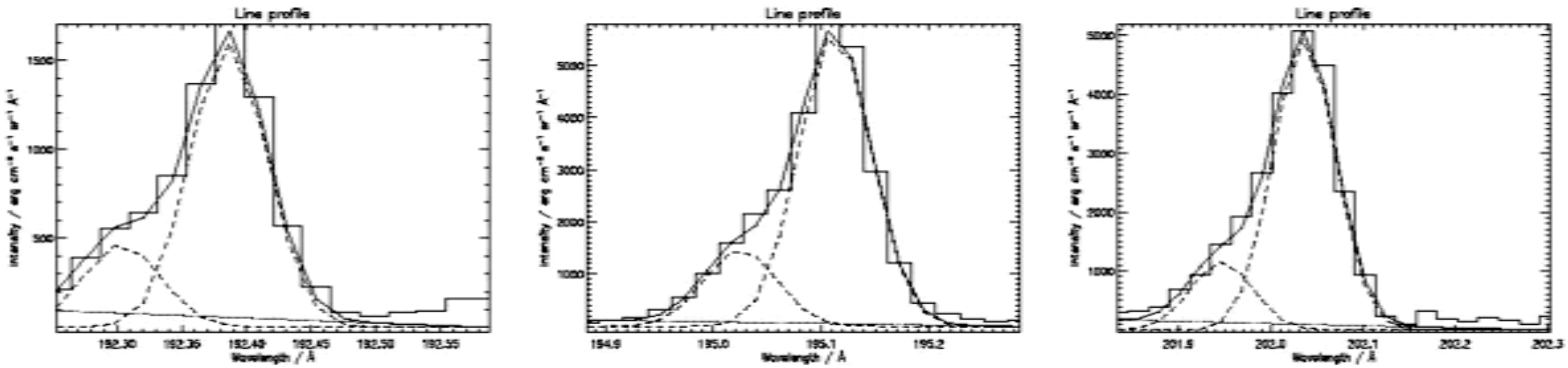
- The high speed solar wind (~ 800 km/s) comes from open field regions such as coronal holes.
- The sources of the slow solar wind (~400 km/s) are not known. Both slow and fast wind is relevant for Space Weather.
- EIS and XRT on *Hinode* have confirmed that large outflows occur at the edges of active regions, but it is not clear that these outflows result in solar wind. They may be simply confined to very long closed flux tubes.
- Magnetic field extrapolations out into the heliosphere indicate that active regions might be a significant source of the slow solar wind.

Active Region Flows – A Source of the Solar Wind?

Bryans, Doschek, & Young (2009)



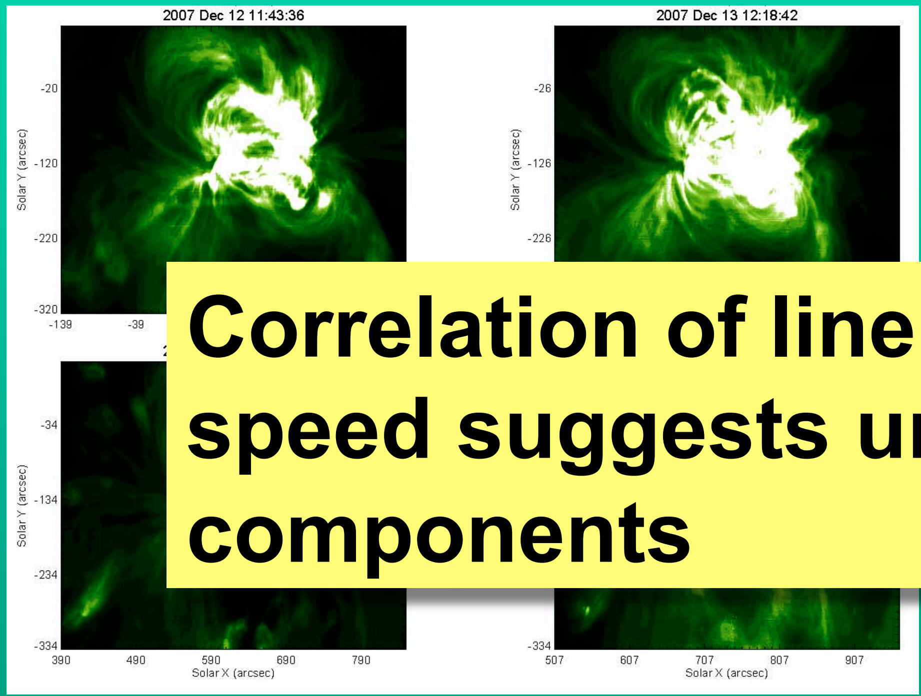
Active Region Flows

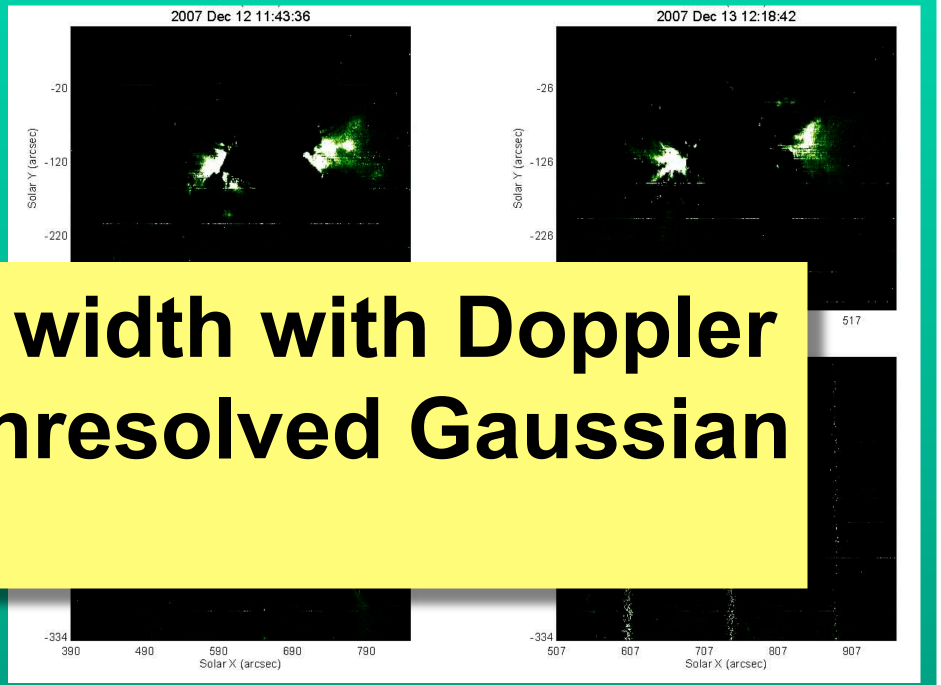


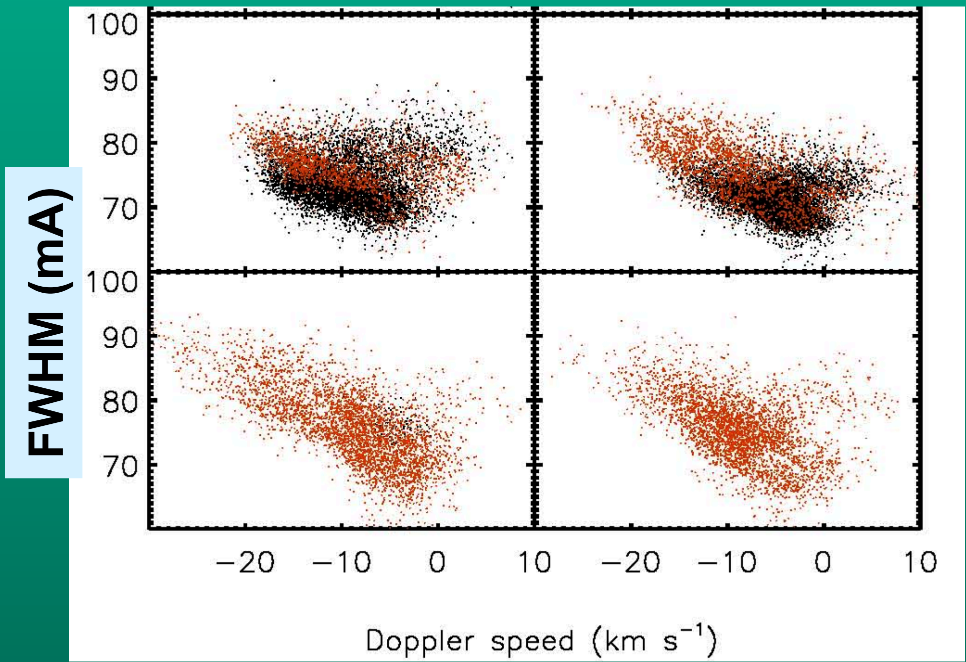
(a) Fe XII 192.39 Å (b) Fe XII 195.12 Å (c) Fe XIII 202.04 Å

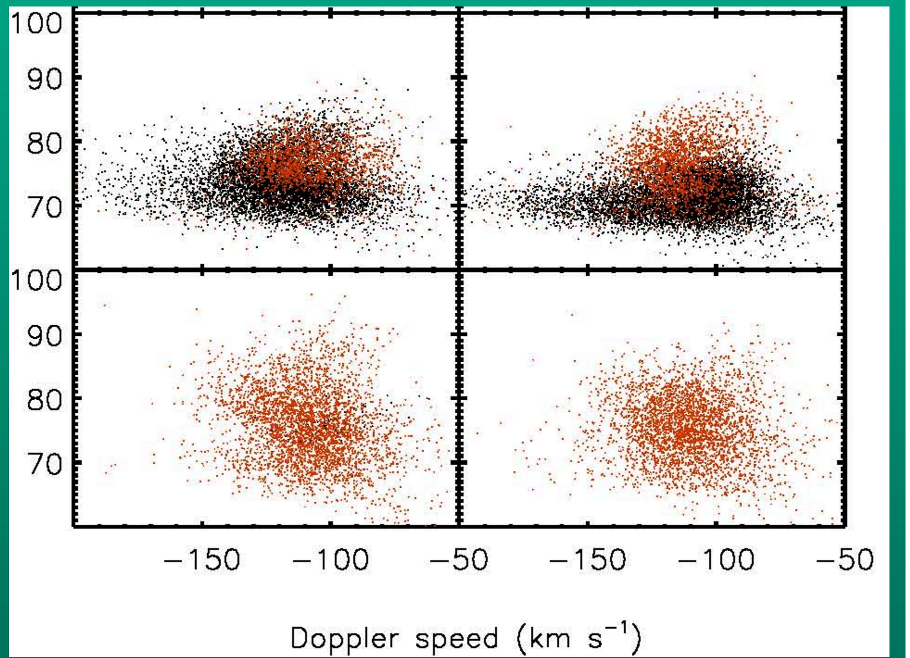
Two flow speeds: 20 and 200 km/s
The active region contains unresolved multiple Gaussian components

Correlation of line width with Doppler speed suggests unresolved Gaussian components

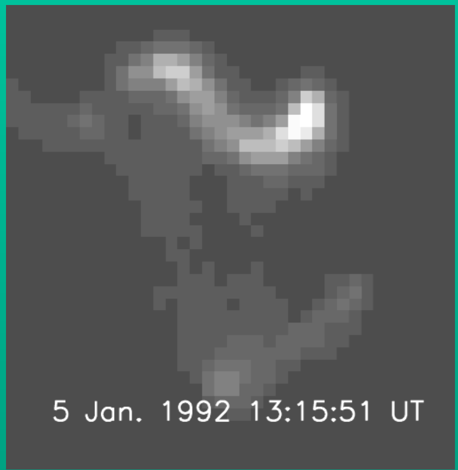


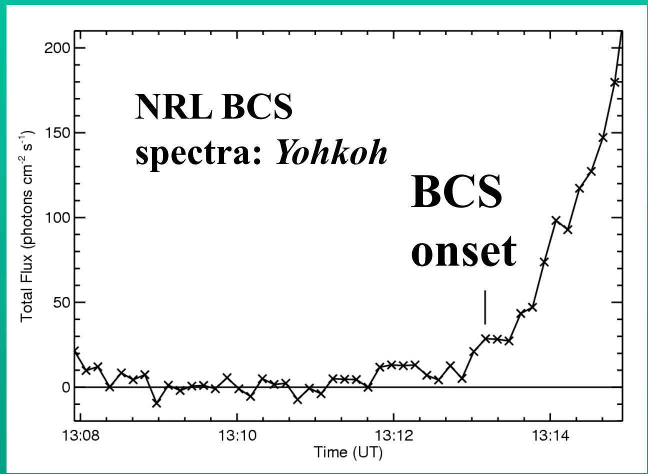






The First Sign of Multi-million Degree Solar Flare Loops is in the Corona – Unresolved Magnetic Threads





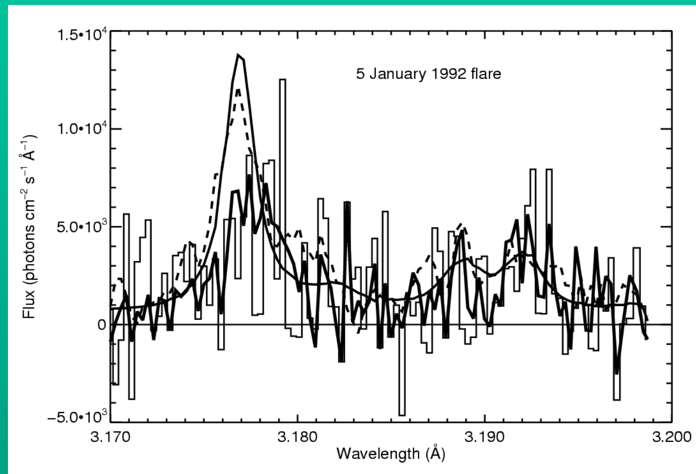


Table 2: Soft X-ray Flare Onset Time Parameters

Parameter	1992 Jan. 5	1992 Sep. 6 (05 UT)	1992 Sep. 6 (08 UT)
Electron Temperature (K)	12×10^6	12×10^6	12×10^6
Emission Measure (cm^3)	6.4×10^{46}	4.9×10^{46}	5.9×10^{46}
Electron Density (cm^{-3})	3.8×10^{10}	3.0×10^{10}	3.7×10^{10}
Loop Volume (cm^3)	4.4×10^{25}	5.4×10^{25}	4.2×10^{25}
Energy Content (ergs)	8.3×10^{27}	8.2×10^{27}	7.7×10^{27}

Linking the origin of the coronal activity to the energy sources in the photosphere requires high spatial resolution

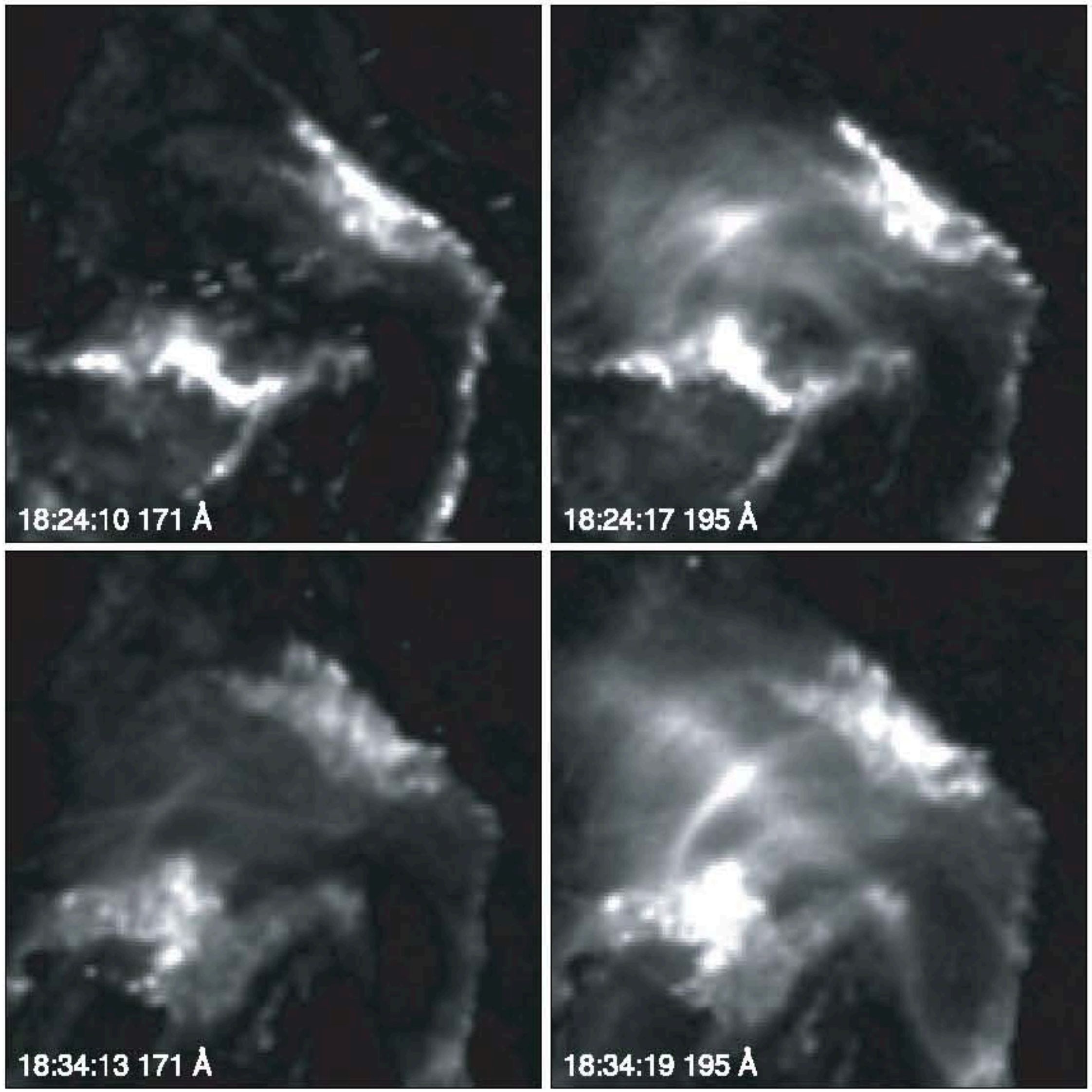
Images of Multi-million Degree Flare Loops

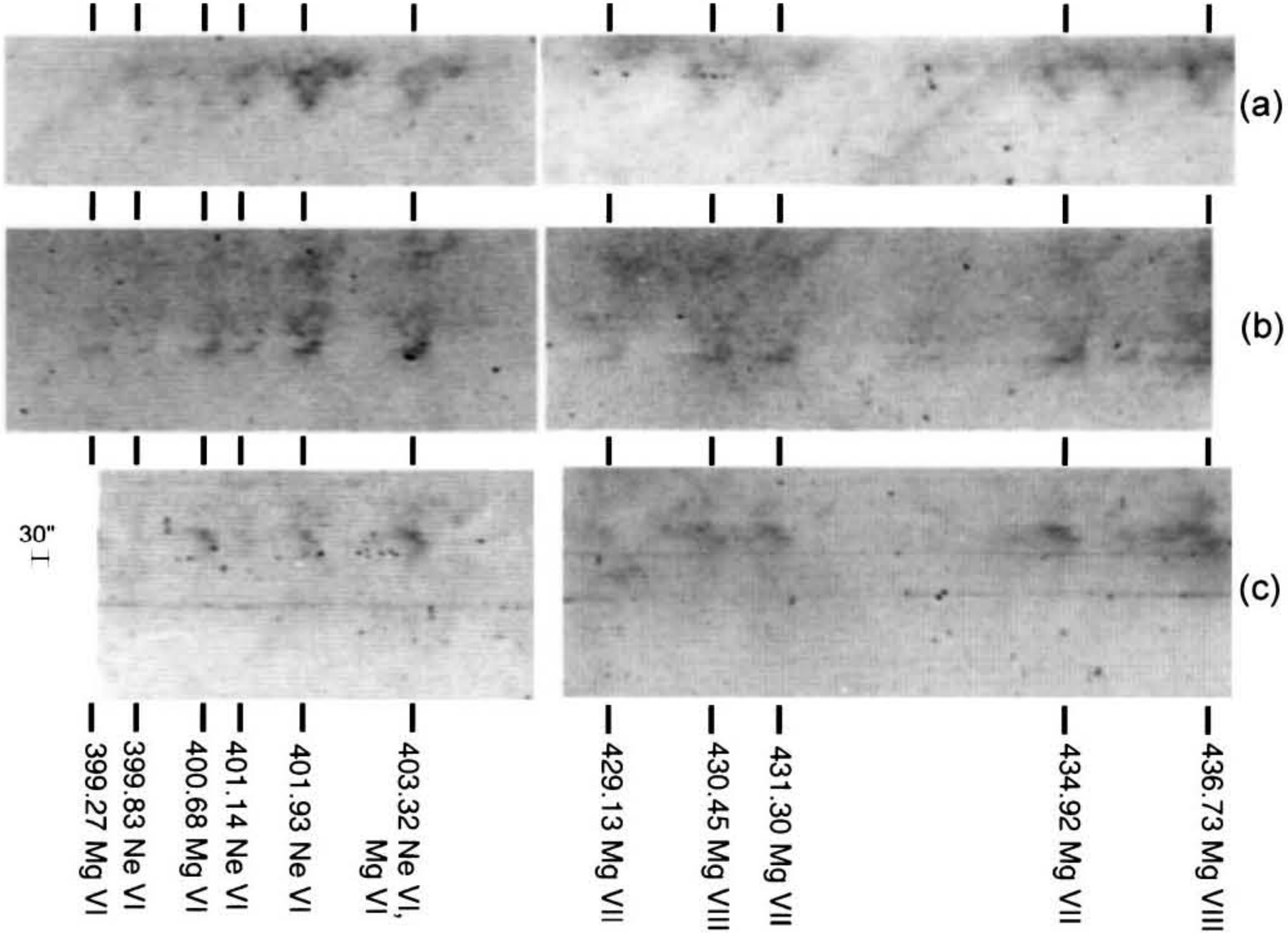
- Do flare loops at temperatures of 12-25 MK look like what we expect?
  - No, they don't, but as they cool to 1-3 MK they look more and more like respectable 1D loops should.

TRACE/*Hinode* observations confirm the gross flare loop morphology seen by *Yohkoh*, but the higher Plan B resolution allows far more detailed observations of the reconnection region and current sheet.

Solar Flare Arcade from TRACE

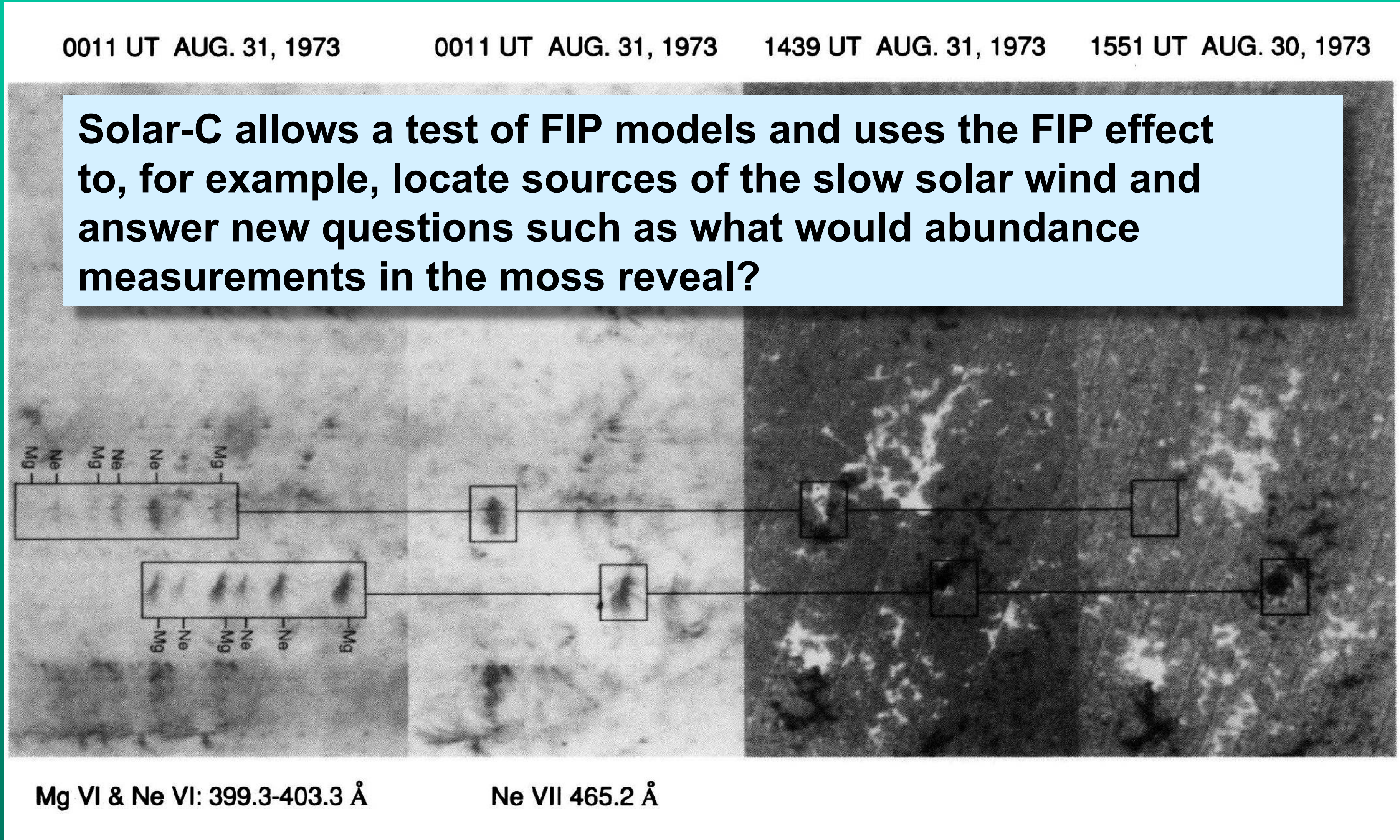
Testing the solar flare Standard Model requires continuous temperature coverage from <0.1 MK to >20 MK. Hot spots at the tops of "reconnected" loops and non-uniform intensity distributions in the multi-million degree loops are difficult to understand with the Standard Model. (See Reeves et al., ApJ, 668, 1210 (2007) for an explanation of the hot spots).





(a)
(b)
(c)
30"
399.27 Mg VI
399.83 Ne VI
400.68 Mg VI
401.14 Ne VI
401.93 Ne VI
403.32 Ne VI, Mg VI
429.13 Mg VII
430.45 Mg VIII
431.30 Mg VII
434.92 Mg VII
436.73 Mg VIII

• Abundances can trace the origins of plasma (e.g., slow solar wind)
• Abundance measurements are best with neon and argon in the corona
• Abundance measurements require high resolution spectroscopy



Solar-C allows a test of FIP models and uses the FIP effect to, for example, locate sources of the slow solar wind and answer new questions such as what would abundance measurements in the moss reveal?

Sheeley, ApJ, 440, 884 (1995)

Conclusions

- *Hinode* is teaching us much about active region heating and dynamics.
  - Loop model tests (e.g., nanoflare models)
  - Newly discovered coronal flows that might contribute to the solar wind
- However, the work with *Hinode* raises new questions that require higher spatial resolution, more spectral coverage, and higher temporal resolution to answer.
- Plan B, with the combination of high spatial/spectral resolution and throughput, coupled with large spectral range, is NOT an incremental advance. It is a quantum leap forward.
- A personal view: To do Plan B properly, there should be *equal emphasis on all temperature regions of the solar atmosphere. Neglect of any temperature region is unacceptable.*