High Resolution X-ray – UV Solar Spectroscopy: Past Achievements and Future Directions

by
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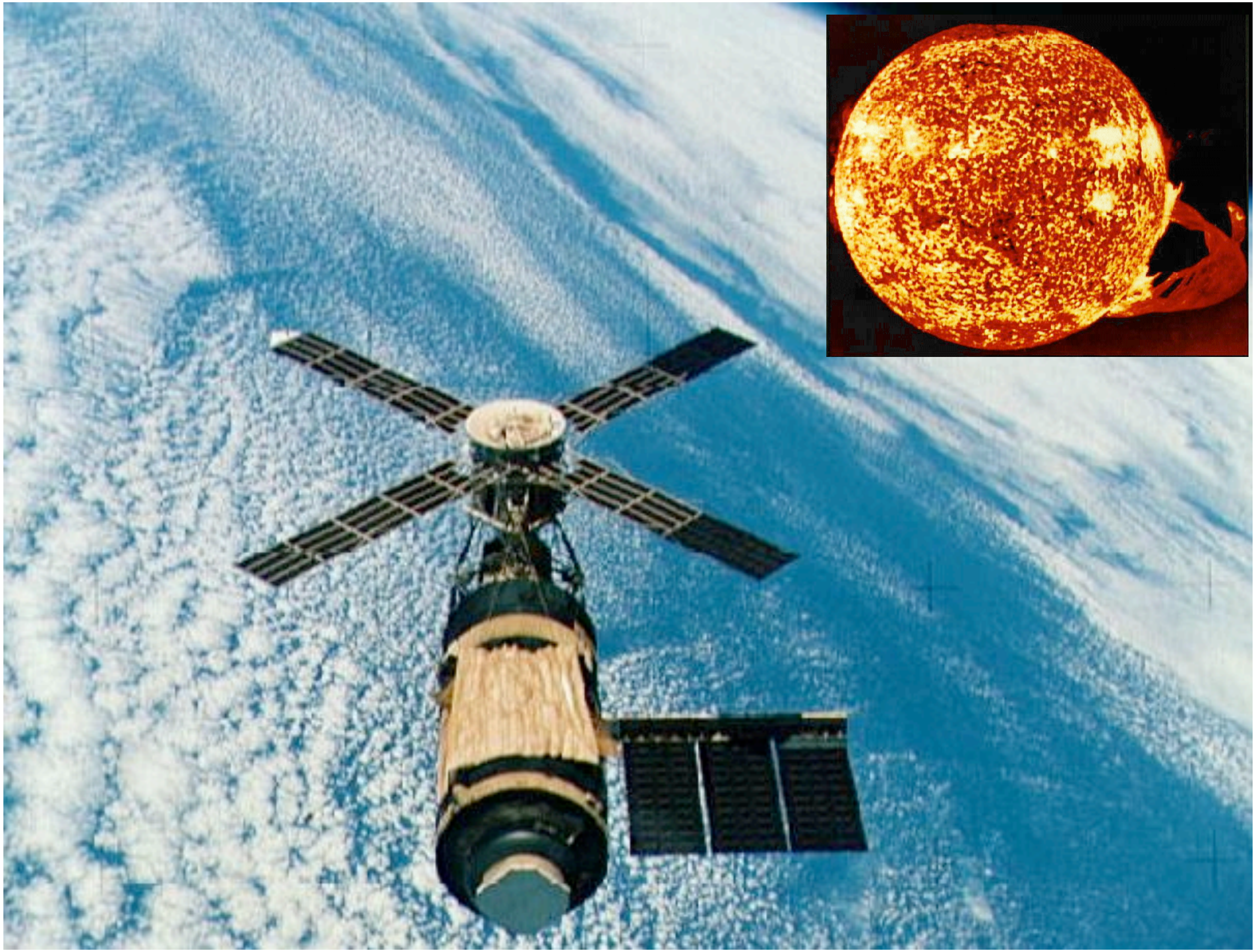
Presented at: Solar Plasma Spectroscopy: Achievements and Future Challenges (Celebrating the Career of Dr. Helen Mason)

DAMTP, University of Cambridge, 13-15 September 2010

Skylab Manned Space Station and Apollo Telescope Mount - 1973



Solar Spectroscopy in the Early 1970s

- *Pure Spectroscopy*: Many strong spectral lines were not identified (e.g., Fe XXIII 263 Å in flares).
- *Atomic Physics*: There were very little atomic data (e.g., excitation rate cross sections, radiative transition probabilities) for highly ionized atoms such as found in the solar transition region and corona. People used the Gaunt factor approximation.
- *Plasma Diagnostics*: Very little knowledge of useful spectral diagnostics for highly ionized atoms, e.g., density sensitive line ratios. No user-friendly computer programs for calculating differential emission measure distributions, etc. The FIP effect was unknown.
- As a result, there was no CHIANTI !! (Arghhh !!!!!!!!)

Spectroscopically Exploring the Solar Atmosphere in Temperature Space

- **Visible to ~1900 Å: Dominated by the continuum, mostly absorption lines**
- **1700 – 1100 Å: The photosphere, chromosphere, lower transition region. A few coronal lines for above the limb (no coronal disk observations)**
  - **UV allowed and intersystem lines of ions, e.g., C I – C IV, N IV, N V, O I – O V, Si IV, S IV**
  - **Forbidden and intersystem lines of coronal ions, e.g., Si VIII, Fe X, Fe XI, and Fe XII; flare forbidden line of Fe XXI**
  - **Temperatures from 1 x 10^4 K to about 2.5 x 10^5 K**
- **1100 Å – 500 Å: the lower and upper transition region but limited coronal access for disk observations, some forbidden lines for flares, e.g., Fe XVII, Fe XVIII, Fe XIX, Fe XXII**
  - **UV/EUV allowed lines of ions such as O II – O VI, H I, He I, He II**
  - **Temperatures from 2.5 x 10^5 K up to about 1 x 10^6 K**
- **500 Å – 170 A: the corona and flares (some transition region lines)**
  - **Coronal allowed lines of many ions (e.g., Fe IX – Fe XVII, Ca XIV – Ca XVII), flare lines of Fe XXII, Fe XXIII, Fe XXIV**
  - **Temperatures from about 8 x 10^5 K up to about 20 x 10^6 K**
- **Below 170 Å : flare allowed lines of Fe XVIII through Fe XXIII between about 90 Å and 140 Å.**

Astron. Astrophys. 73, 74–81 (1979)

ASTRONOMY AND ASTROPHYSICS

Fe XXI as an Electron Density Diagnostic in Solar Flares

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Summary. New atomic data have been calculated for Fe XXI and the theoretical intensity ratios for many transitions are tabulated. Fe XXI lines in wavelength regions 1–25 Å, 90–200 Å and 300–2500 Å are discussed with reference to presently available solar and laboratory spectra. We find that Fe XXI is an excellent density diagnostic for solar flare and tokamak plasmas, when densities are in the range 10^{11} to 10^{15} cm^{-3}. The theoretical calculations are applied to flare spectra obtained from OSO-5 and an electron density of $<10^{13}$ cm^{-3}, for a temperature of 10^7 K is deduced. The results are somewhat ambiguous in several cases because of the limited spectral and temporal resolution of these earlier spectrometers. However, the calculations will be important for forthcoming solar projects such as the Solar Maximum Mission.

Key words: solar flare – Fe XXI – atomic structure – electron collision strength

5th 1973 flare). Using data recorded by the AS & E X-ray telescope on Skylab, Pallavicini et al. (1975) obtained a density of 1.5 $\rightarrow 5\ 10^{10}$ cm^{-3} for the flare of 15 June 1973 for plasma at temperatures above 10^6 K.

There are two main uncertainties concerning the results quoted above. First, the internal consistency of the mathematical methods involved in 'emission measure' distribution analyses has been questioned (see for example Craig and Brown, 1976). Secondly, and more important, it is possible that filamentary structures exist in the flare which are smaller than the spatial resolution of the instrument. In this case, the "filling factor" is no longer unity as assumed in these analyses and the derived densities are lower limits that can be in considerable error. It is therefore necessary to obtain density estimates which are independent of both of these uncertainties. This can be achieved by using intensity ratios of two lines from the same ion as a density diagnostic. Such studies have already been carried out for several coronal ions (Dere et al., 1978) for Ca XVII (Doschek et al., 1977)

SDO/EVE flare spectra

Table 6. Theoretical intensity ratios for transitions with $200 > \lambda > 90$ Å as a function of electron density, for an electron temperature of 10^7 K

Tran-sition *j*	*i*	λ(Å) Theory	λ(Å) Kastner et al., (1974)	λ(Å) Kononov et al., (1976)	Theoretical intensity ratios relative to transition 7–1 for $\text{Log}_{10} N_e$ (cm^{-3}) = 11.0	11.5	12.0	12.5	13.0	14.0	15.0
2	1				0.088	0.087	0.085	0.079	0.067	0.022	0.003
7	1	131	128.74	128.73	1	1	1	1	1	1	1
8	2	144	142.18	142 14	0.013	0.023	0.055	0.147	0.379	1.246	1.465
9	3	147	145.66	145.66	0.009	0.027	0.072	0.165	0.331	0.942	1.350
9	4	179			0.001	0.003	0.009	0.020	0.040	0.115	0.165
10	2	120	118.70	118.70	0.002	0.005	0.015	0.043	0.115	0.381	0.448
11	1	109	108.37	108.45	0.048	0.049	0.055	0.069	0.102	0.224	0.261
11	2	119	117.81	117.89	0.168	0.174	0.192	0.241	0.356	0.780	0.910
11	3	125	123.76	124.25	0.030	0.031	0.034	0.043	0.064	0.140	0.163
12	3	122	121.17	121.22	0.015	0.044	0.118	0.271	0.538	1.422	1.886
13	1	92	91.21	91.29	0.039	0.044	0.055	0.081	0.129	0.296	0.368
13	2	98		97.89	0.099	0.110	0.139	0.204	0.327	0.747	0.930
13	3	102		102.23	0.228	0.254	0.321	0.469	0.753	1.720	2.144
14	3	98			0.001	0.002	0.005	0.012	0.031	0.205	0.447
14	4	113	113.45	113.25	0.003	0.008	0.023	0.060	0.159	1.061	2.310
15	2	84			0.000	0.000	0.000	0.001	0.005	0.050	0.126
15	4	99		98.51	0.001	0.001	0.004	0.015	0.059	0.597	1.498
15	5	112	112.52	112.47	0.000	0.000	0.001	0.004	0.014	0.139	0.350

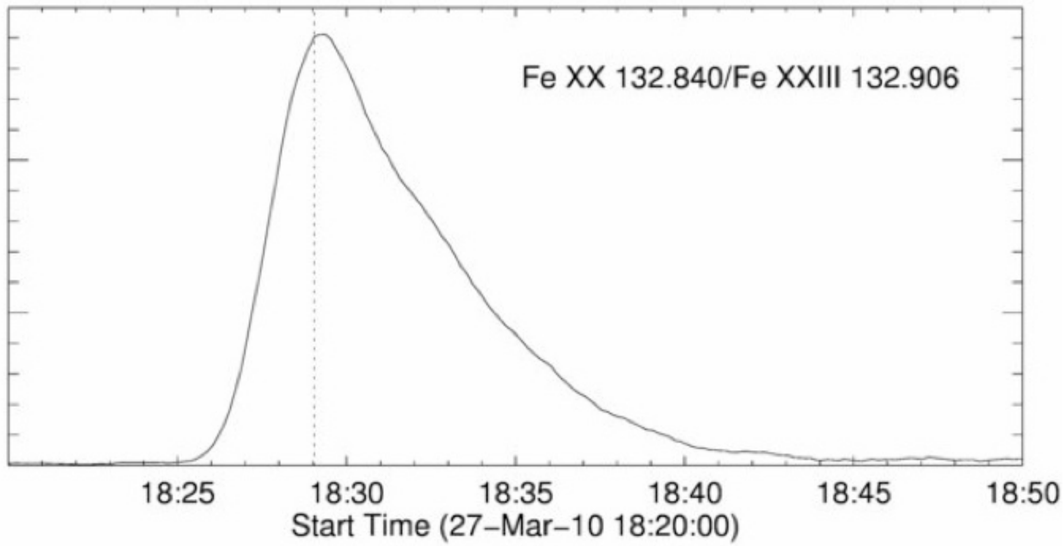
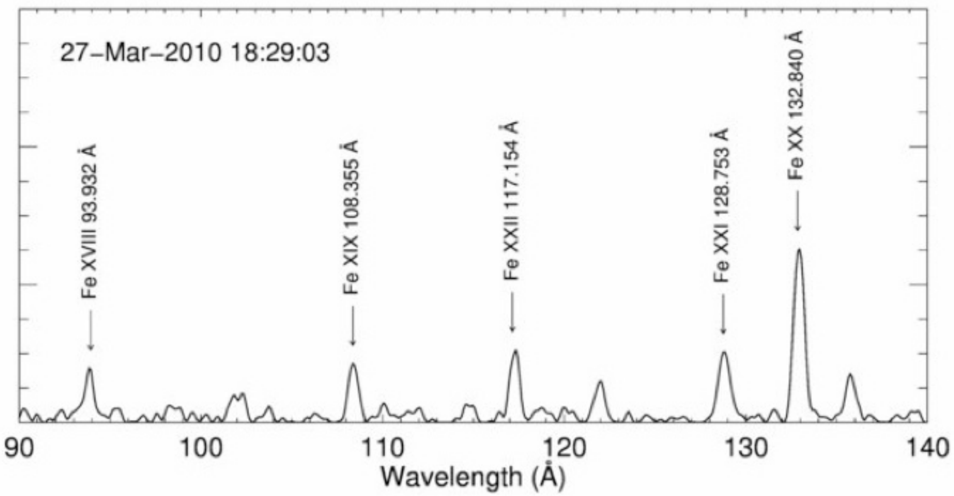
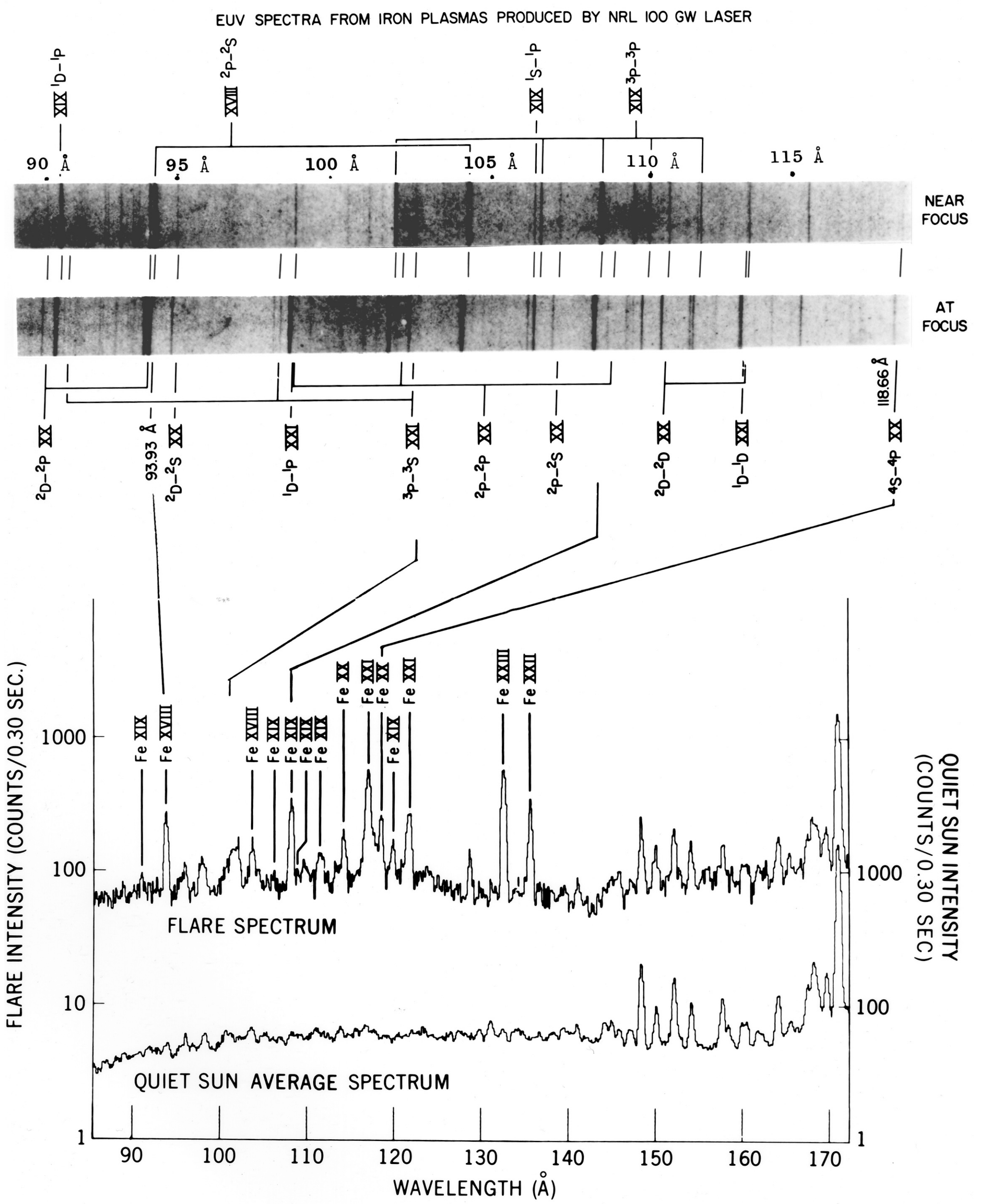


Table 7. Observed intensities for the Fe XXI XUV lines, taken from Table 2 of Kastner et al., 1974

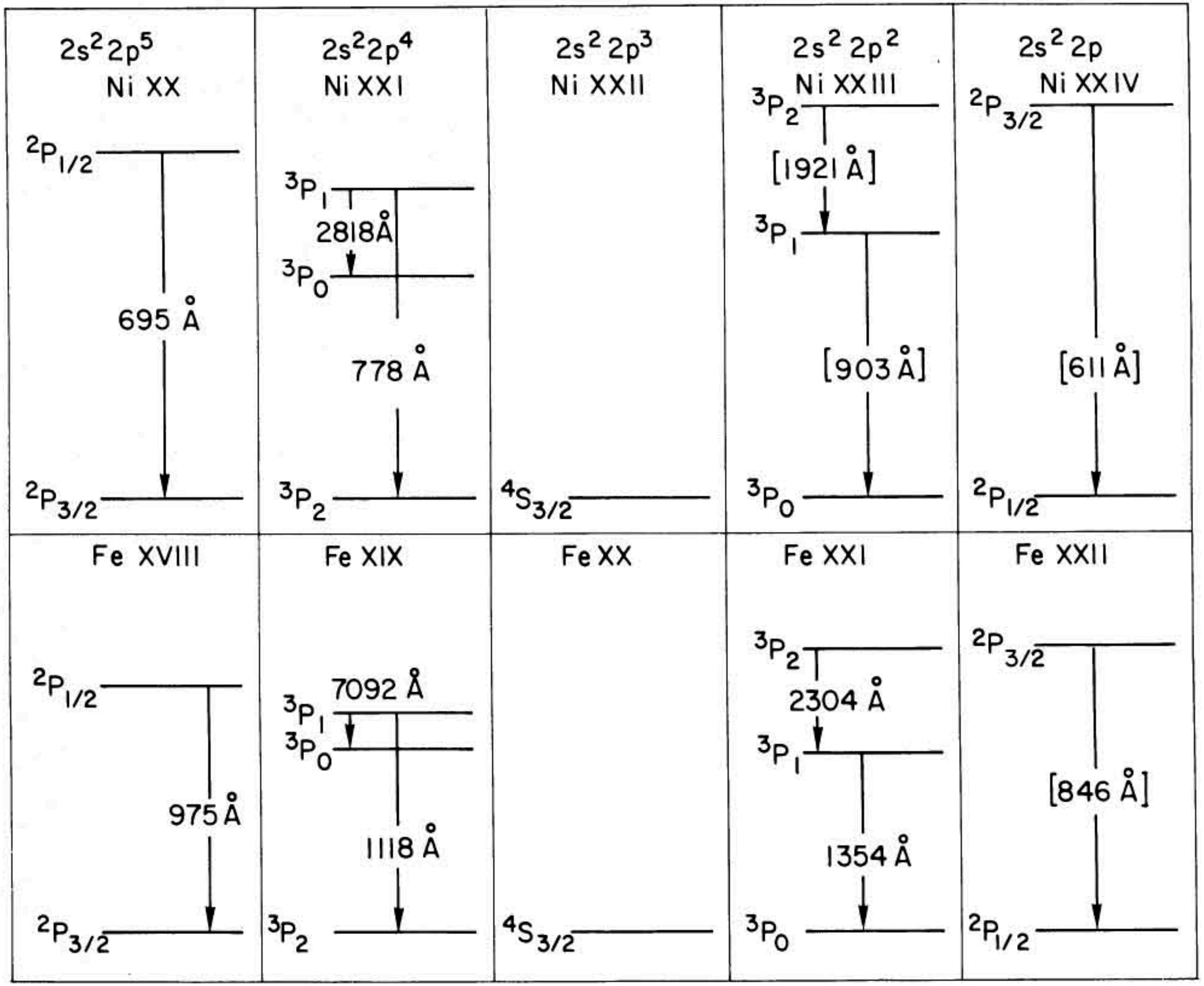
	Flare *E*			Flare *B*		
λ(Å)	Intensity (counts per 0.30 s)	$I_\lambda / I(\lambda 128)$	N_e (cm^{-3})	Intensity (counts per 0.30 s)	$I_\lambda / I(\lambda 128)$	N_e (cm^{-3})
102.35	111	1.2	$<2 \times 10^{13}$	110	0.15	$<10^{11}$
113.45	54	0.6	$<5 \times 10^{13}$	27	0.038	$<2 \times 10^{12}$
121.17	-	-		34	0.048	$<3 \times 10^{11}$
128.74	90	11		712	1	
142.18	15	0.2	$<5 \times 10^{12}$	94	0.132	$<2 \times 10^{12}$
145.66	-	-		45	0.063	$<10^{12}$



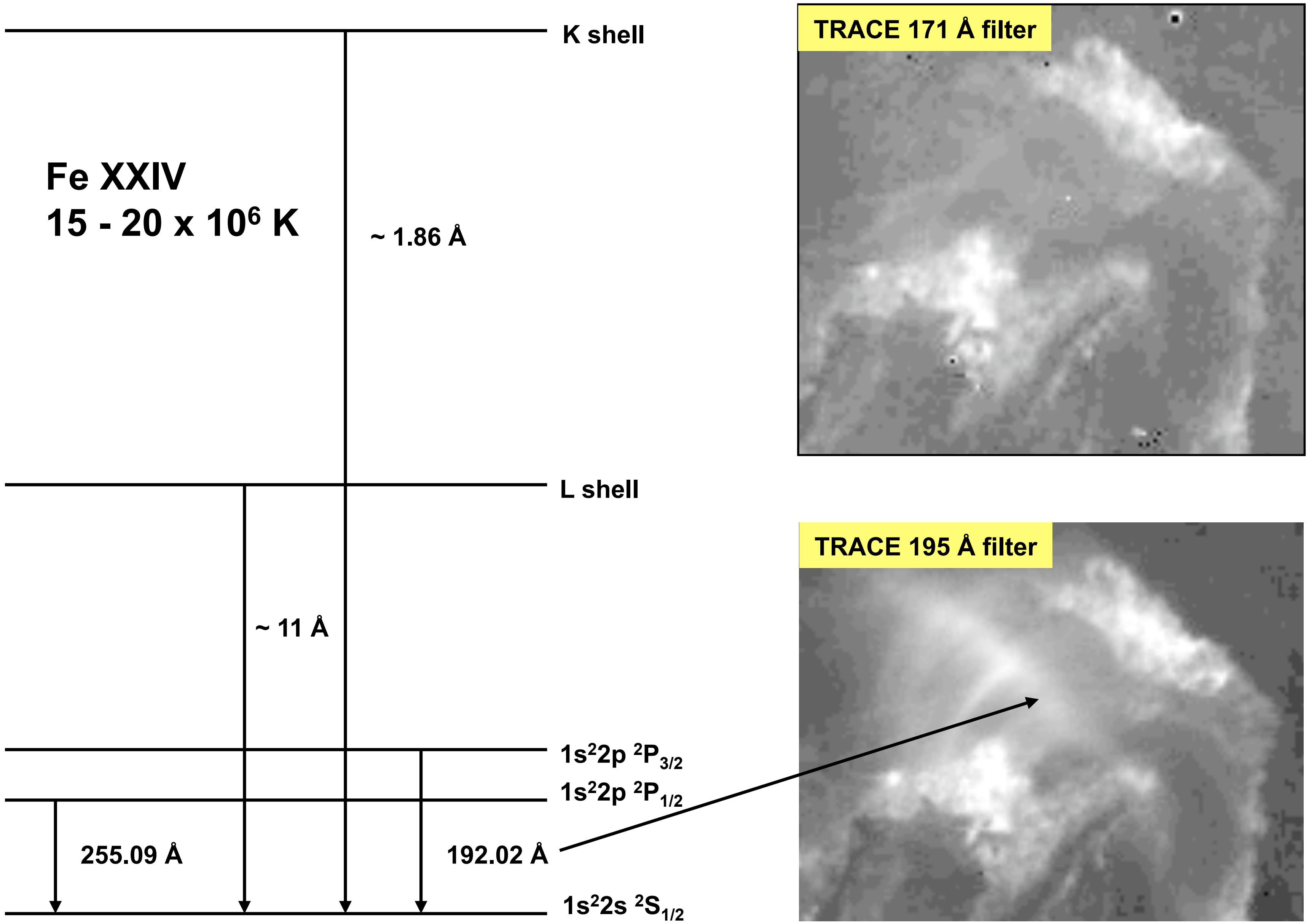
Laser-produced plasmas, tokamaks, and EBITs have been key resources for astrophysical spectroscopy.



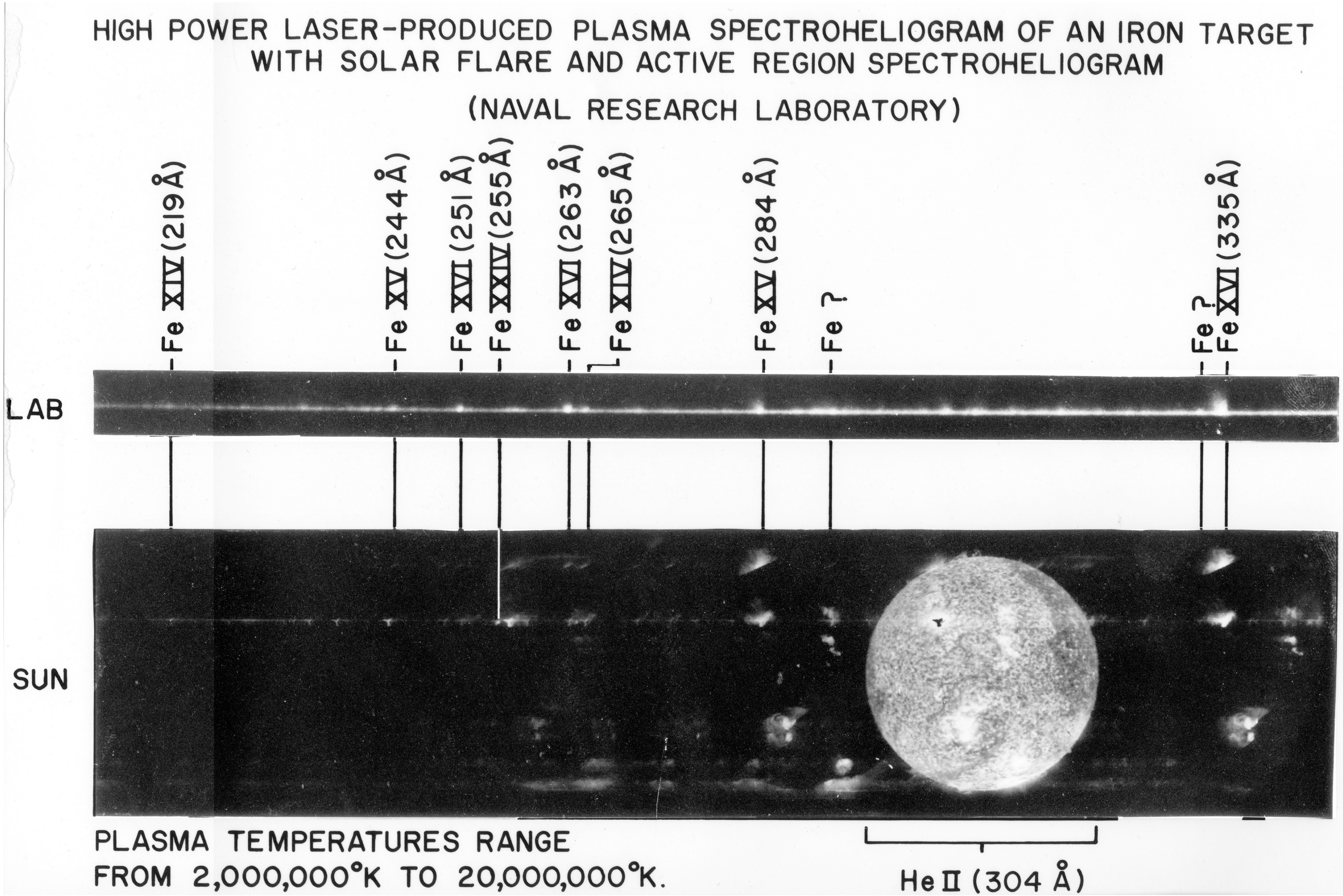
Predictions from laser-produced plasma spectra



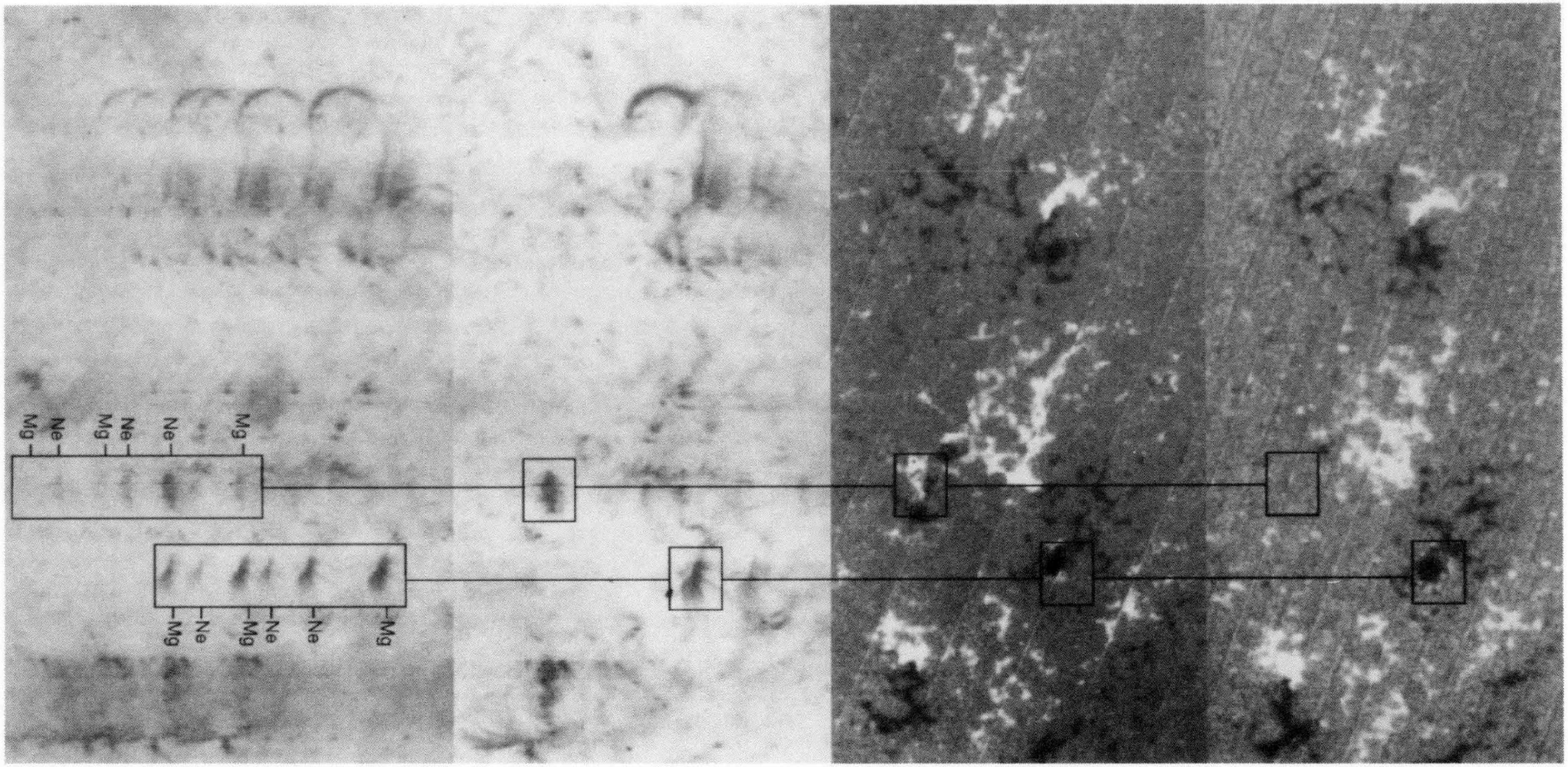
Wavelength = hc/Energy



X-ray/UV spectroscopy of solar and laboratory plasmas, plasma diagnostics, atomic physics



0011 UT AUG. 31, 1973 | 0011 UT AUG. 31, 1973 | 1439 UT AUG. 31, 1973 | 1551 UT AUG. 30, 1973



Mg VI & Ne VI: 399.3-403.3 Å

Ne VII 465.2 Å

From Neil Sheeley

Mon. Not. R. astr. Soc. (1975) **170**, 651–689

THE EXCITATION OF
SEVERAL IRON AND CALCIUM LINES
IN THE VISIBLE SPECTRUM OF THE SOLAR CORONA

H. E. Mason

(Communicated by Professor M. J. Seaton)

THE ASTROPHYSICAL JOURNAL, **226**:720–728, 1978 December 1

DENSITY SENSITIVITY OF THE SOLAR EUV EMISSION FROM BORON-LIKE IONS

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Theoretical intensity ratios for the UV lines of Mg VII, Si IX and S XI

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Mon. Not. R. astr. Soc. (1980) **191**, 631–639 and *Microfiche* MN191/1

Atomic data for Fe XXII

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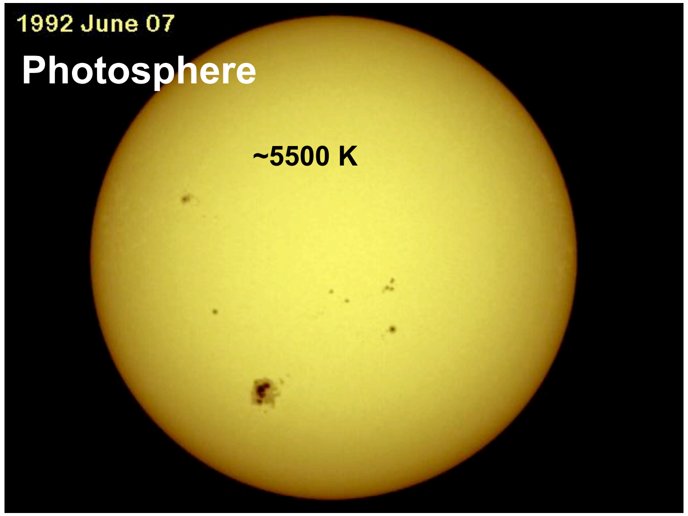
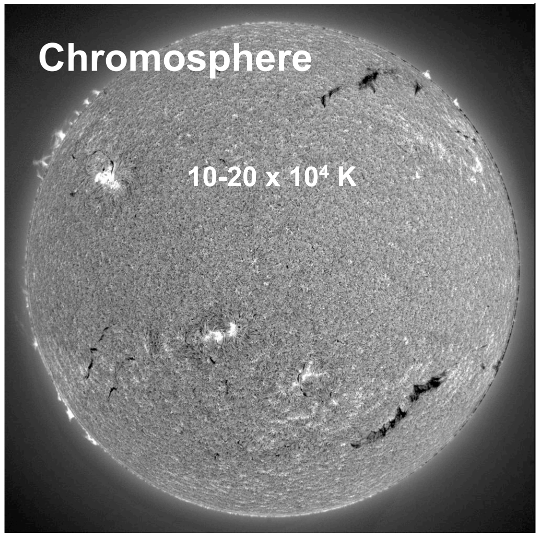
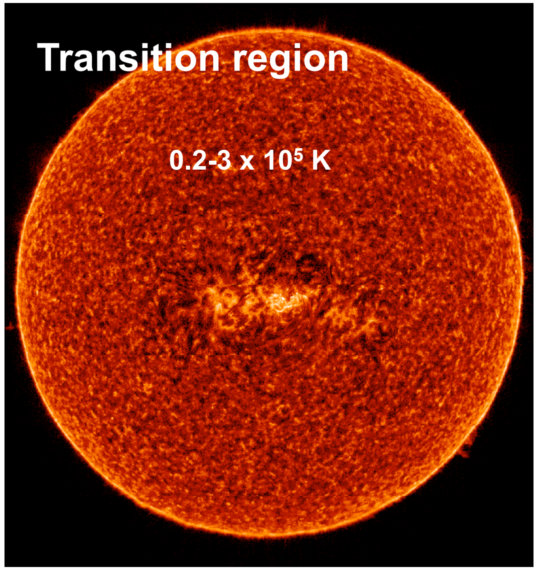
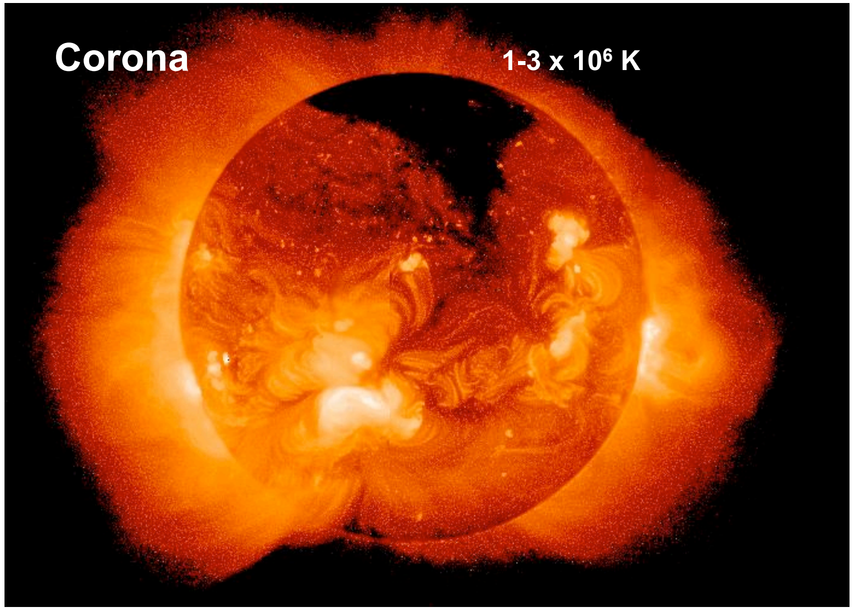
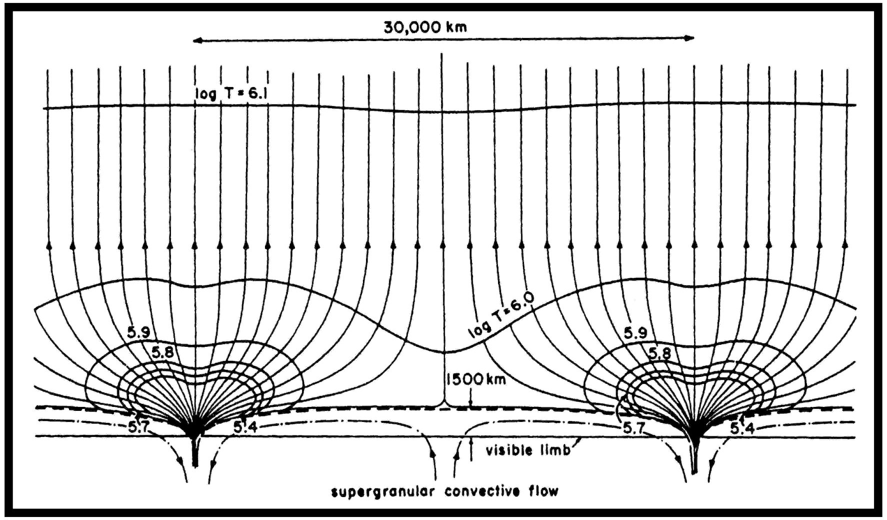

1992 June 07
Photosphere
~5500 K


Chromosphere
10-20 x 10⁴ K

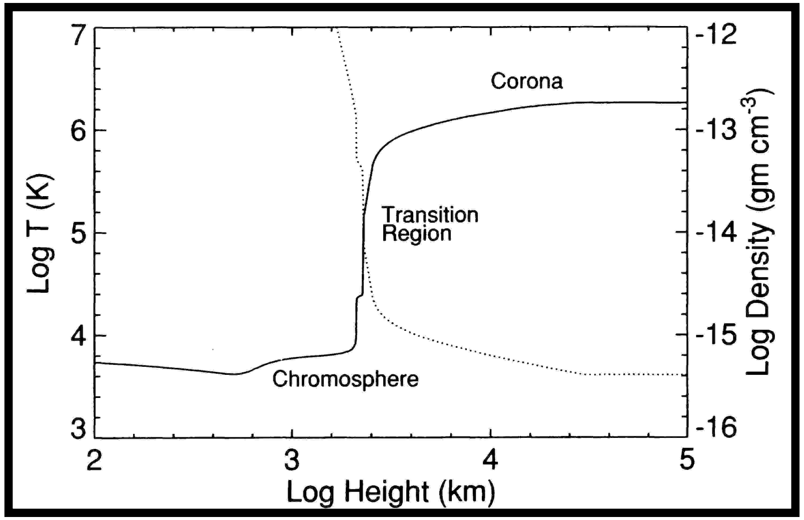

Transition region
0.2-3 x 10⁵ K


Corona
1-3 x 10⁶ K

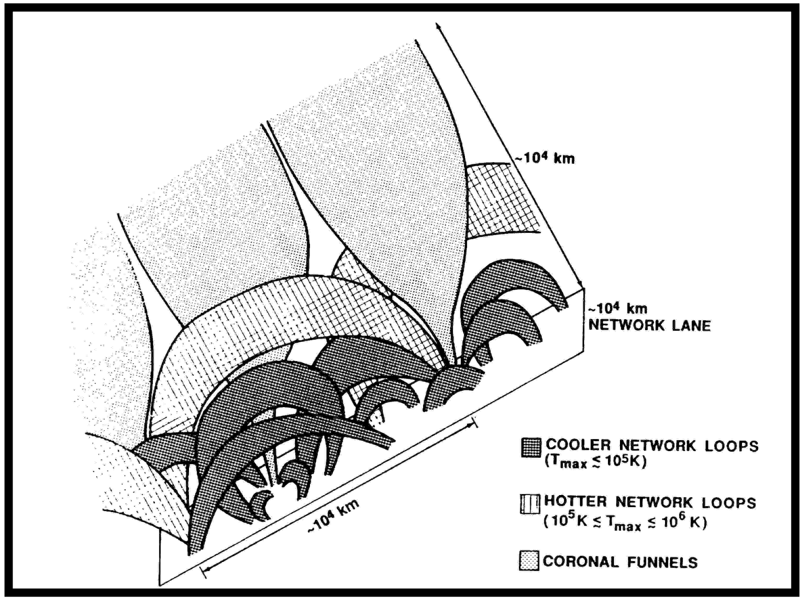
The Structure of the Solar Transition Region



The classical transition region

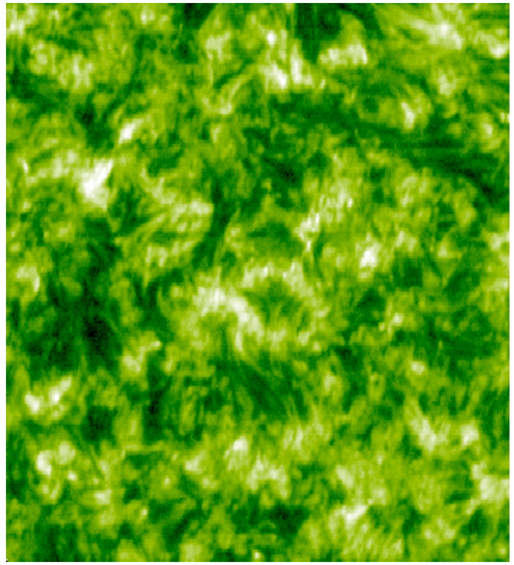


Classical temperature structure



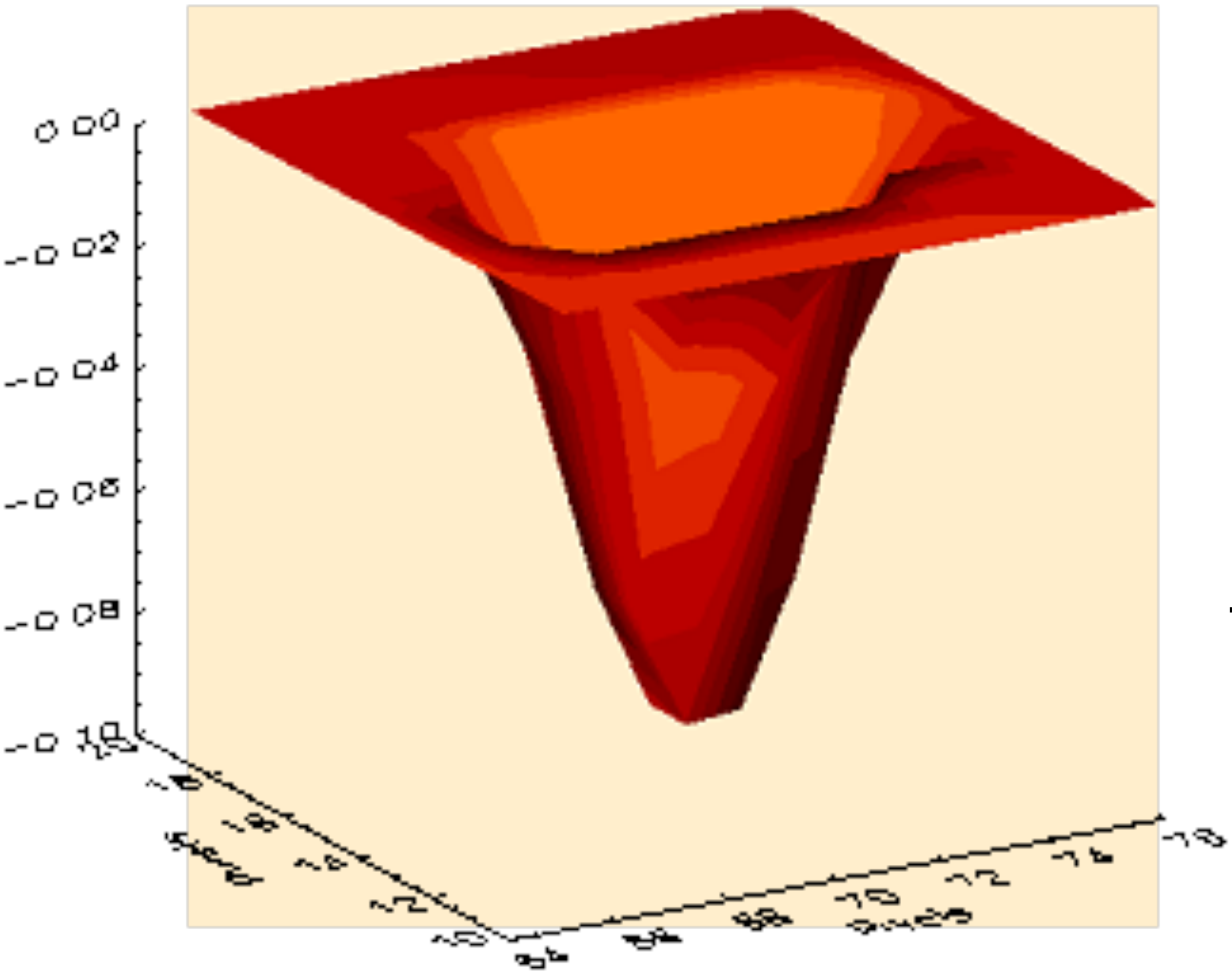
The cool loop/funnel model

What best describes the solar transition region – e.g., the classical transition region, cool loops, or separatrix surfaces? Transition region structures are around 100 km is size, below most current EUV instrument resolution.



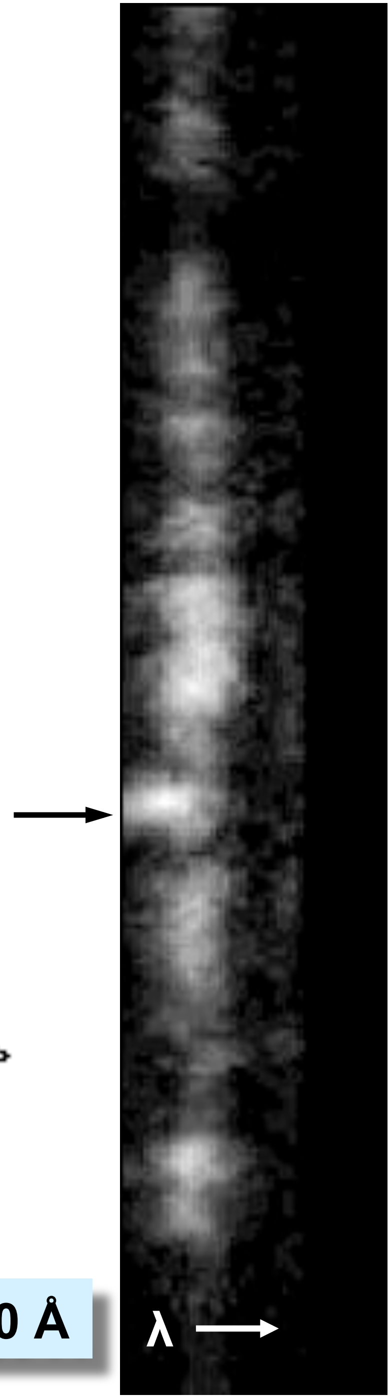
The Sun at 320,000 K
(2 x 10^5 km^2, SUMER)

Transition Region Dynamics

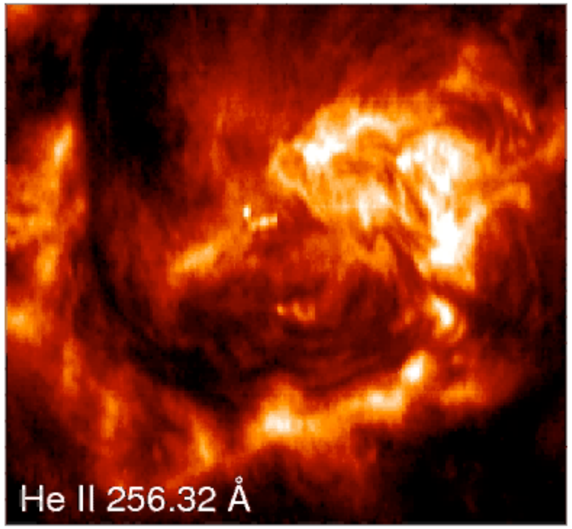


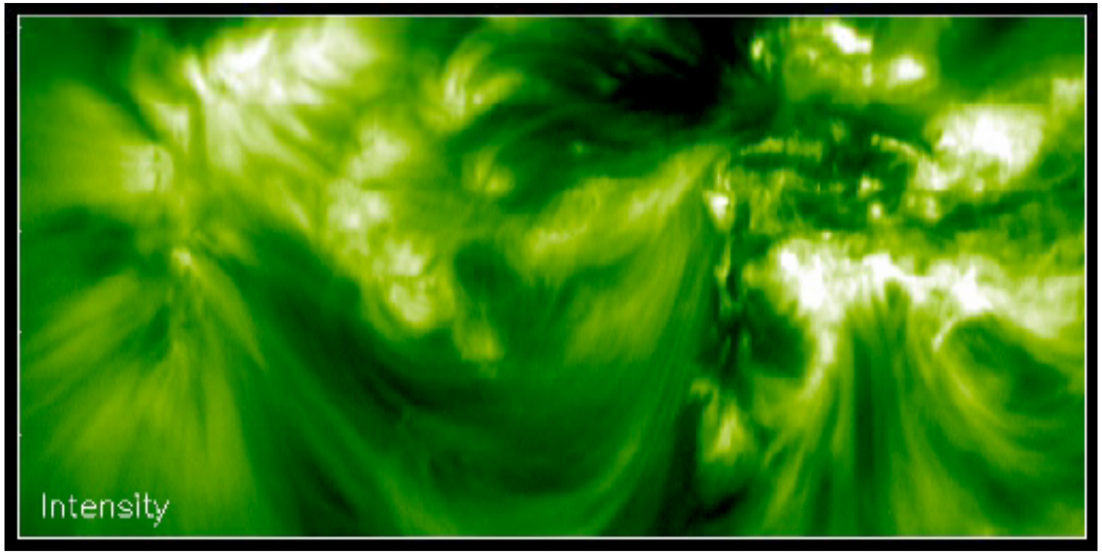
HRTS rocket spectra
SOHO/SUMER
SOHO/CDS

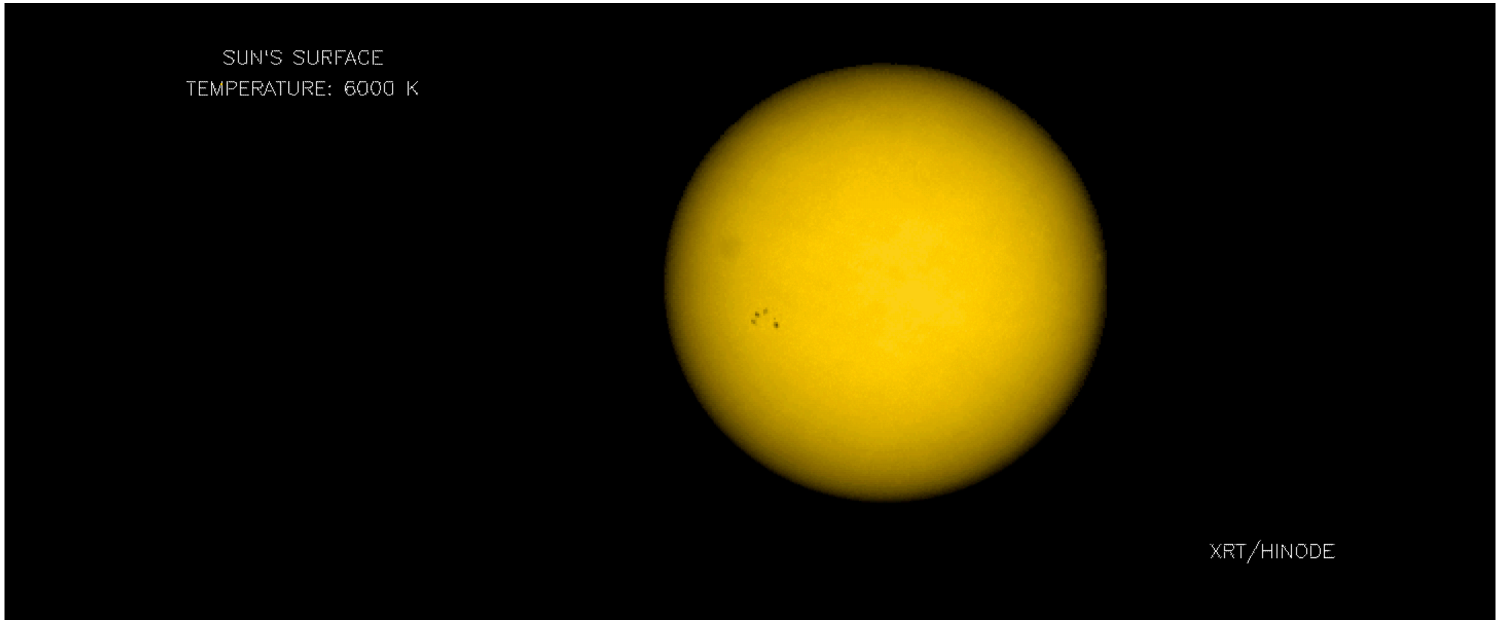
C IV: 1550 Å

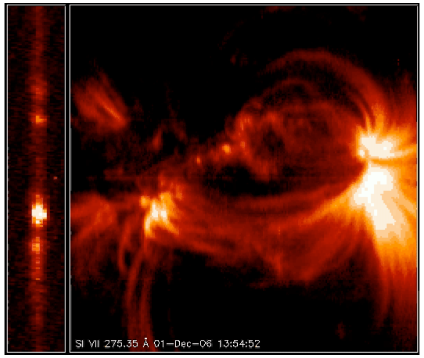


EIS Science Highlights

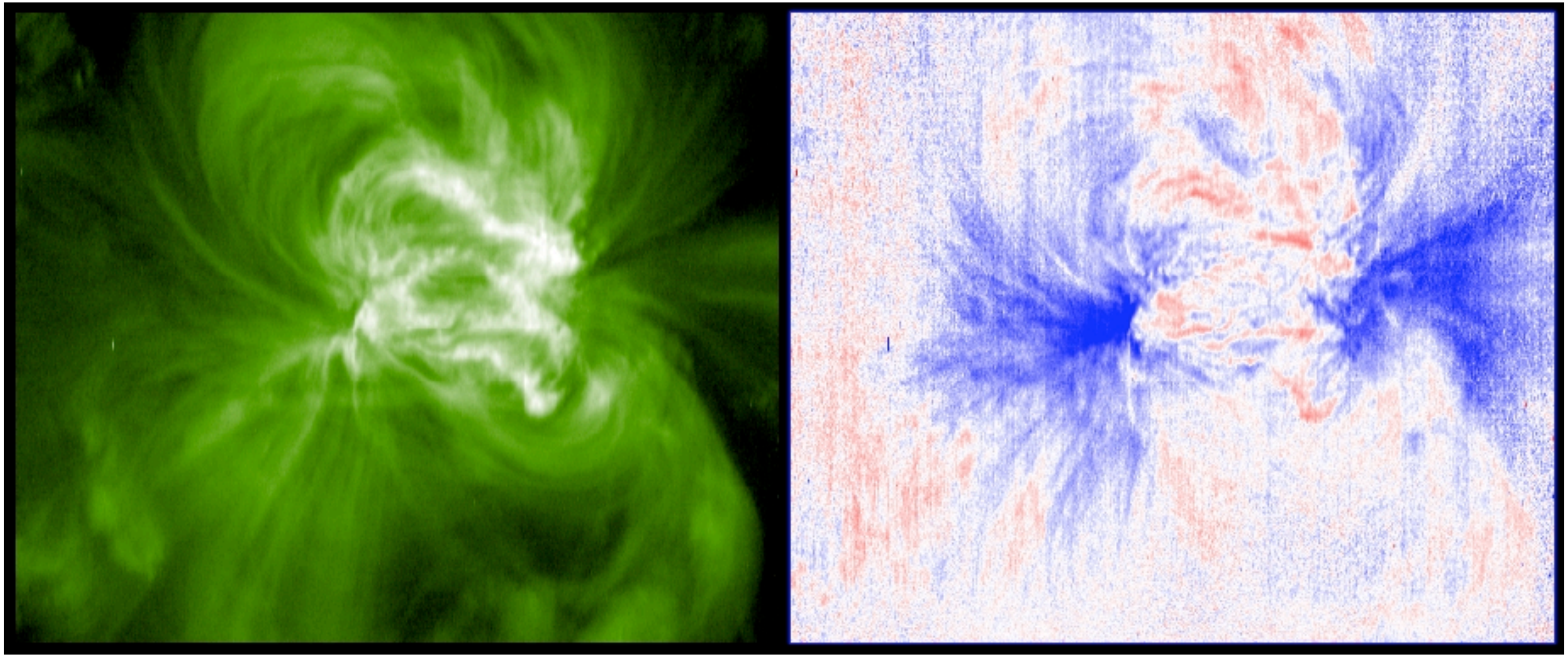






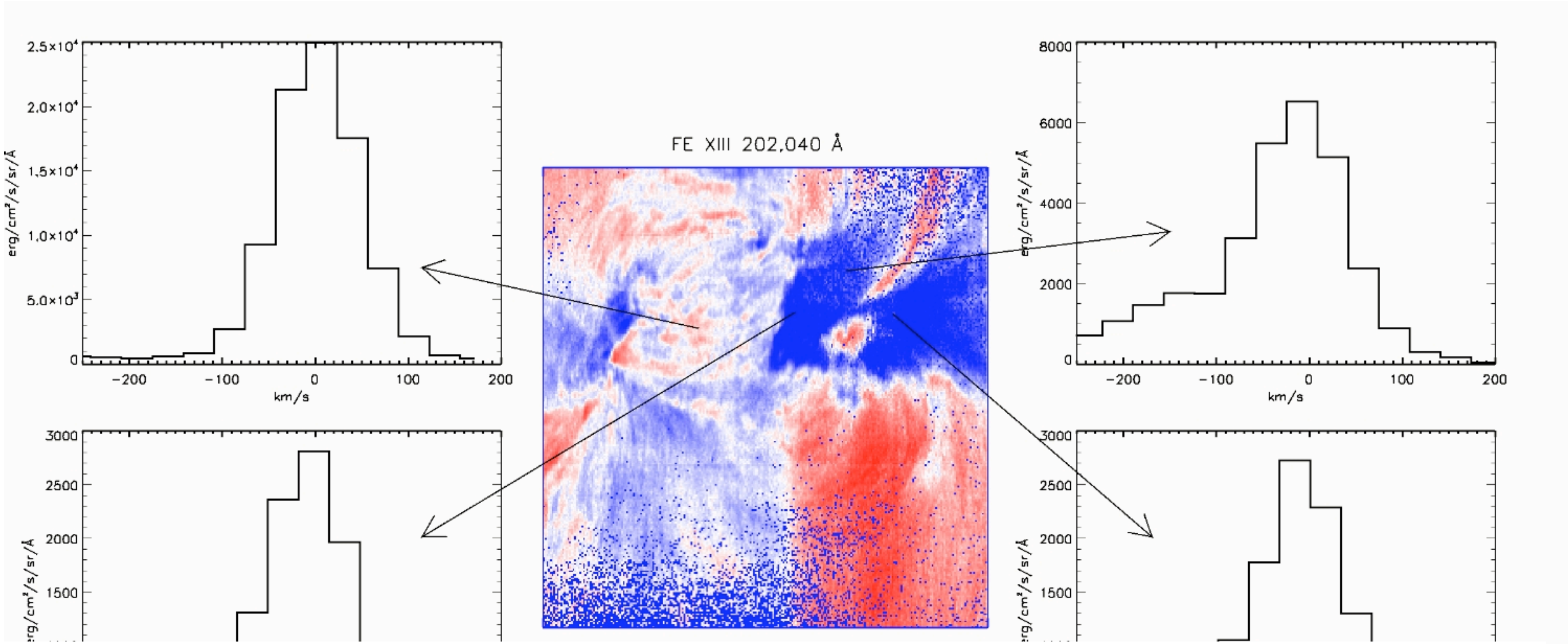


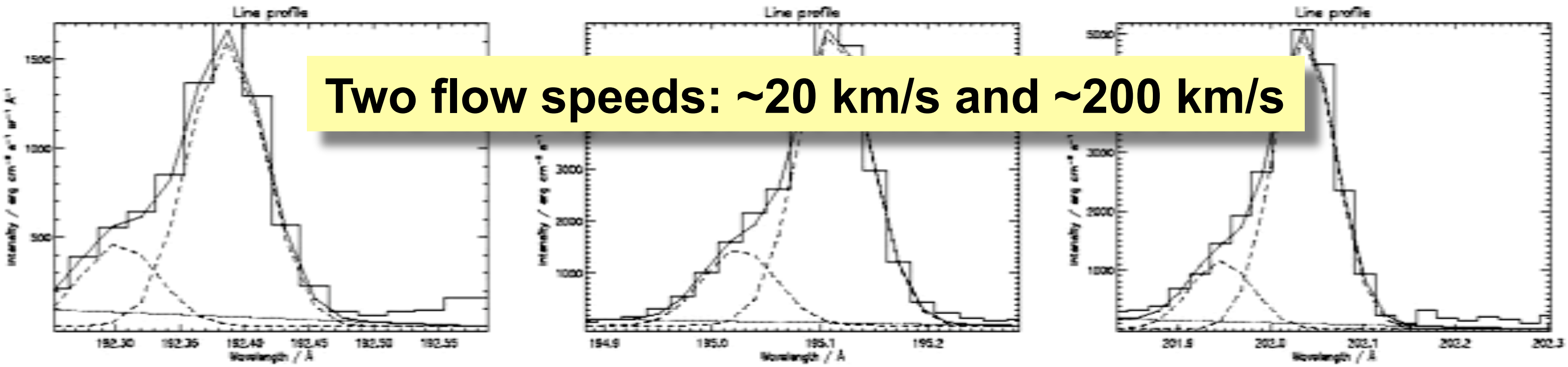
Active Region *Hinode*/EIS raster in Fe XII 195.12 Å



Intensity

Doppler Speed



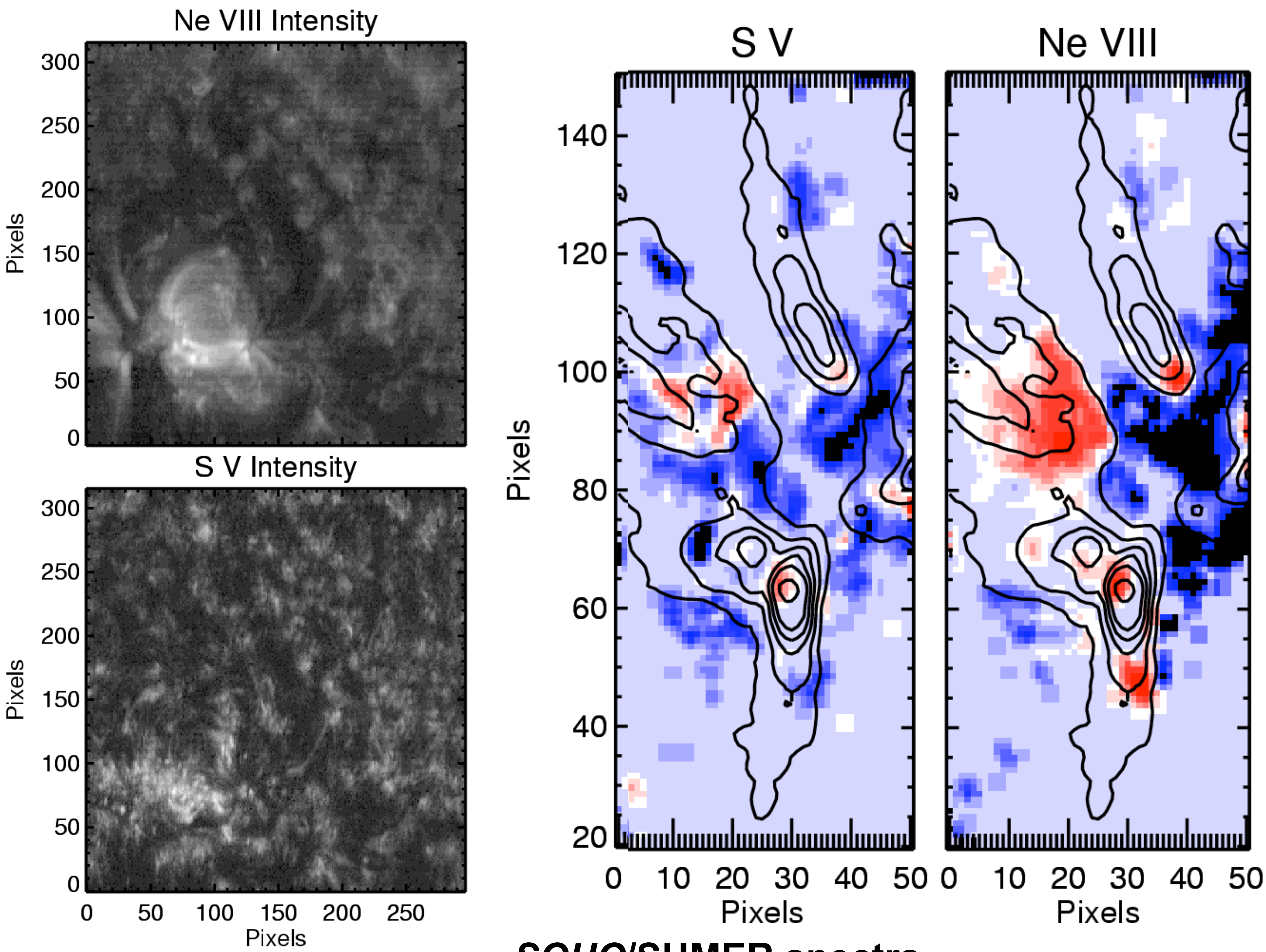


Two flow speeds: ~20 km/s and ~200 km/s

(a) Fe XII 192.39 Å

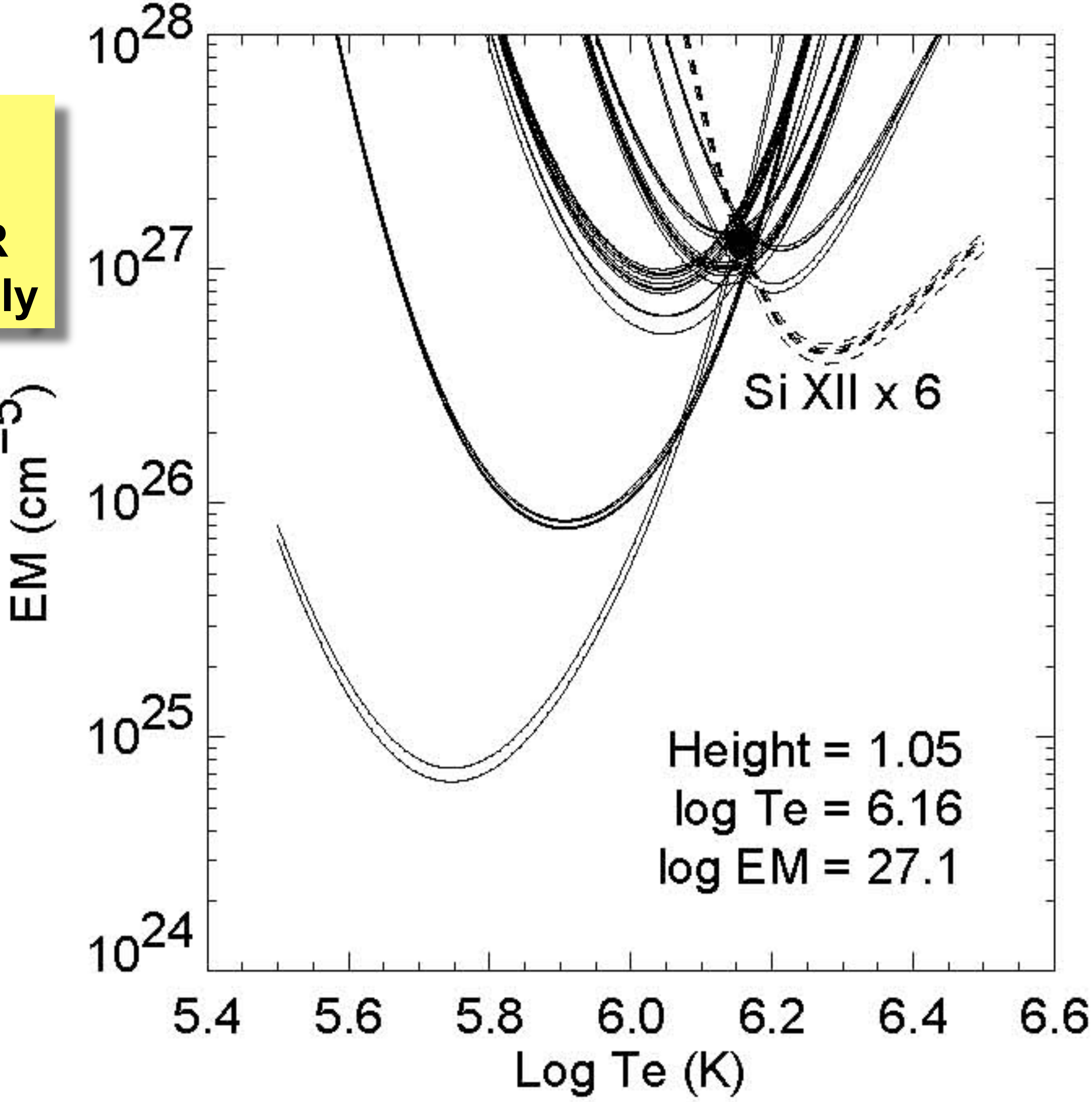
(b) Fe XII 195.12 Å

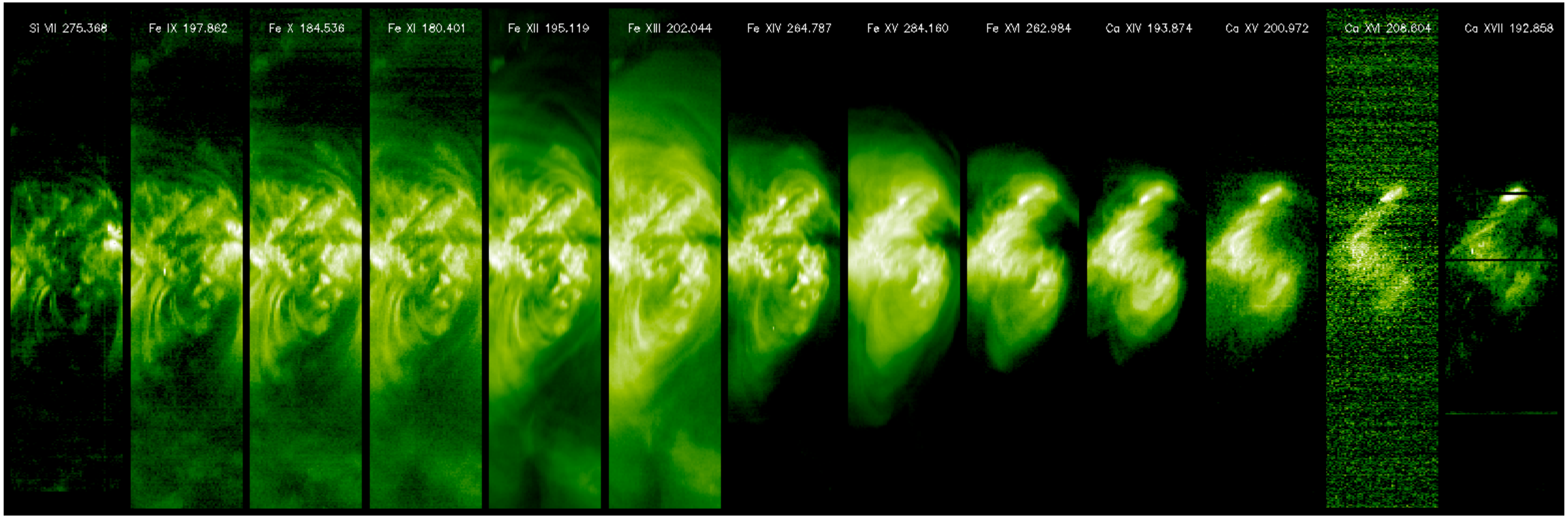
(c) Fe XIII 202.04 Å



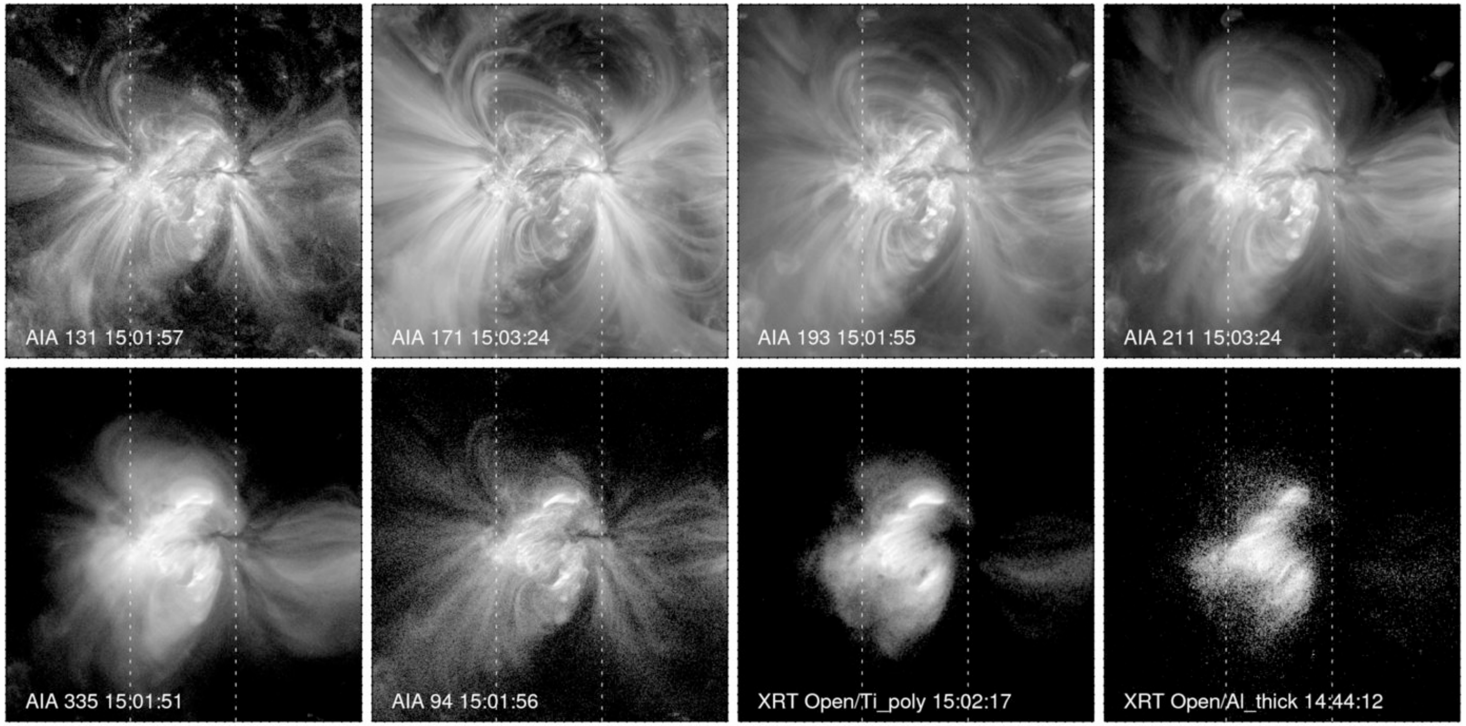
SOHO/SUMER spectra

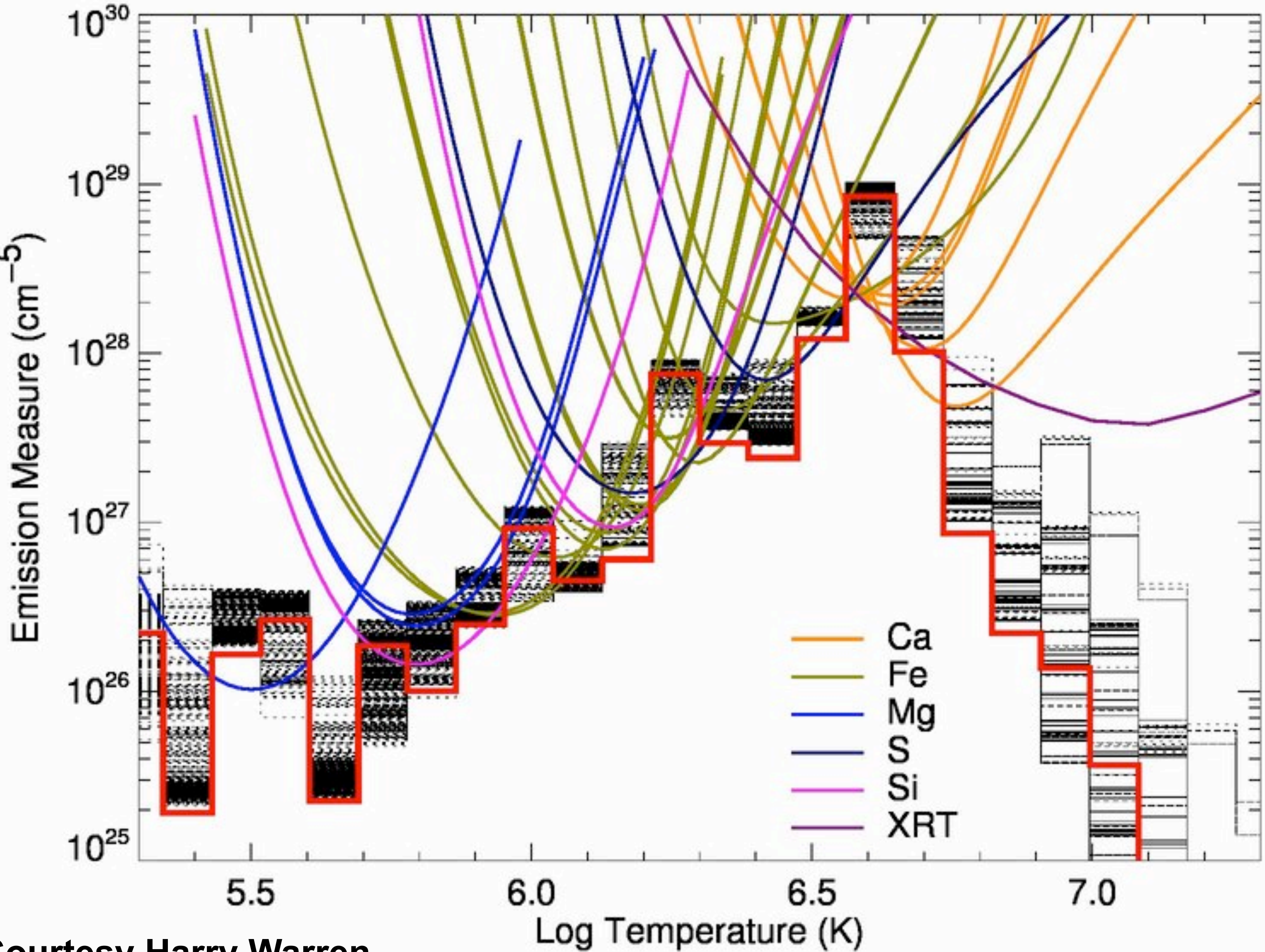
Jordan emission measure loci plot: *SOHO*/SUMER spectra, Si lines only





Courtesy Harry Warren





Courtesy Harry Warren

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ACTIVE REGION LOOPS: *HINODE*/EXTREME-ULTRAVIOLET IMAGING SPECTROMETER OBSERVATIONS

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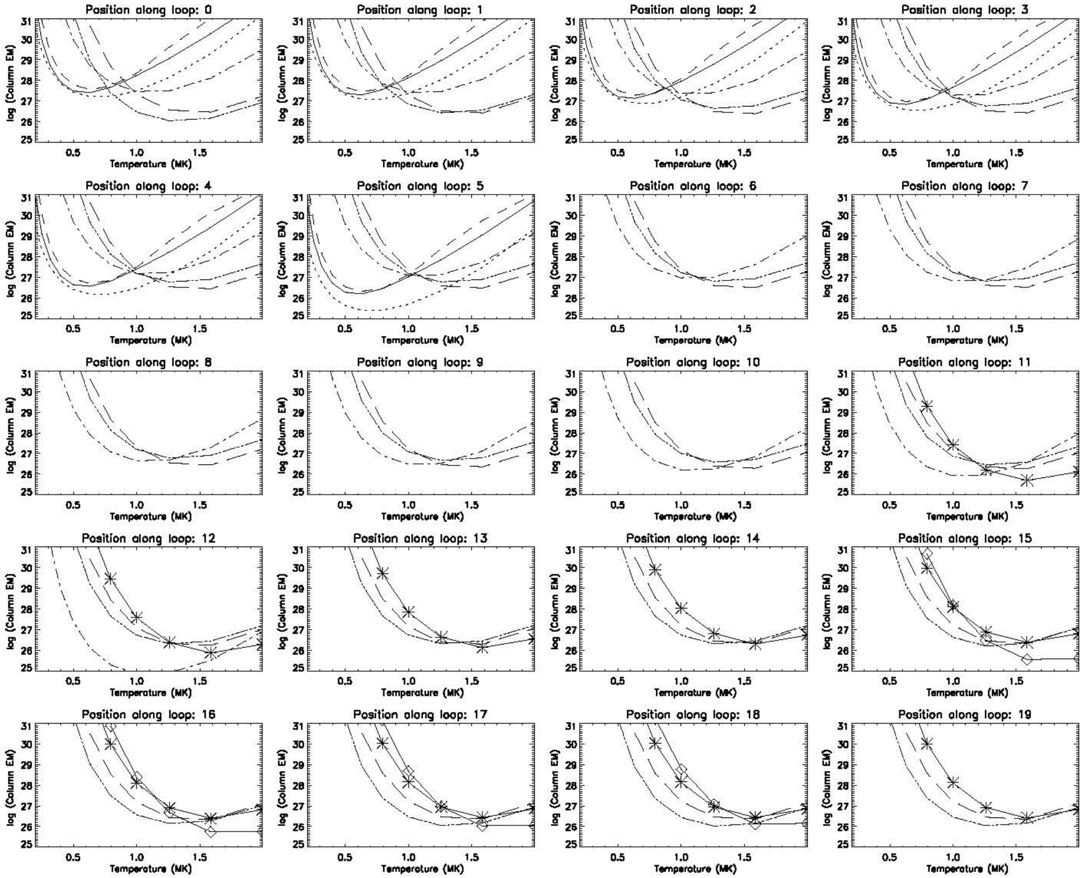

Figure 6. Emission measure curves obtained from the background-subtracted line intensities for loop A. Different plots correspond to different data points chosen along the loops. In the plots, the solid lines represent the EM-loci of Si vii, dotted lines Fe viii, dashed lines Mg vii, dashed–dotted Fe x, dashed–triple dotted Fe xii, and long-dashed lines represent Si x. The solid lines overplotted with asterisks and diamonds represent the EM-loci of Fe xiii and Fe xiv, respectively. The emission measure was calculated using Arnaud & Rothenflug (1985) ionization fraction and coronal abundances of Feldman (1992).

Unsolved Problems in Solar Physics

- The Photosphere-Coronal Connection
  - Spatial resolution to resolve the morphology of the atmosphere
- The Origin and Energetics of the Solar Wind
  - Trace measured coronal outflows, e.g., active regions back into the chromosphere/photosphere
- The Basic Building Blocks of the Solar Atmosphere
  - Modeling active region loops and coronal heating
- The Dynamics of Highly Transient Phenomena – Magnetic Reconnection
  - The reconnection region of solar flares
  - Small scale phenomena such as bright points

Summary

- High resolution spectroscopy has graduated into high resolution *imaging* spectroscopy.
- The key to truly understanding the physics of the solar atmosphere is high resolution imaging spectroscopy.
- Solar-C Plan B has enormous promise for solving the key problems of solar physics.