Connecting Chromospheric Condensation Signatures To Reconnection Driven Heating Rates In An X1.0 Flare

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Background

Chromospheric Condensation is an observational signature of solar flares that allows for an estimation of flare energy release. Seen as redshifted/red-asymmetries of chromospheric spectroscopic lines, condensation dynamics are characterized by two properties: peak downflow plasma velocity and duration.

In previous work, one-dimensional simulations were run to determine how energy flux affects the nature of chromospheric condensation dynamics. We found both condensation properties to be contingent on the energy flux delivered to the flare loop.

Here we perform a forward model to determine the relationship between observed condensation signatures and flare energy release. Energy flux is first inferred from flare ribbon emission using the UV Footprint Calorimeter (UFC) method, where it is then used to drive a 1D flare model simulation. This simulation is then compared to an observed condensation event in order to test our understanding of the reconnection-condensation relationship.

X1.0 Flare

The event chosen for this work occurred during the GOES X1.0 SOL2014-10-25T17:08:00 flare in active region AR12192. High-cadence sit-and-stare IRIS observations, with the spectrographic slit crossing the westernmost of three flare ribbons, were used to identify a single flare ribbon pixel exhibiting clear condensation behavior. We interpret this pixel as the footpoint of a single flare loop.

The condensation is observed as temporally-evolving λ1402.77 Si IV spectral lines. We found the profiles of these lines to be well modeled as a pair of Gaussians - a stationary and a dynamic red-shifted component - with the red component describing the dynamics of the condensation.

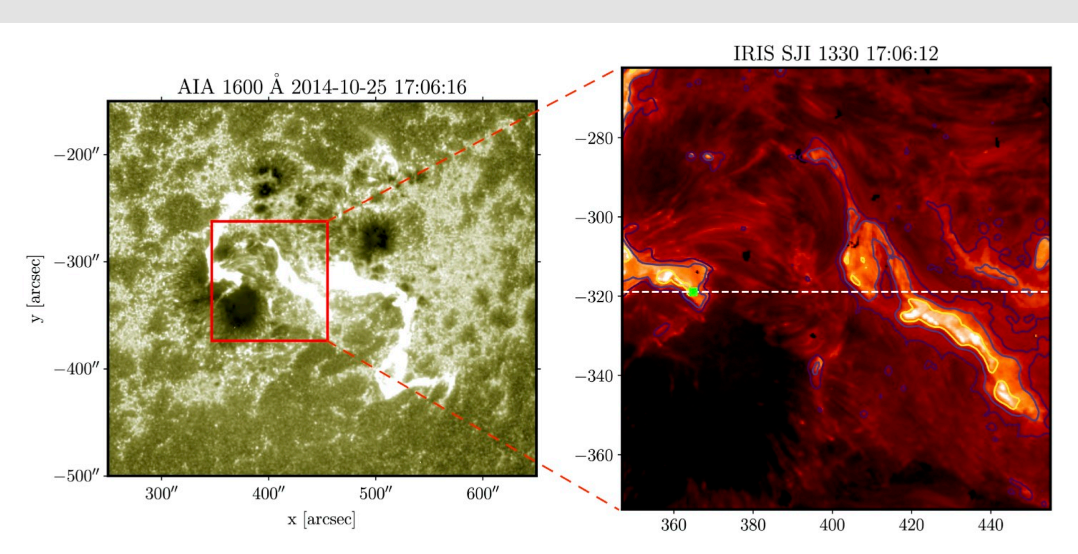

Figure 1: AIA 1600Å image showing the three flare ribbons during peak emission. IRIS SJI FOV is outlined in red, with the closest corresponding SJI 1330Å image shown on the right. The IRIS slit is illustrated by the white dashed line and the selected pixel is given by the green square. Contours show the levels of high AIA 1600Å emission at 17:06:16.

References

(1) Ashfield, W. H., & Longcope, D. W. 2021, ApJ, 912, 25
(2) Qiu, J., Liu, W.-J., & Longcope, D. W. 2012, ApJ, 752, 124
(3) Qiu, J., & Longcope, D. W. 2016, ApJ, 820, 14
(4) Klimchuk, J. A., Patsourakos, S., & Cargill, P. J. 2008, ApJ, 682, 1351
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HXR Emission

Data taken using the RHESSI spacecraft during this flare show HXRs concentrated at the apex of a flare loop appearing in 171Å at a later time. As HXR emission is the typical signature of accelerated electrons, this observation not only provides evidence of energy transport from the corona to the chromosphere via thermal conduction, but it also suggests this flare is not an efficient particle accelerator overall.

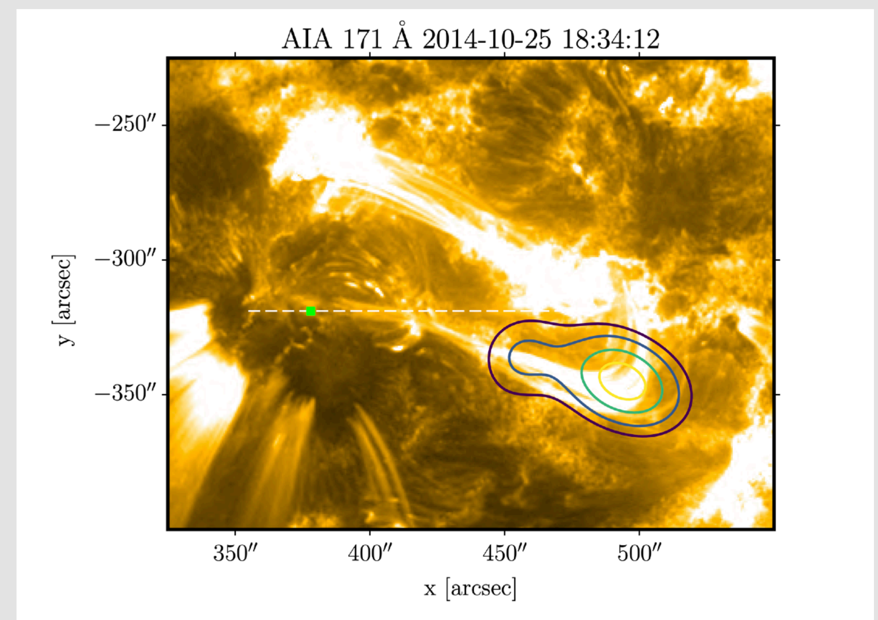

Figure 2: AIA 171Å image with RHESSi 25-50 keV contours overlaid. The contours correspond to emission occurring at 17:05:45-17:06:01 and are shifted to coalign with the AIA image. The IRIS slit is illustrated as a white dashed line, and the selected pixel is highlighted in green.

Condensation Event

In Ashfield & Longcope (2021), evolution of the downward condensation velocity was found to be well described by:

$$u(t) = \frac{u_0}{1 + t/\tau} \qquad (1)$$

Once the Si IV spectra were fit using the double-gaussian routine, the time series of the red components was fit to the above equation. We found the condensation to have a peak velocity of 36 km/s and a half life of τ=16s. Using the results of Ashfield & Longcope (2021), these values give a chromospheric scale height of H=369 km at the time of energy release.

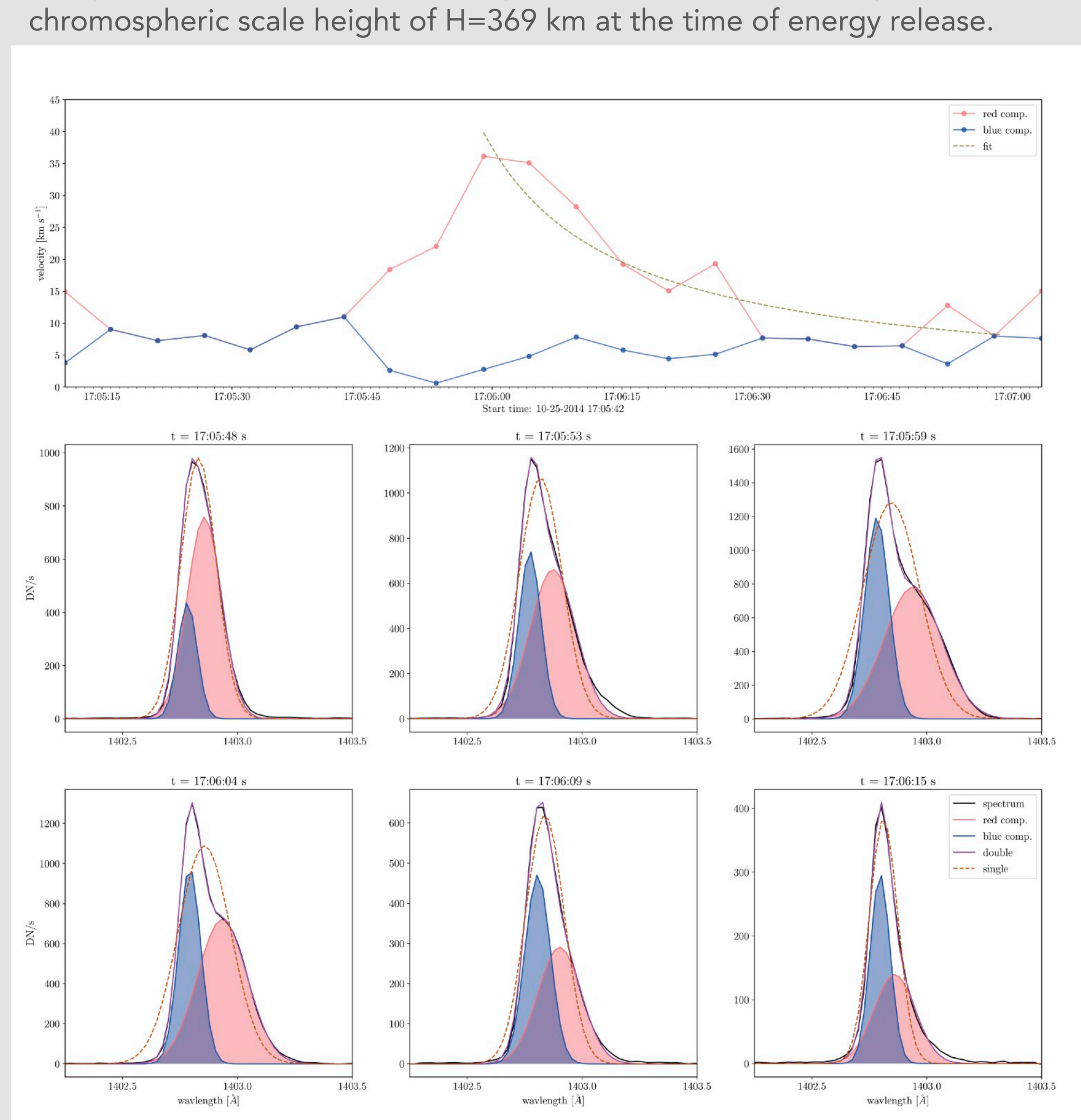

Figure 3: Evolution of the condensation event. Si IV spectra are shown along with their respective single- and double-gaussian fits in the bottom two panels. The top panel shows a velocity time series of the blue and red components, along with the fit to the red component.

UFC Method

The energy flux deposited into our flare loop was estimated using the UFC method [2,3]. Using AIA 1600Å observations as a proxy for heat deposition into the flare loop footpoints, the method converts UV emission into a volumetric heating rate of a flare loop using an empirical free parameter, λ. This conversion is accomplished by first computing the response of each flaring pixel to a gaussian heating profile using the 0D EBTEL model [4]. Synthetic lightcurves of all coronal AIA bands are produced and then compared to the observed lightcurves by scaling λ until a best match is achieved. This method thus gives a scaling factor λ that converts UV photon count in DN per second per pixel into a heating rate of units erg/s/cm² for the entire flare.

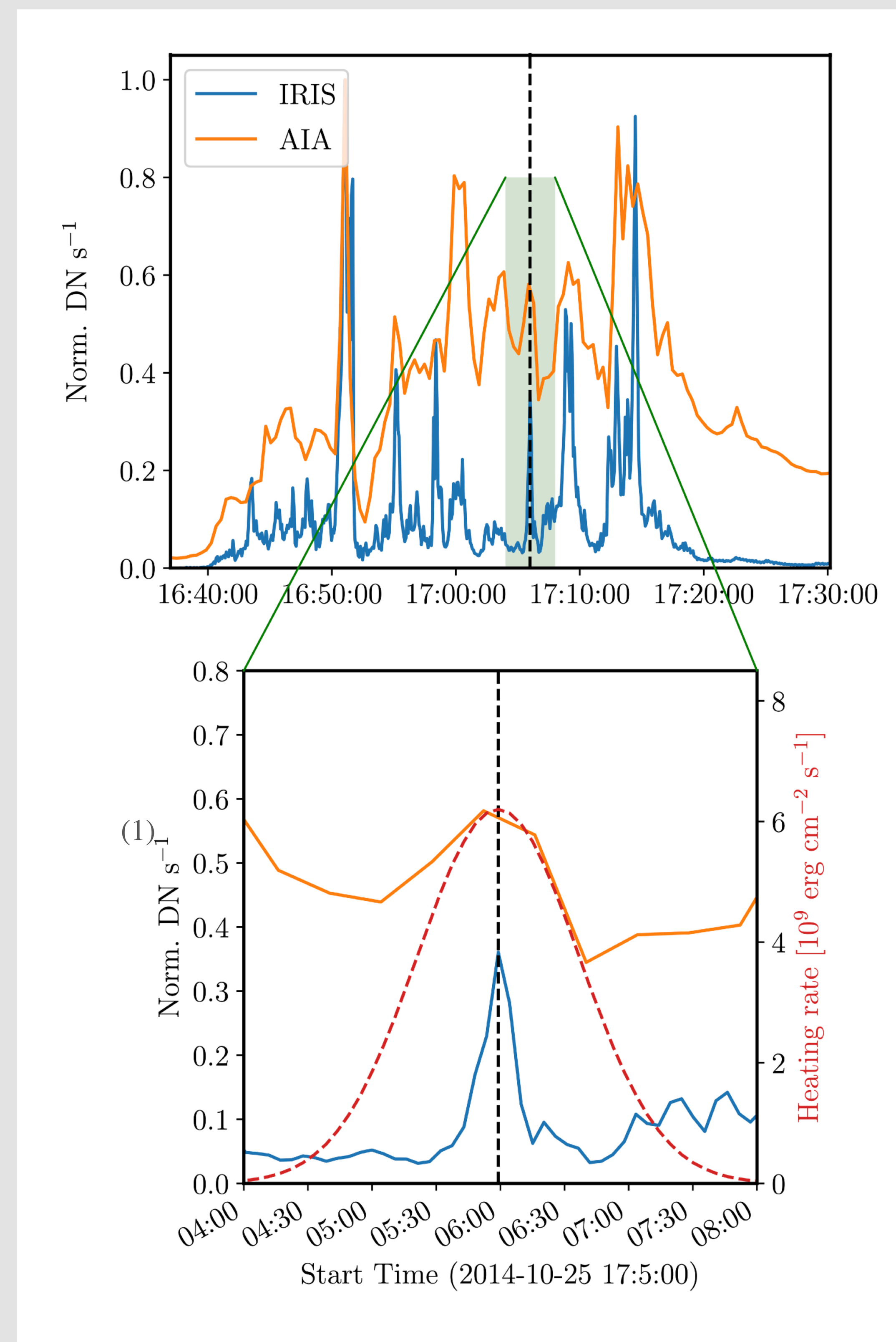

Figure 4: Lightcurves of the 2014 October 24th X1.0 class flare. The top panel shows coaligned AIA 1600Å and IRIS Si IV 1400-1405Å lightcurves for the selected pixel. The period corresponding to our condensation event is enlarged in the bottom panel. The red dashed line is the heating rate derived from the UFC method, read against the axis on the right.

The calculated value of λ was then applied to determine the heating rate of a single brightening in AIA 1600Å, corresponding to our condensation event. Figure 4 shows the coaligned lightcurves of AIA 1600Å and IRIS Si IV 1402.77Å for our single pixel, where we see a concurrent brightening in AIA at the moment of peak emission in Si IV (black dashed line). This single brightening was found to be equal to a Gaussian heating profile, with a peak energy flux of F = 6.2 × 10^9 erg/s/cm² and a total energy deposition of 6 × 10^{11} erg/cm². We interpret the energy deposition into the flare loop footpoint as the same flux driving the observed condensation event. The results of Ashfield & Longcope (2021) predict that peak flux should product a peak condensation velocity u_0=34 km/s. This agrees well with the measured doppler velocity shown in Fig. 3.

1D Flare Modeling

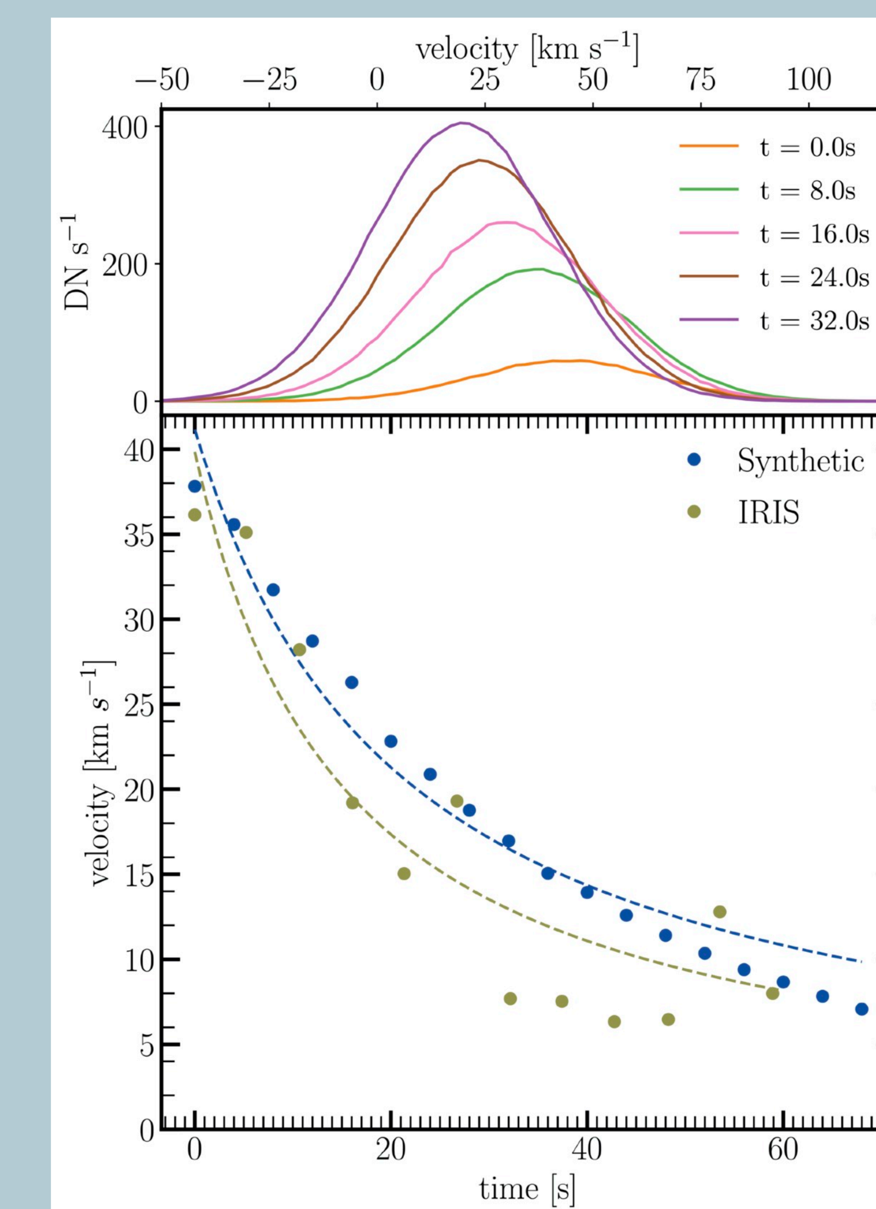

Figure 5: Results from the PREFT model. The top panel shows the temporal evolution of synthetic Si IV 1402.77 spectra, with t=0s corresponding to peak downflow velocity. A time series of the velocity measured from the synthetic spectra is shown in the bottom panel, along with the IRIS condensation observation. The dashed lines show the respective fits to each time series.

The energy flux derived from the UFC method was used as an *ad hoc* heating input for a 1D simulation of the flare loop - performed using the PREFT numerical code [5]. The loop was initialized with a length of L=85 Mm, obtained from a magnetic model of the flaring loop emanating from the selected pixel, and was anchored to an isothermal chromosphere of temperature 10,000 K. The chromosphere was also gravitationally stratified with density scale height H=369Mm, derived from the fit shown in Figure 3. Heat was then deposited at the apex of a flare loop, where it traveled via thermal conduction to the chromosphere, driving condensation in the form of a downward propagating hypersonic shock.

Synthetic Si IV emission spectra were created using the simulation results. These spectra where then averaged over 4 seconds to match the IRIS data and fit with a single gaussian, as a double-gaussian shape was not produced. The time evolution of the synthetic velocity was fit with equation (1), giving a peak velocity of 38 km/s and a half life of τ=21s. Shown in Figure 5, the simulated results agree well with the IRIS observation.

Conclusion

A 1d loop simulation driven by a flare heating rate derived from the UFC model was able to reproduce the condensation observed using IRIS with relatively good accuracy, suggesting our relationship between flare energy release and condensation is well corroborated. We also found the energy was transported via thermal conduction, rather than a beam of non-thermal electrons. However, several discrepancies between observation and simulation exist despite the successes of this model. First, the synthetic spectra do not exhibit double gaussian profiles, which may be attributed to the fundamental scale of the loop footprint. Second, the energy flux - lasting over four minutes - produces condensation lasting roughly one minute. Not only does the condensation decay before much of its energy is released, the simulated loop itself cools much faster than what is observed in the coronal AIA bands. This cooling may be explained by a second heating phase, and will be explored in future work [3,6].