Call and Response: A Time-Resolved Electron Driver and its Consequences

Sean G. Sellers [1] Ryan O. Milligan [2] R.T. James McAteer [1]

[1]Department of Astronomy, New Mexico State University [2]Astrophysics Research Centre, School of Mathematics & Physics, Queen's University Belfast

Abstract

We study an X1.6 solar flare produced by AR 12602 on 2014 October 22. The entirety of this event was covered by *RHESSI*, *IRIS*, and *Hinode/EIS*, allowing analysis of chromospheric response to a nonthermal electron driver. We derive the total energy released in nonthermal electrons via *RHESSI* spectral fitting, and link the time-dependent parameters of this call to the response in Doppler velocity and nonthermal width across a wide temperature range. The total energy injected was on the order of 4.8×10^{30} erg, lasting 352 seconds. This energy injection drove explosive chromospheric evaporation, with a clear delineation in both Doppler and nonthermal velocities at the flow reversal temperature. The time of peak electron injection (14:06 UT) corresponded to the time of highest velocities. At this time, we find unexpected 200 km s^{-1} blueshifts in the core of Fe XXIV, which is typically assumed to be at rest. Shortly before this time, the nonthermal electron population has the shallowest spectral index (≈ 6), corresponding to the peak nonthermal velocity in Si IV, and Fe XXIV. This study provides one of the most comprehensive time-resolved sets of chromospheric diagnostics for a large X-class flare, along with the corresponding energy injection profile, ideal for further modeling studies.

Event Overview

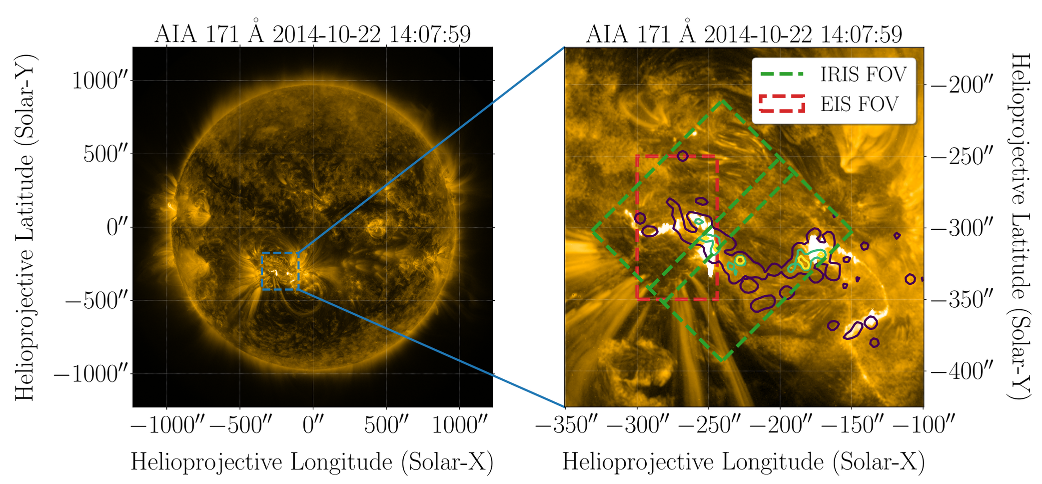

Figure 1. AIA 171 Context Image with RHESSI 40+ keV Contours

The X1.6 flare selected for study occurred on 2014 October 22, beginning at 14:02:00 UT, and was one of the largest flares produced by flare-productive NOAA AR 12192. The *GOES* soft X-ray (SXR) flux plateaued through much of the event, resulting in a significant offset between the hard X-ray (HXR) and SXR peak times (14:06 UT versus 14:28 UT). The focus of this study is on the times surrounding the HXR peak, where the impulsive phase of this event was captured by the *RHESSI*, *EIS*, and *IRIS* instruments. We present detailed *RHESSI* spectral fit parameters in order to quantify the the nonthermal electron energy profile. Parameters pertaining to chromospheric evaporation are tracked through intensities and Doppler and nonthermal velocities across time and temperature.

The Electron Beam

RHESSI spectra were obtained with 16 second time bins for detectors 1, 3, 6, 8, and 9, which were the only detectors with consistently high peak counts during the flare, signifying that they retained sufficient sensitivity to be usable. Background subtraction and spectral fits were performed using the OSPEX package available within SSW. The thermal portion of the spectrum was fit with a multithermal model, characterized by a power-law differential emission measure (DEM). The nonthermal portion of the spectrum was best fit by a thick-target electron beam model, with an electron distribution characterized by a single power law.

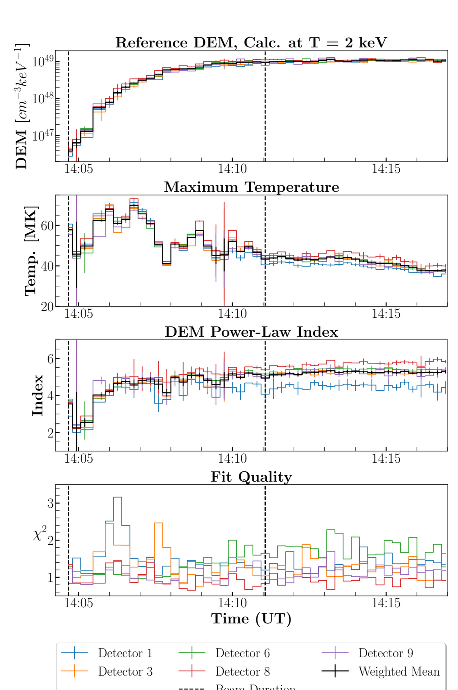

Figure 2. RHESSI Thermal Parameters

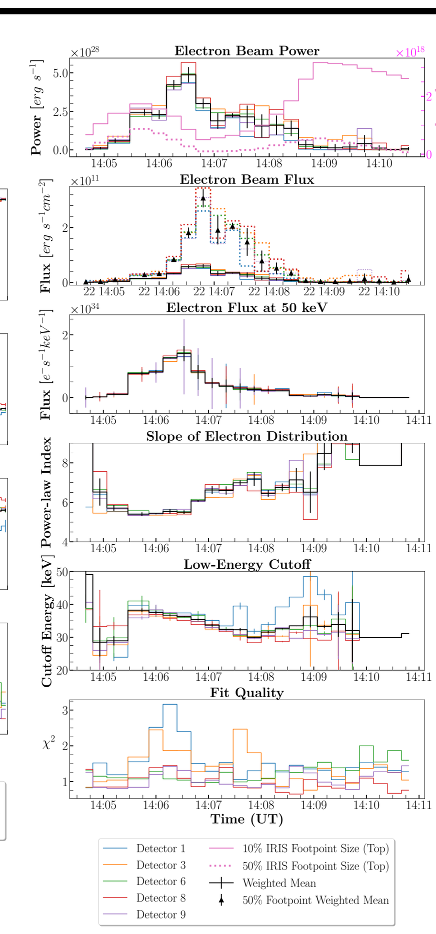

Figure 3. RHESSI Nonthermal Parameters

For the determination of electron energy flux, *IRIS* slit-jaw images were used to determined the size of the emitting area. *RHESSI* spectral fits for this event characterize the electron beam as lasting for 352 seconds, over which $> 4.8 \times 10^{30}$ erg of energy was deposited. The peak energy flux caused by nonthermal electron injection occurred between 14:06:40–14:06:56 UT, reaching $3.07 \pm 0.34 \times 10^{11}$ erg s^{-1} cm^{-2}, for a compact footpoint case.

Response in EIS

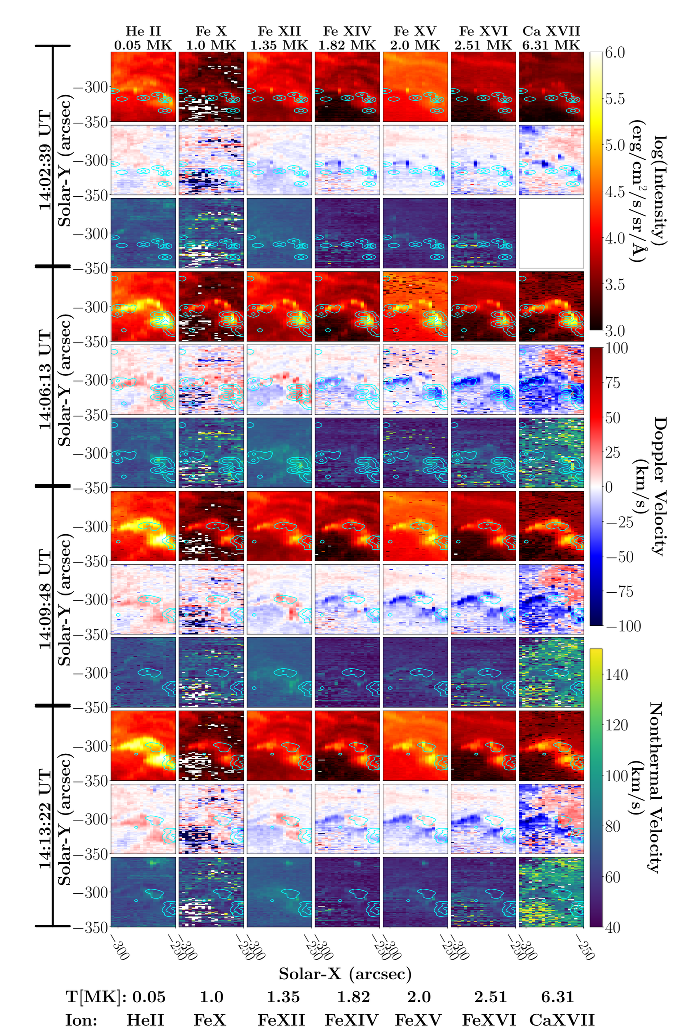

Figure 4. EIS ions T < 10 MK

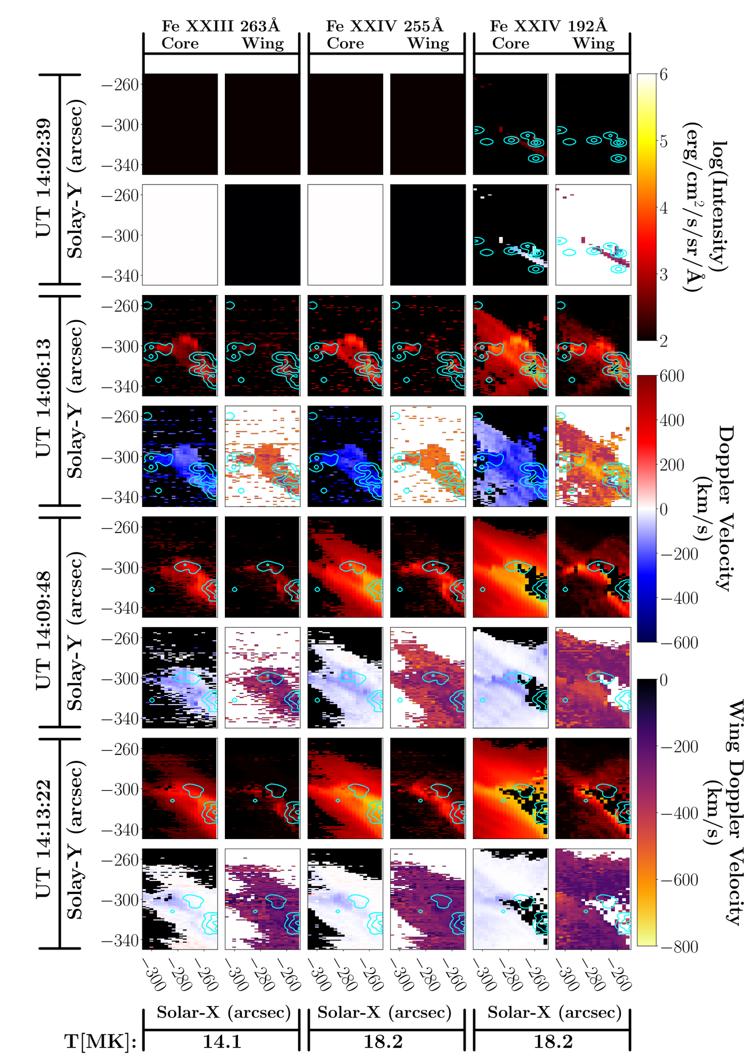

Figure 5. EIS ions T > 10 MK

EIS data are used to constrain the flow reversal temperature (FRT), the temperature division between evaporative upflows, and condensation downflows. For this event, the FRT was found to be between 1.35–1.82 MK after 14:06:13 UT. In the raster prior, the Doppler velocity signature is more consistent with gentle, rather than explosive chromospheric evaporation, possibly due to the presence of nonthermal electrons below the *RHESSI* detection threshold. The FRT also marks a division in nonthermal velocity widths. At temperatures below the FRT, nonthermal velocities rise with temperature. At the FRT, they drop suddenly before again rising.

In the hottest ions, Fe XXIII and Fe XXIV, in addition to significant blue wing enhancement after 14:06:13 UT, strong core blueshifts are observed during the same time interval. These are observed in all three lines for both species, and are greatly reduced by the 14:09:48 UT raster, and finally absent by the 14:13:22 UT.

The Curious Case of Fe XXIV

In addition to exhibiting significant core blueshifts, both Fe XXIV lines exhibit complex profiles during the 14:06:13 UT raster. Several examples of this are seen below, most notably in the right-hand column of Figure 6 which shows a strong blueshifted core component, with a further blueshifted wing, but also an additional redshifted component, completely separated from the blueshifted core. Both profiles are extracted from a region within the first slit position, within the primary flare footpoint. They are a product of the sudden increase in electron energy flux occurring at this time. It is unlikely that this can be attributed to blends, given the identical velocity signatures between the two line complexes.

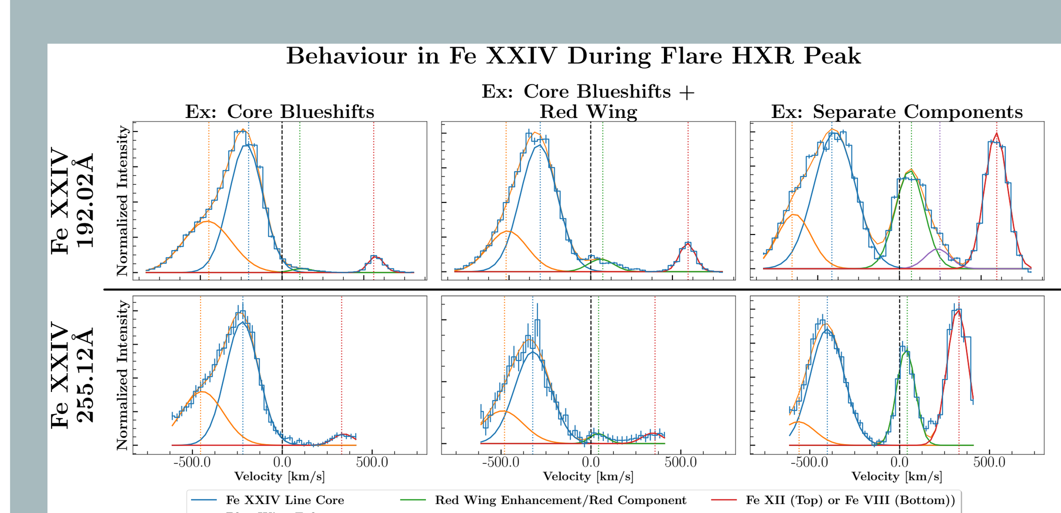

Figure 6. Variety of Fe XXIV profiles found during the flare peak

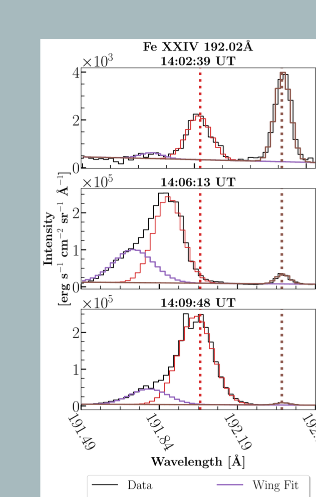

Figure 7. Fe XXIV profiles through time

Acknowledgements

This work was funded by NASA grant NNX17AD31G and support from DoD Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI) Basic Research Funding Opportunity Announcement W911NF-17-S-0010, Proposal Number: 72536-RT-REP, Agreement Number: W911NF-18-1-0484.

Response in IRIS

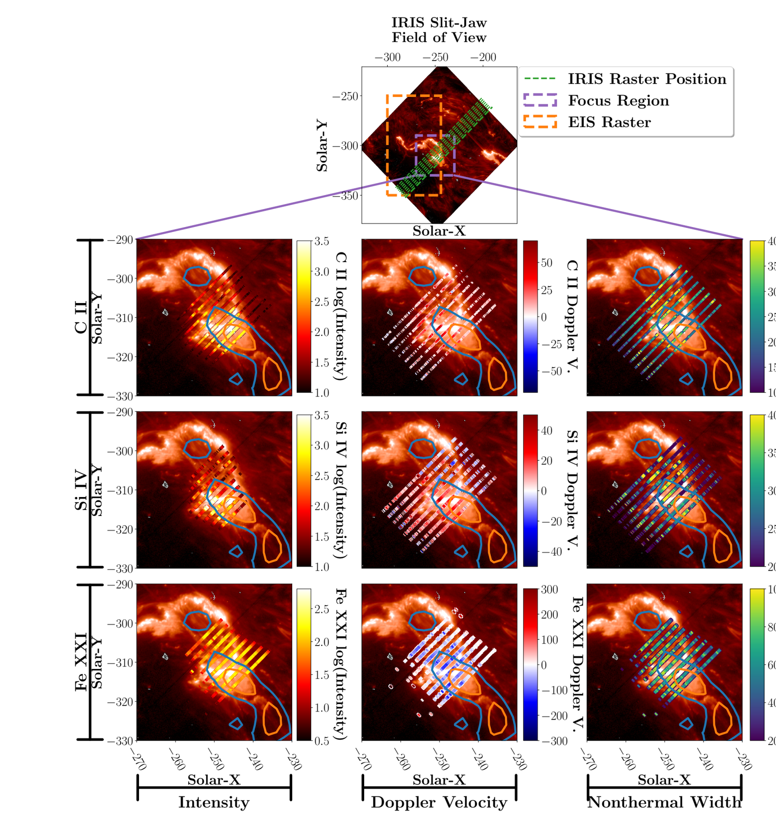

Figure 8. IRIS spectral fit parameters in context

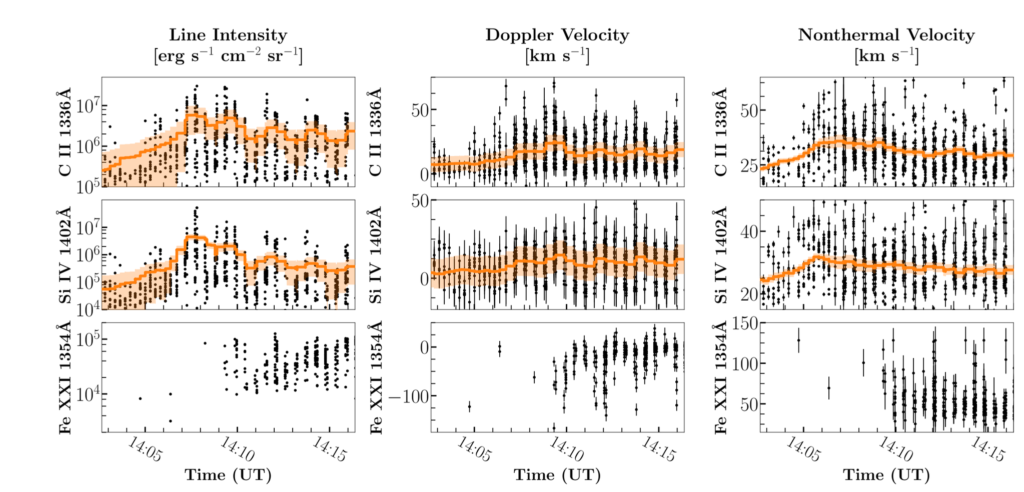

Figure 9. IRIS spectral fit parameters

Figures 8 and 9 provide results of *IRIS* spectral fits for the C II 1335Å line pair, the Si IV 1402Å line, and the Fe XXI line. Figure 8 shows the variation of parameters across the flare ribbon captured in the *IRIS* slit. These field-of-view effects are reflected in the spread of parameters in Figure 9. Interestingly, when combined with results from *EIS*, the dependence of temperature on the observed structure is clearly seen. Velocities and intensities in ions as warm as Ca XVII (6.31 MK) trace the flare ribbon. Hotter ions (Fe XXI, Fe XXIII, and Fe XXIV) initially trace this structure, but by 14:09:48 UT trace instead the filling post-flare loop.

Of additional note is the behaviour of nonthermal velocities as found in Si IV. The running mean of this quantity peaks early, at 14:06:49 UT, with an average nonthermal velocity of 31.9±1.0 km s^{-1}. This is coincident with the time of the hardest electron distribution, with a spectral index $\delta < 6$. As the spectral index increases, the Si IV nonthermal velocities decrease, and finally plateau around 14:10 UT, one minute before the electron injection ceases. For Si IV, at least, it appears that excess line widths may be linked to the deposition of energy from nonthermal electrons.

Summary

- *RHESSI* spectral fits reveal an electron injection profile that lasted 352 seconds and deposited more than 4.8×10^{30} erg into the chromosphere.
- Prior to the onset of nonthermal emission, gentle chromospheric evaporation was observed in *EIS* rasters, characterized by compact blueshifted regions observed in ions with T $\geq$ 1.35 MK.
- The FRT was found to be between 1.35–1.82 MK after 14:06:13 UT.
- *IRIS* results support and contextualize these results. *IRIS* results are consistent with the trends observed in *EIS* Doppler and nonthermal velocities.
- The Fe XXIV line complex exhibited significant unexpected blueshifts to the core component, as well as a complex spectral shape implying significant unresolved flow structure. The core blueshifts of these lines follows the trend of other hot lines, with the blue wing enhancement as a significant velocity outlier.

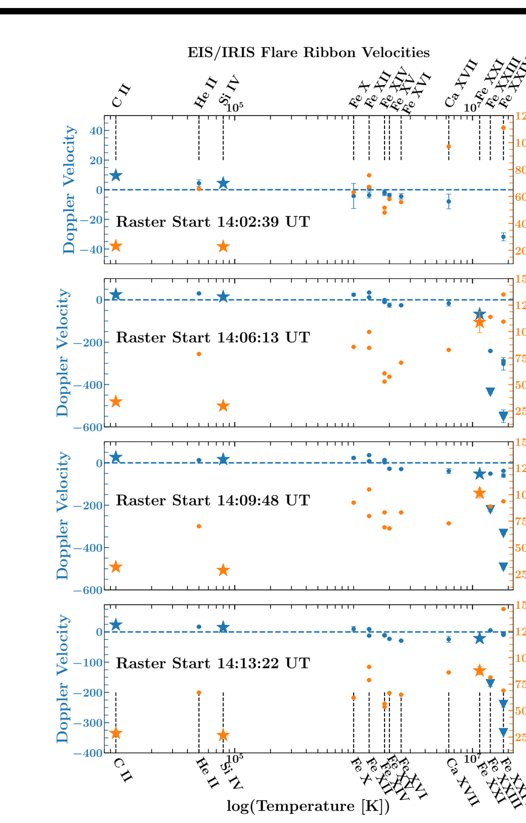

Figure 10. Selected IRIS/EIS Velocities

sellers@nmsu.edu