Pinning Down Coronal Heating Properties in the Presence of Non-Equilibrium Ionization

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I. Motivation

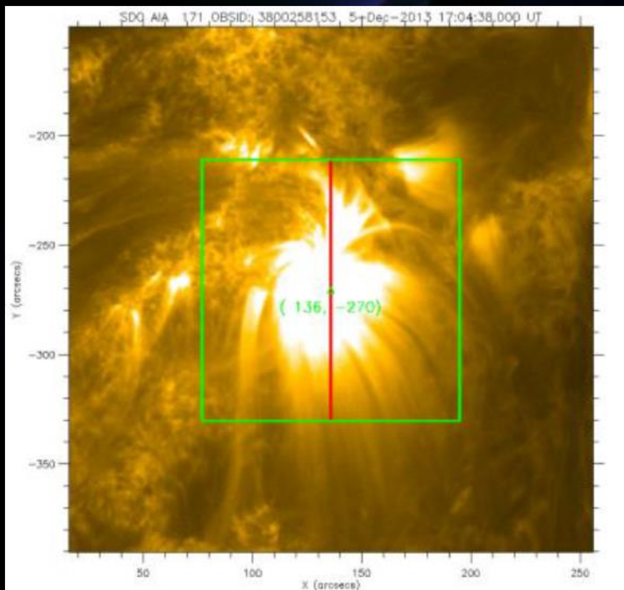
- Numerical models of nanoflare heating predict temperatures in the range of 3-5 MK at the onset of radiative cooling.
- Higher temperature (> 8 MK) plasma would be strong evidence for nanoflares.
- Difficult to observe: low density; thermal conduction; non-equilibrium ionization.
- Can we find indirect nanoflare signatures in transition region emission observed by IRIS?

II. Scientific Questions

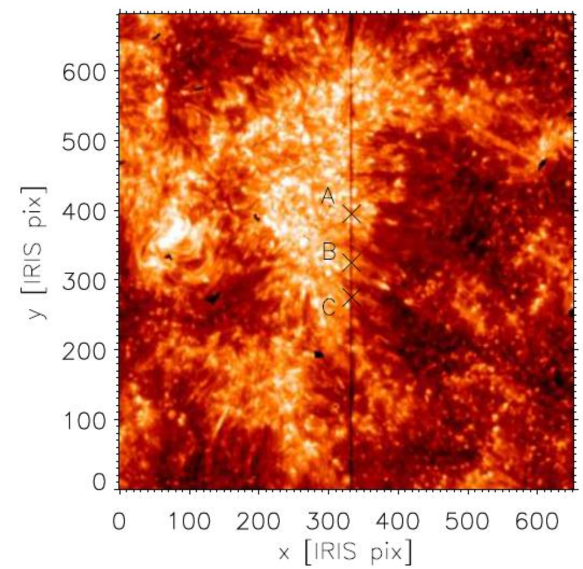
1. What are the signatures of non-equilibrium ionization in the transition region emission detected by IRIS?

2. How can the properties of coronal heating be diagnosed with IRIS data formed by a non-equilibrium population of emitting ions?

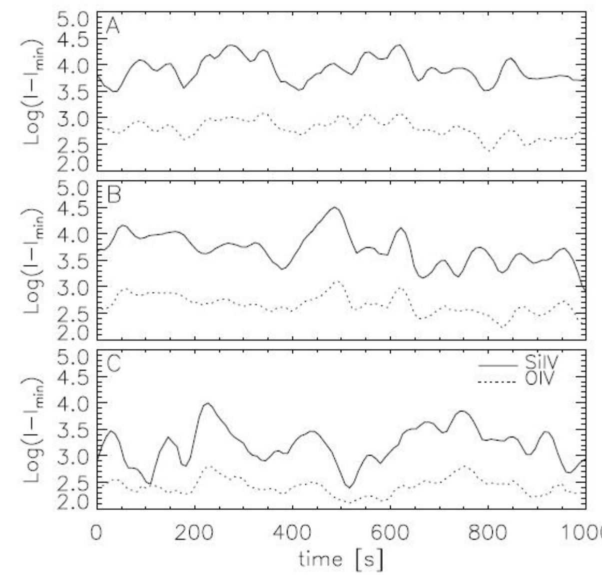
III. IRIS (and Complementary) Data



SDO/AIA 171 Å context image showing the IRIS slit-jaw field of view (green square) for a sit and-stare observation (the slit (red line) remains at the same spatial position).



IRIS 1400 Å (Si IV) slit-jaw image. Three positions (A, B, C) are labelled along the slit (black vertical line).



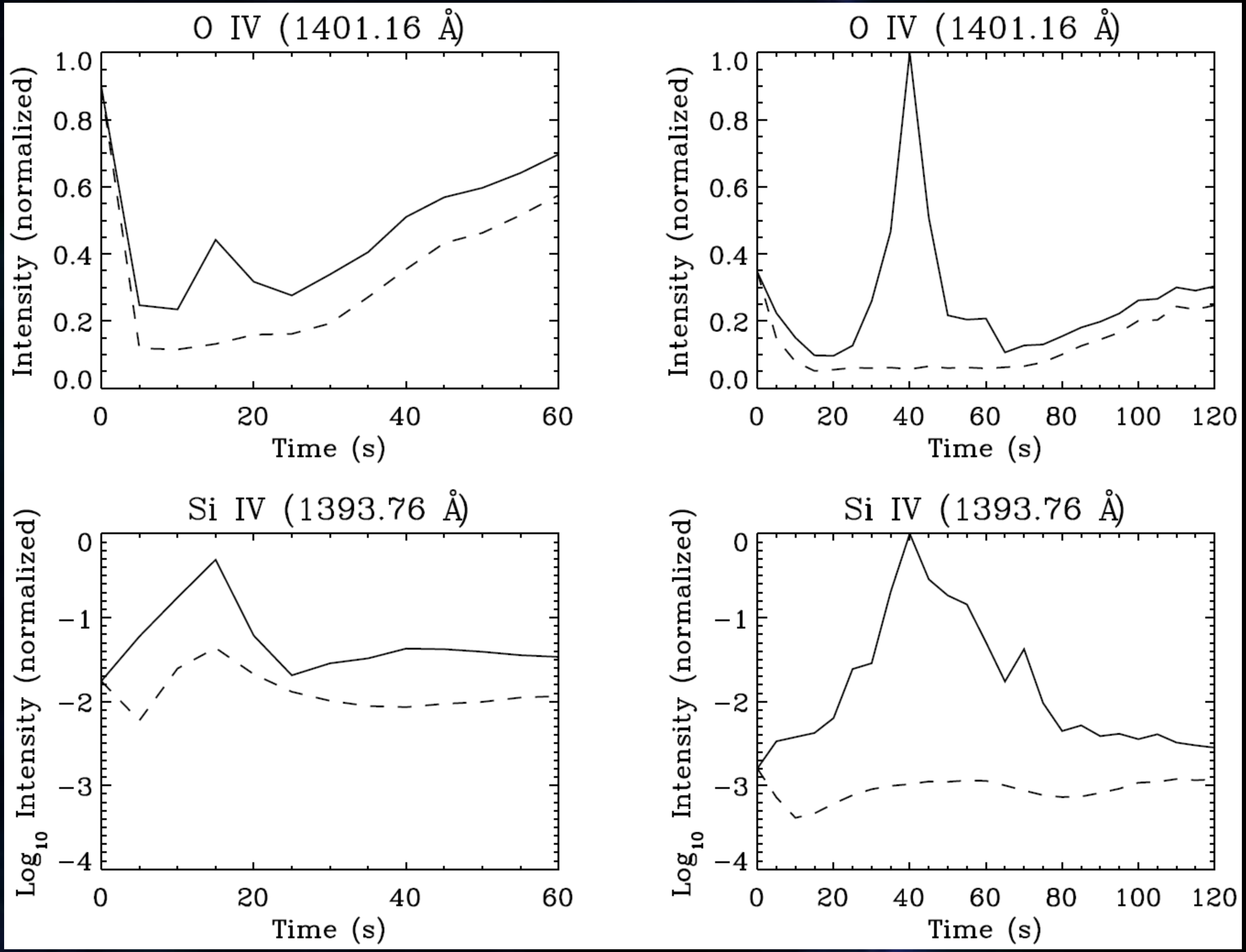
Courtesy P. Testa

Light-curves observed by IRIS in a Si IV (1393.76 Å) line and a O IV (1401.16 Å) line, corresponding to positions A, B, and C. Significant variability on short timescales (< one minute) is evident.

IV. Signatures of Non-Equilibrium Ionization

Predicted emission for two spectral lines in the IRIS wavelength range assuming equilibrium ionization (dashed) and allowing the ion populations to depart from equilibrium (solid).

<u>Left column:</u> the results for a numerical simulation of a 15 s nanoflare.
<u>Right column:</u> a 60 s nanoflare. The total energy deposited was the same in both cases.

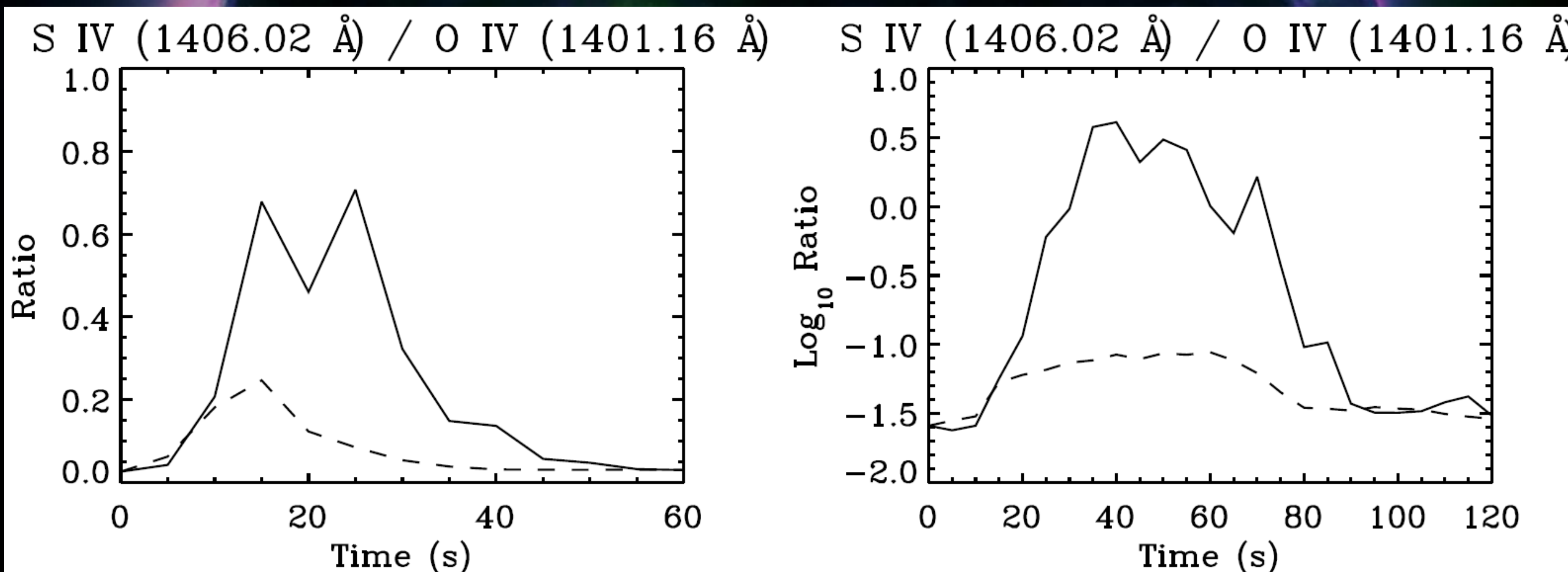


Different characteristic patterns of evolution and order-of-magnitude intensity differences due to non-equilibrium temperature broadening of ion population into denser atmospheric layers.

Non-equilibrium effects more pronounced at higher coronal density due to pressure forcing.

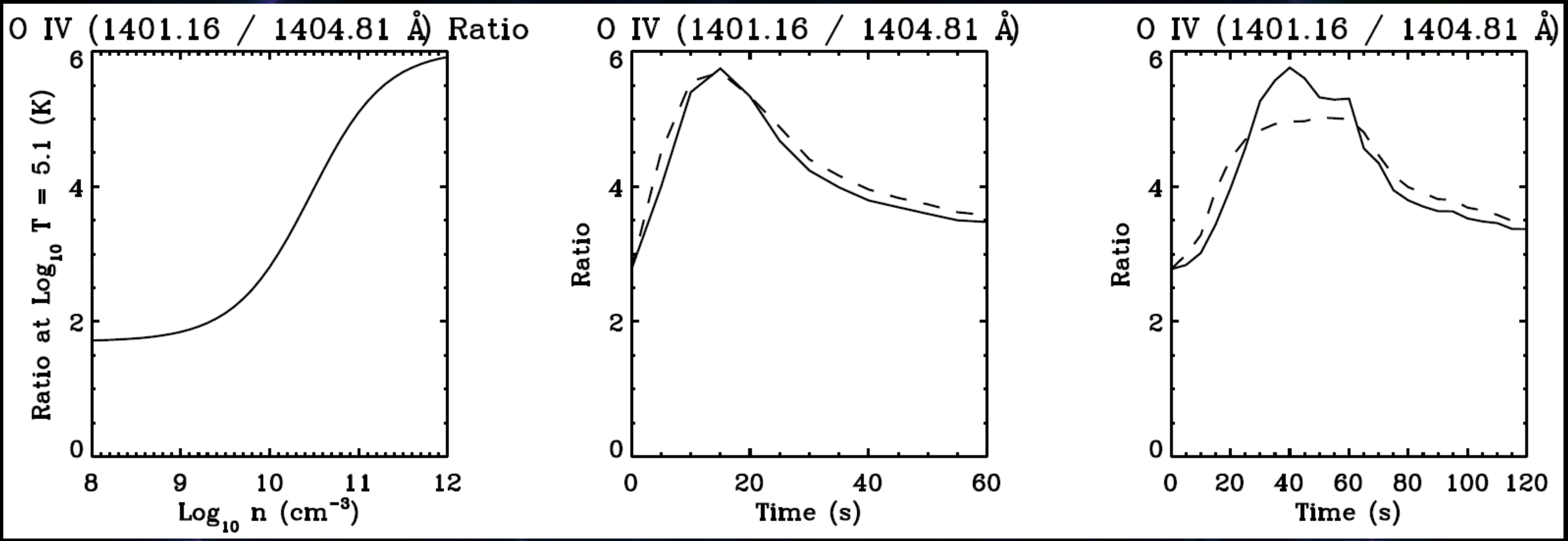
Examine ratios of emission lines from ions with significantly different ionization timescales.

The ionization rate of S IV is ≈ three times greater then O IV and Si IV at their peak equilibrium population temperatures (0.08-0.12 MK).



The ratio of two spectral lines in the IRIS wavelength range assuming equilibrium (dashed) and non-equilibrium (solid) ionization. Left: the results for a numerical simulation of a 15 s nanoflare. Right: the results for a 60 s nanoflare. The total energy deposited was the same in both cases.

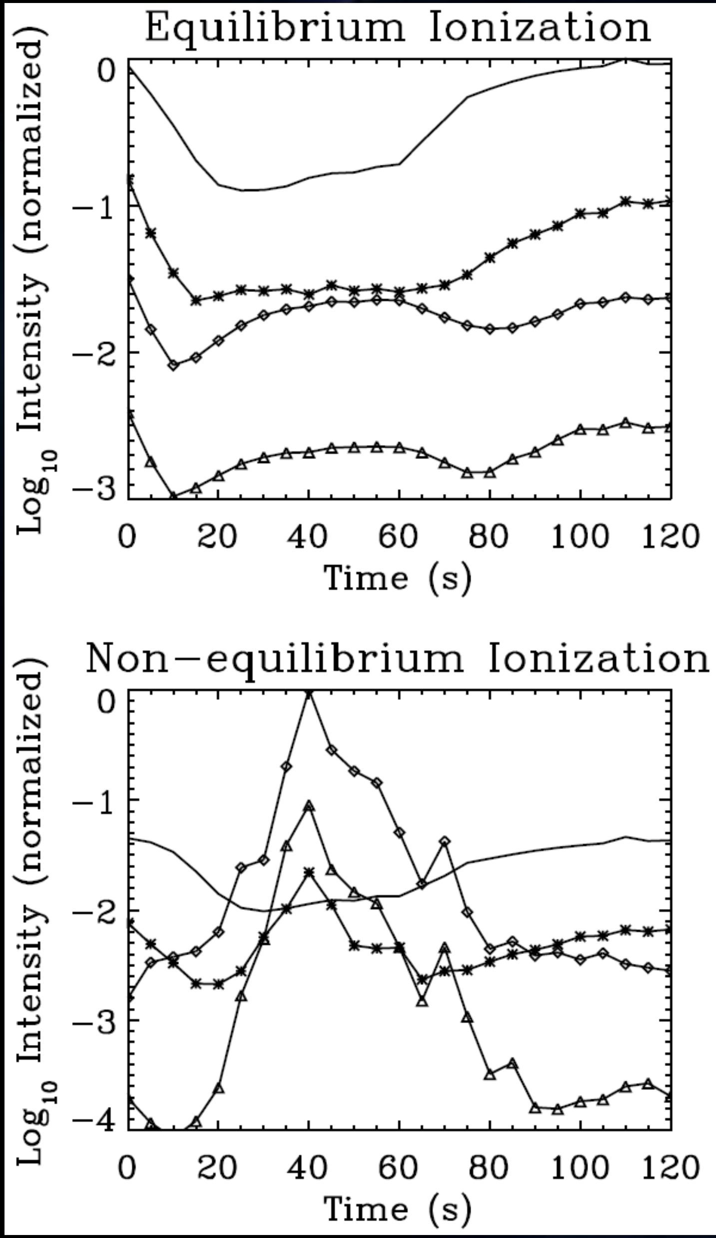
Consider the implications for transition region density diagnostics.



Left: the density sensitive O IV (1401.16 / 1404.81 Å) line ratio calculated by CHIANTI. Center: the ratio during the 15 s nanoflare experiment. The ratios have been calculated for equilibrium (dashed) and non-equilibrium (solid) ionization. Right: the ratio during the 60 s nanoflare.

Equilibrium and non-equilibrium ratios are 5.0 and 5.75 (10^{11} and $10^{11.6}$ cm^{-3}) at 40 s for the 60 s nanoflare. The density in the simulation at 0.12 MK (formation of O IV) is $10^{11.15}$ cm^{-3}.

V. Diagnosing Coronal Heating



Fe XII (1349.40 Å, solid line), O IV (1401.16 Å, asterisk), Si IV (1393.76 Å, diamond) and S IV (1406.02 Å, triangle) emission for the 60 s nanoflare heating experiment.

No clear timescale in the predicted variability that directly recovers the heating timescale.

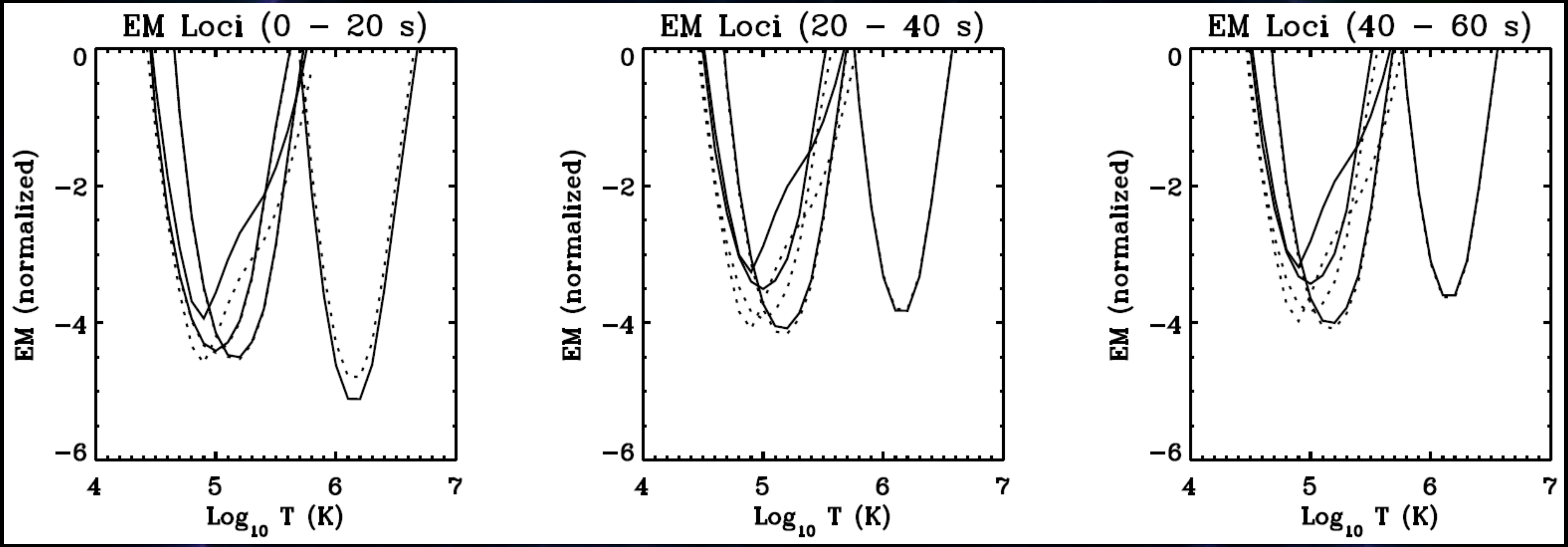
Fe XII variability is comparable in the equilibrium and non-equilibrium ionization cases.

Fe XII, Si IV and S IV variability is considerably broader in time than the underlying heating event.

O IV emission most closely follows the heating timescale. May represent the best opportunity to uncover the heating timescale.

When observational diagnostics indicate strong non-equilibrium ionization then search for evidence of this pattern in the data. Use numerical findings to estimate the heating timescale.

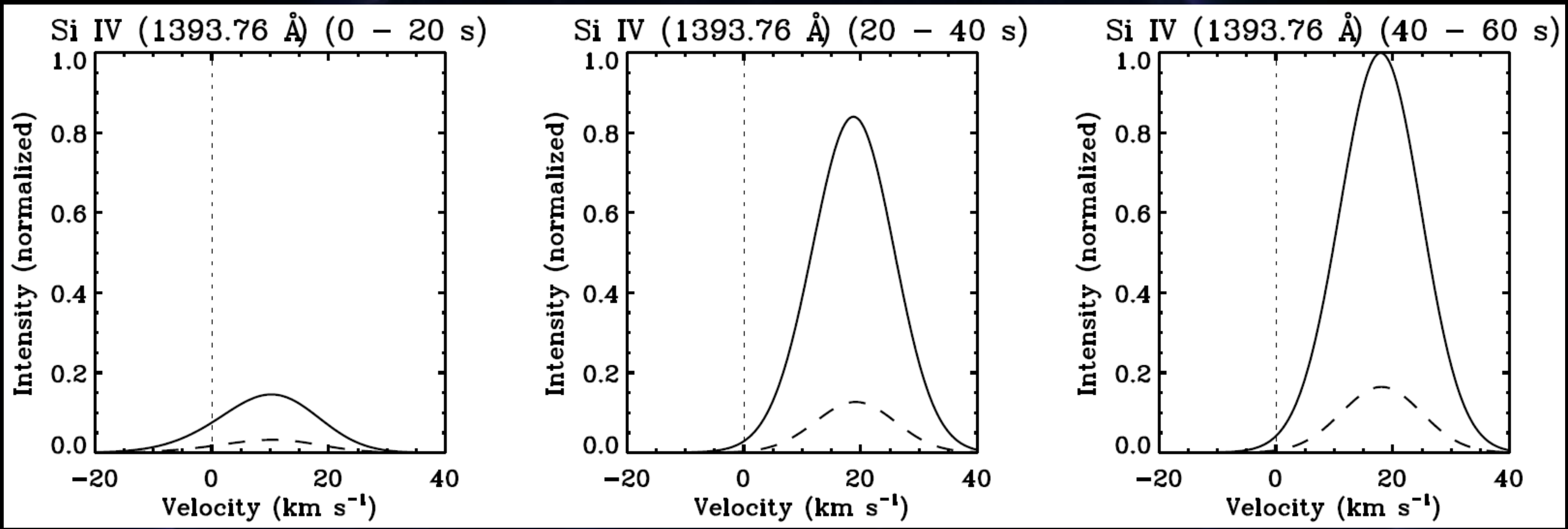
Use other observables to help constrain the heating properties.



The evolution of the emission measure, integrated over 20 second intervals, during the 60 s nanoflare experiment. The curves are EM-loci curves for the O IV (1401.16 Å), Si IV (1393.76 Å), S IV (1406.02 Å) and Fe XII (1349.40 Å) IRIS lines. They show the temperature sensitivity range of the ions and define an upper limit to the emission measure.

EM-loci curves calculated from the observed intensity / contribution function (in equilibrium!)

The slope of the emission measure provides a potential diagnostic of the nanoflare frequency.



The evolution of the Si IV (1393.76 Å) spectral line profile during the 60 s nanoflare heating event. The solid lines correspond to non-equilibrium ionization in each plot. These data will be supplemented by datasets provided by other instrumentation (e.g. Hinode/EIS).

Numerical experiments must recover the physical properties and the time-evolution of the EM-loci curves and the spectral line profiles.

Iterate on the heating properties and the loop properties to find agreement.

Strong constraints because there are more predicted quantities than input parameters.

VI. Summary and Conclusions

- IRIS line intensities expected to exhibit different characteristic patterns of evolution and order-of-magnitude intensity enhancements due to non-equilibrium ionization.
- Counter-intuitively, non-equilibrium effects are more pronounced for:
    - longer heating timescales because the non-equilibrium temperature broadening of the ion populations penetrates to deeper layers / higher densities over longer times.
    - higher initial coronal densities, because the greater coronal pressure forces the transition region to lower altitudes.
- Ratios of emission lines from ions with significantly different ionization timescales are a feasible diagnostic of non-equilibrium ionization.
- Density diagnostics are subject to significant uncertainty due to non-equilibrium ionization, regardless of the lines being emitted by the same ion.
- Particular transition region lines (e.g. from O IV) may capture the underlying timescales of heating activity more reliably than others.
- Heating properties and initial conditions will be strongly constrained by matching the physical properties and time evolution of many observables.