

Strong Photospheric Heating Indicated by Fe I 6173 Å Line Emission During White-Light Solar Flares

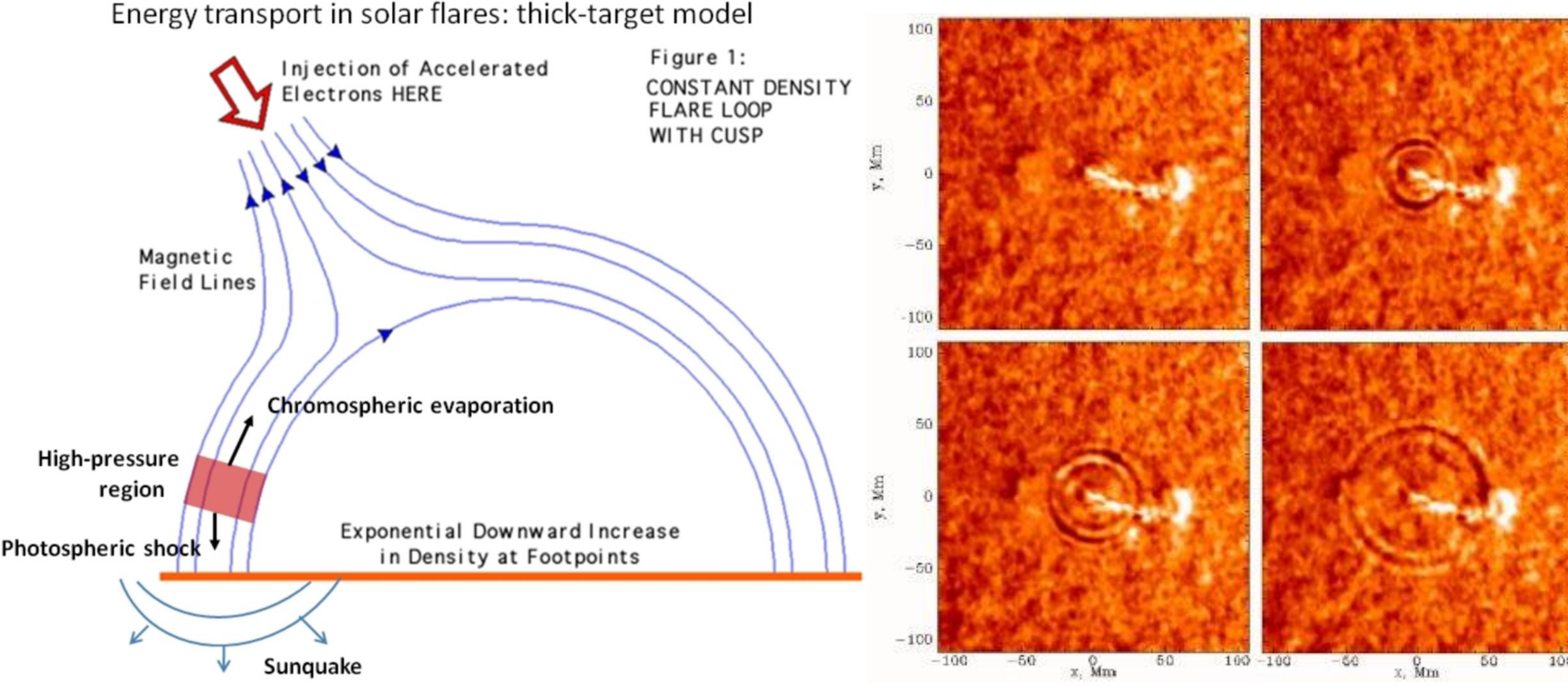
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Introduction

The origin of WLFs, particularly their compact and transient cores, has been a subject of long-standing debates. Spectroscopic and photometric studies suggest that the observed white-light emission originates from heating of the lower chromosphere and upper photosphere. Traditional thick-target electron beam models of solar flares struggle to explain WLFs, as most energy is deposited in the upper chromosphere. Reconciling observations with models that include electron and proton beams has proven challenging, as current models often require unrealistic particle energies or fail to match the observed phenomena. SDO HMI observations have revealed that WLF events coincide with significant variations, including line-core emission, in the Fe I 6173 Å line profile, a deep photospheric line, along with excitation of helioseismic acoustic waves (sunquakes). This provides unambiguous evidence that the flare hydrodynamic impacts affect photospheric and subphotospheric layers on the Sun. While RADYN proton beam models suggest that strong line core emission can be explained by proton beams with cut-off energies $E_c \geq 500$ keV, stronger helioseismic impacts are driven by proton beams with $E_c \leq 100$ keV. A unified model explaining both X-ray and optical observations of WLF cores remains undeveloped.

Origin of Sunquakes



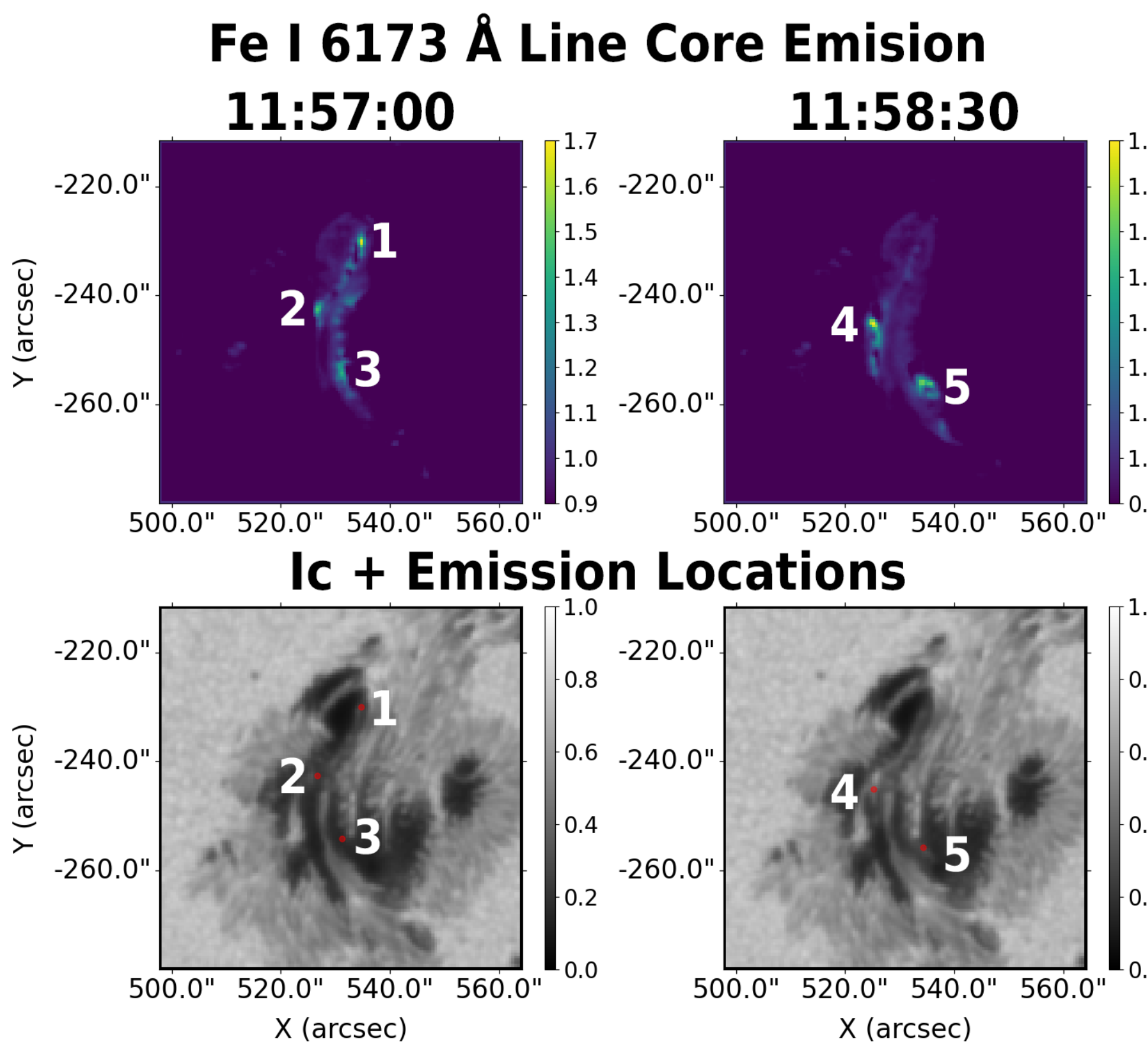
Methods

- Compile and analyze Stokes data from SDO HMI observations of sunquake-producing solar flares
- Identify locations where the line goes into full emission, and record line behavior over time at these locations
- Compare timing of these line emission events with GOES soft X-ray and KONUS-WIND hard X-ray data to find correlation with precipitating electrons
- Compare HMI observations with simulated line profiles computed using RADYN RHD code and RH1.5D RT code

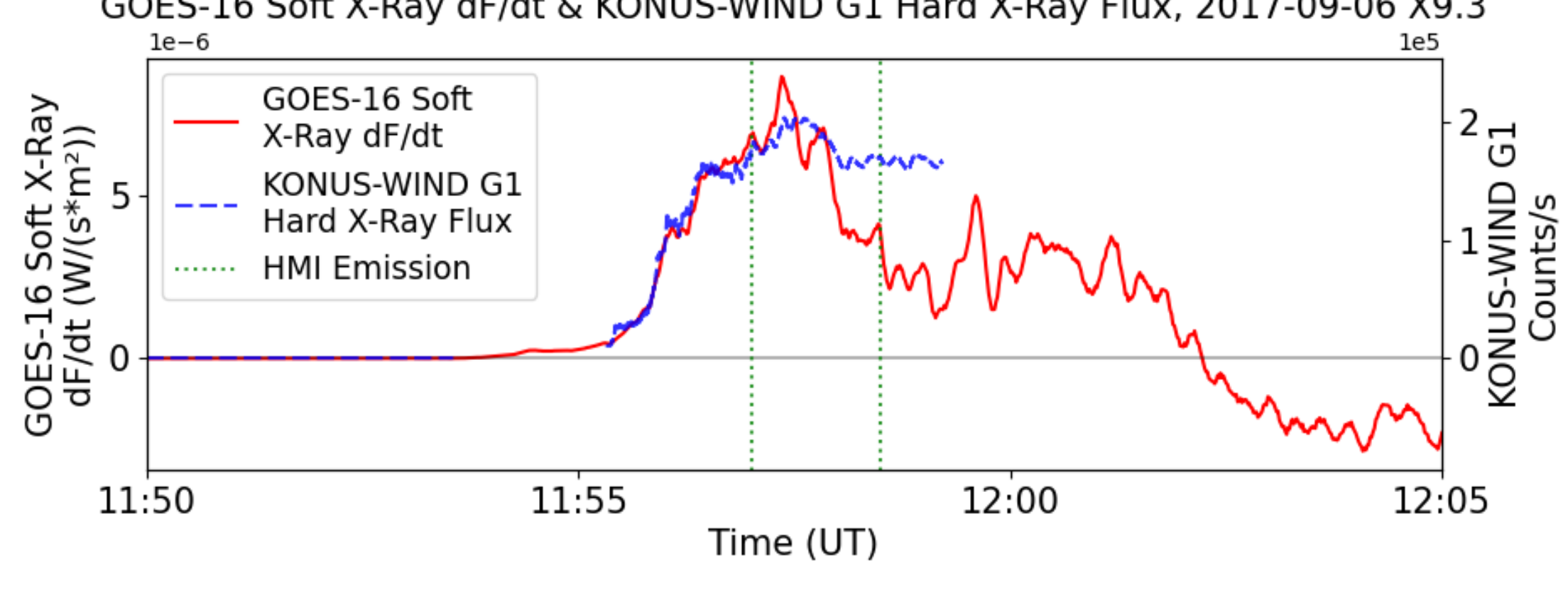
SDO HMI WLF Line-Core Emission Observations

- Rapid, short-lived increase in line-core emission precedes or concurrent with continuum intensity increase, indicating core emission may occur in higher layers of photosphere.
- Line-core emission primarily occurs above umbra and umbra-penumbra border.
- Lasting magnetic field changes following flare peak indicate reconfiguration of magnetic field at the flare location.
- Line-core emission occurs near peak in hard X-ray emission / soft X-ray derivative, indicating that emission occurs near peak electron flux.
- Determining the true line profile and the exact relative timing of events is difficult due to the sampling delay between the six wavelength channels and the 90 s cadence.

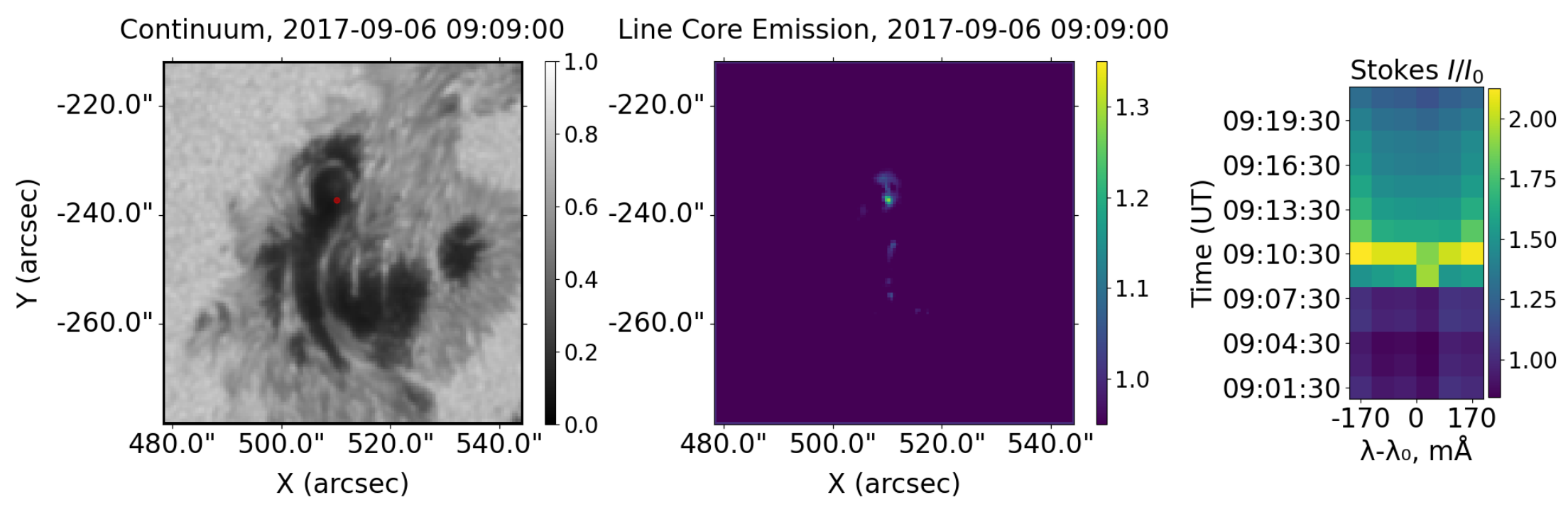
September 6, 2017: X9.3 Flare



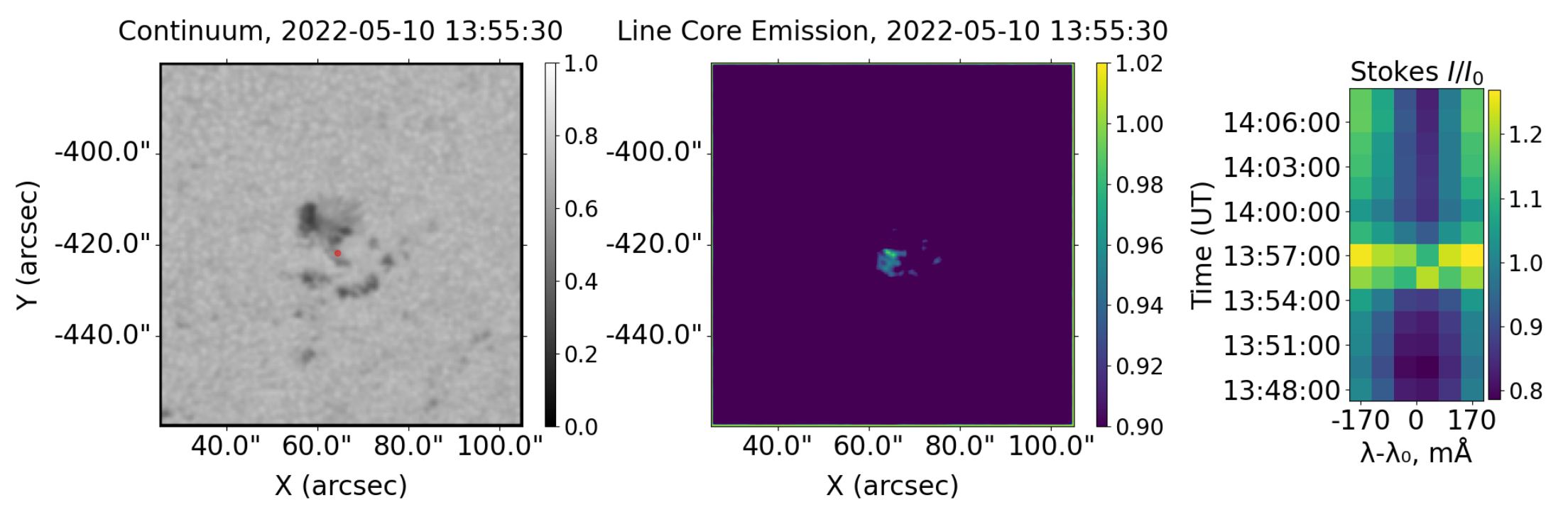
Hard X-ray + Soft X-ray dF/dt



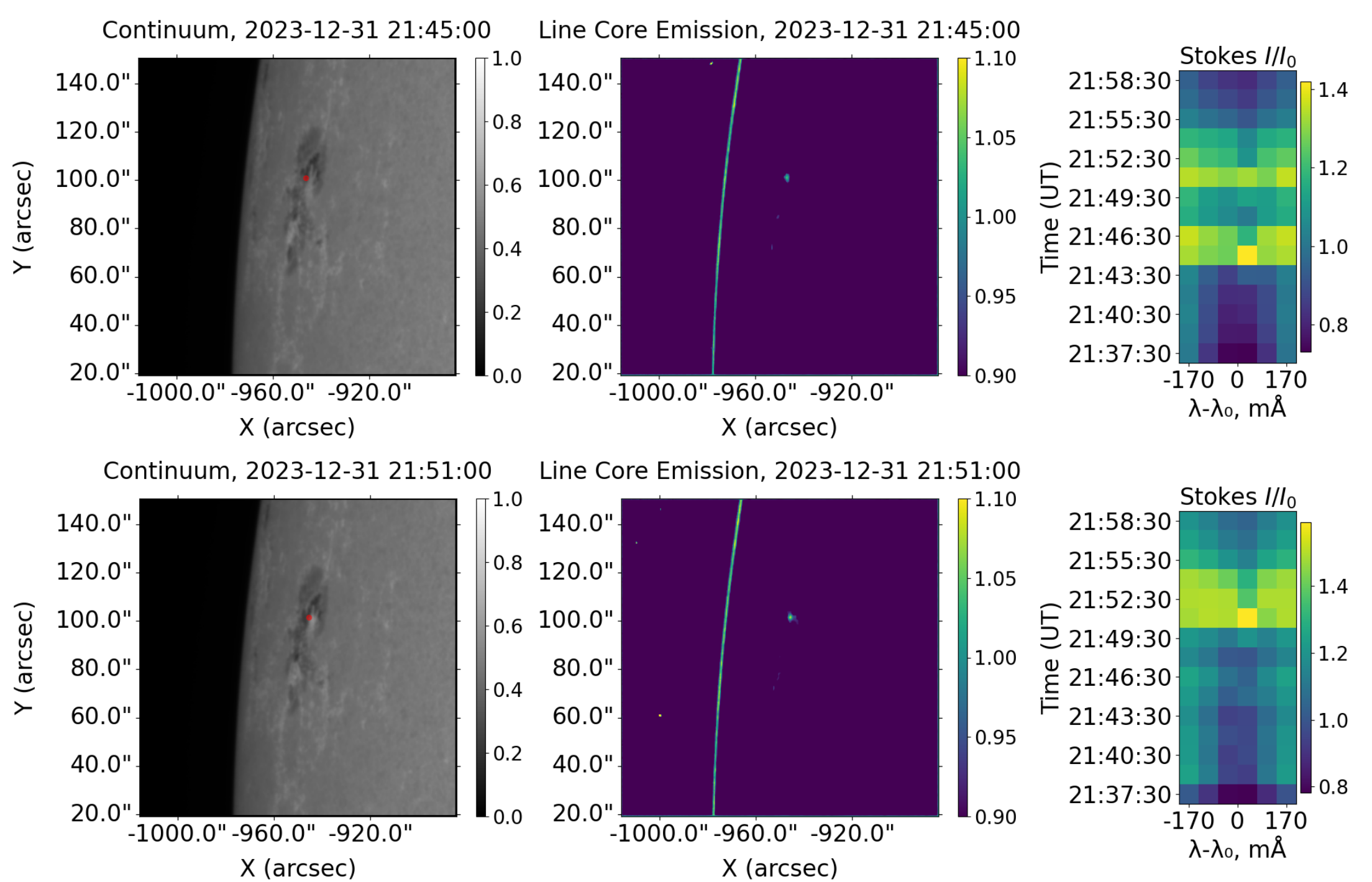
September 7, 2017: X2.2 Flare



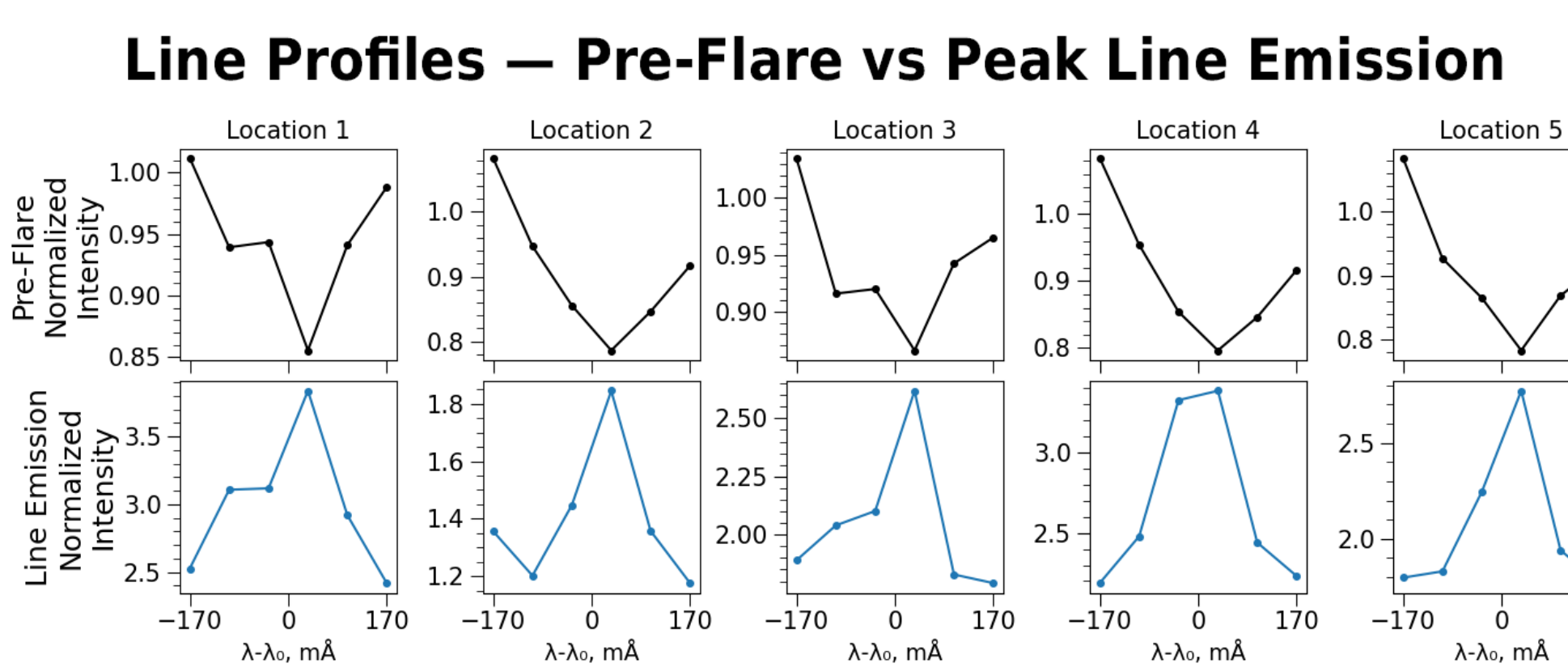
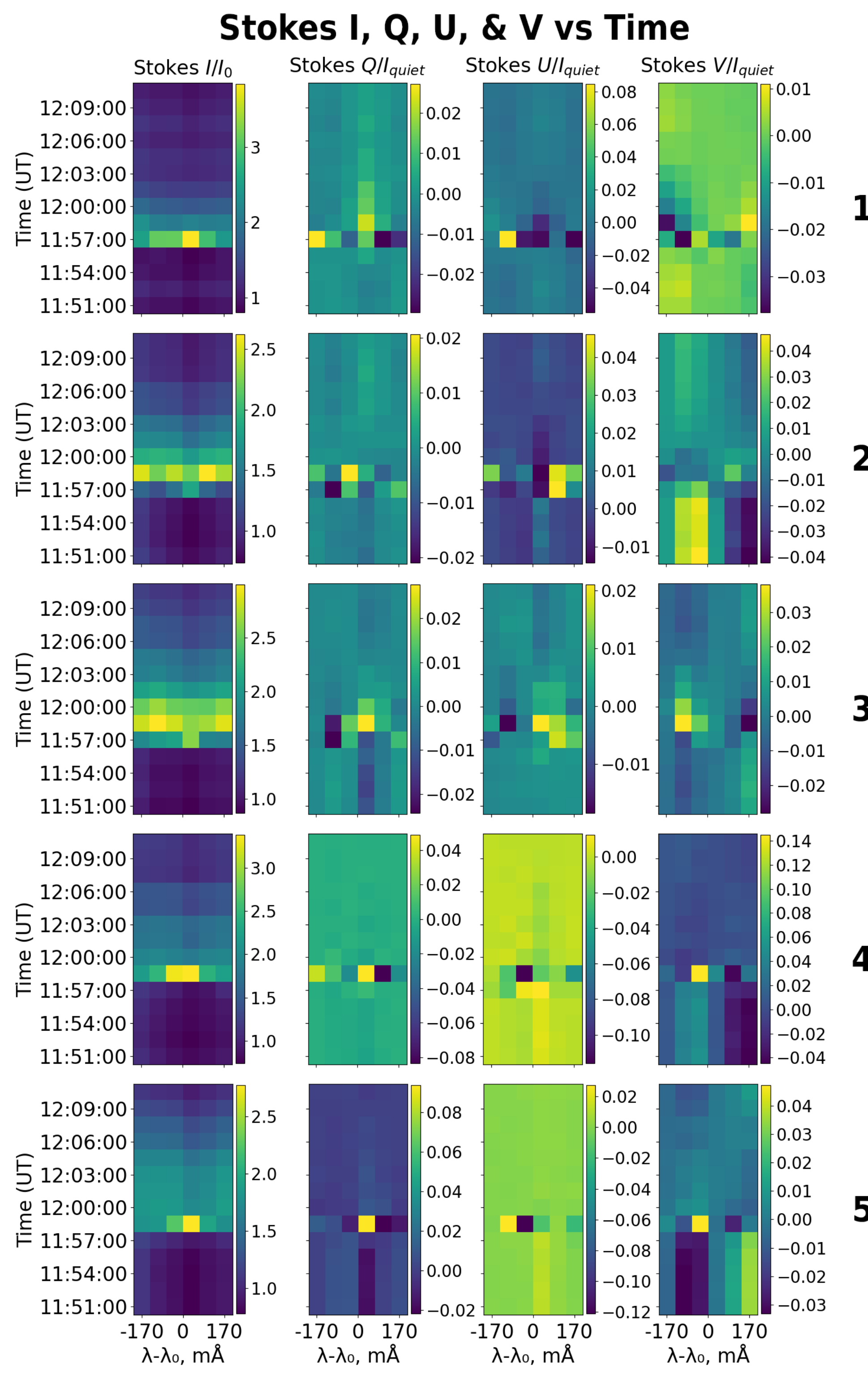
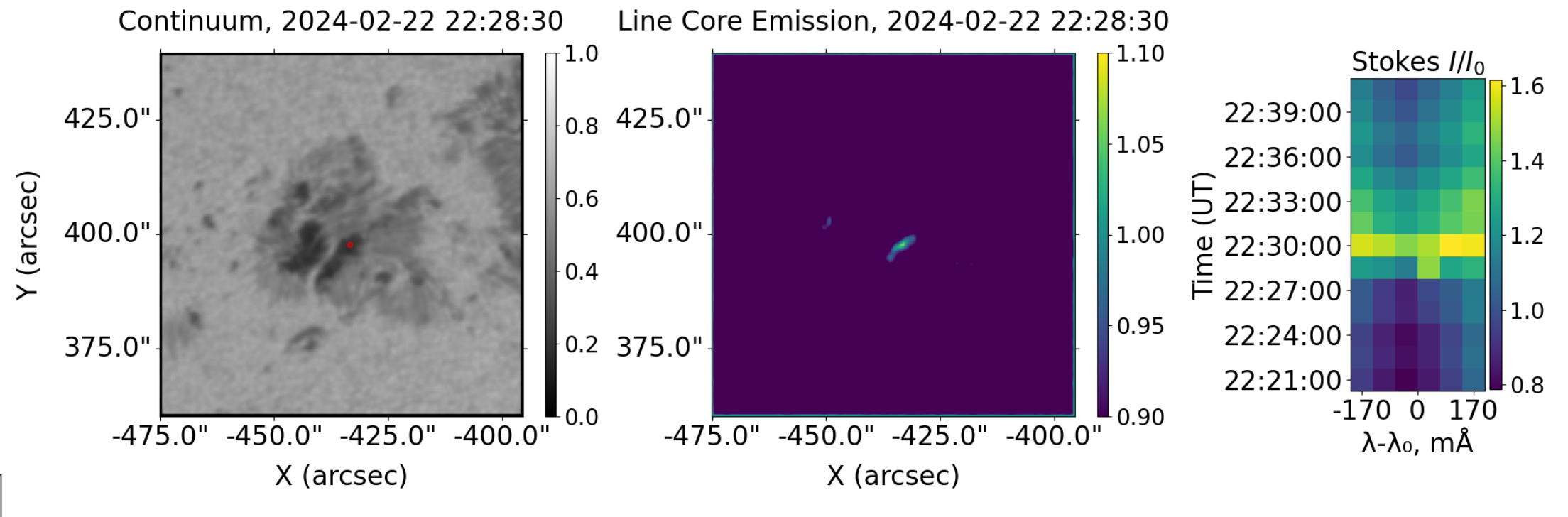
May 10, 2022: X1.5 Flare



December 31, 2023: X5.0 Flare



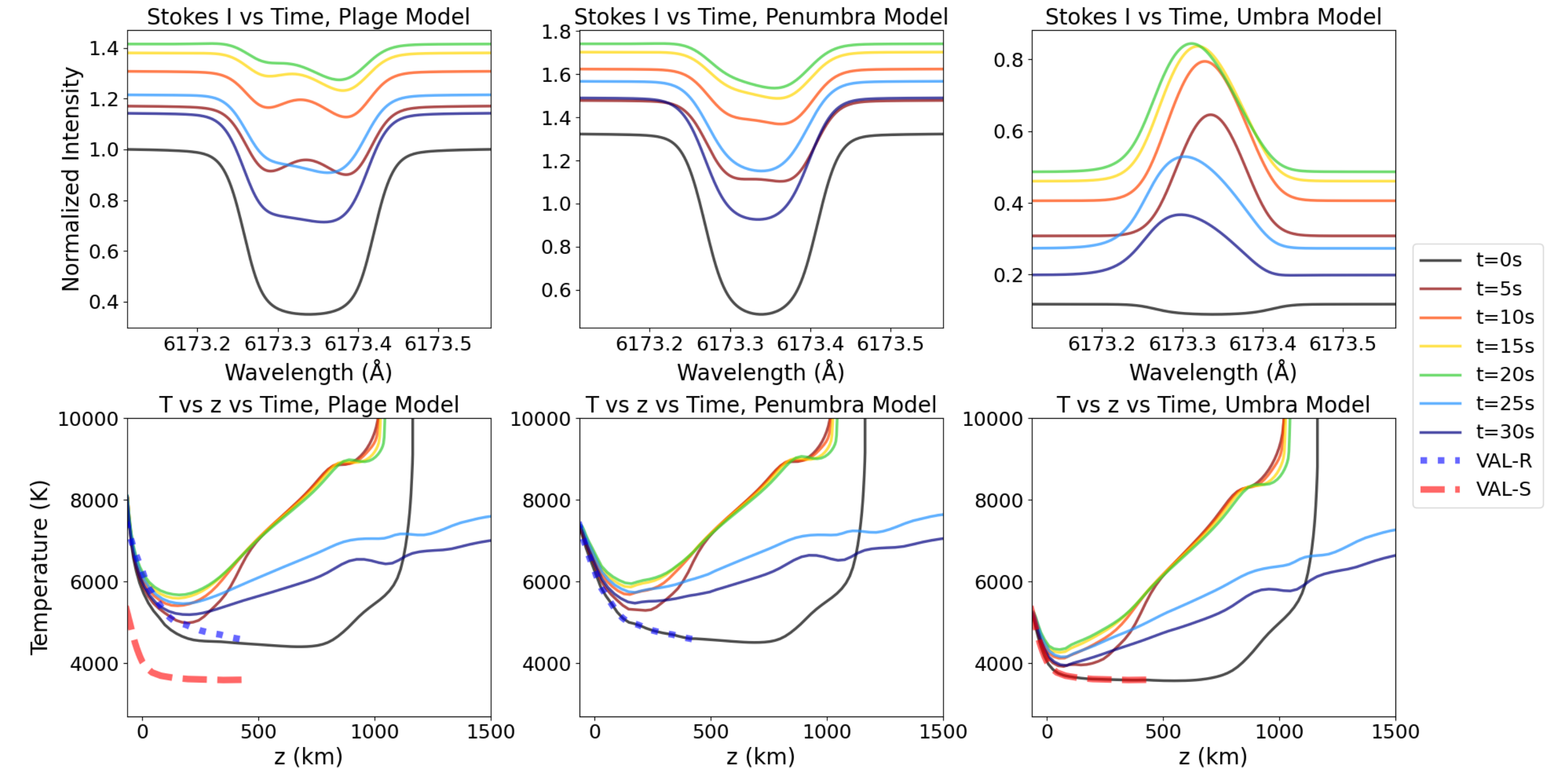
February 22, 2024: X6.3 Flare



Semi-Empirical RT Modeling of Colder Atmospheres

- RADYN proton beam model: 20s heating, $\delta = 3$, cutoff energy $E_c = 3$ MeV, and total energy flux density of $1 \cdot 10^{11}$ erg s^{-1} cm^{-2}
- Temperature profile for RADYN VAL-C – like plage model modified to match VAL-S (umbra) and VAL-R (penumbra) models before heating (t=0)
- Fe I 6173 Å line profile shape computed using RH1.5D code
- Umbral temperature profile results in strong, total line emission
- Plage and penumbra temperature models result in limited line-core emission; however, it does not exceed continuum intensity
- The contribution function distribution is higher in altitude for umbra model compared to penumbra and quiet sun models

Fe I 6173 Å Synthetic Profiles for Plage, Penumbra, and Umbra Models



Conclusions

- HMI has observed several instances where the photospheric Fe I 6173 Å line briefly goes into emission during sunquake-producing flares.
- This line emission, in addition to sunquakes, provides unambiguous evidence of flares affecting the photosphere and subphotospheric regions
- Line emission observed during or near peak electron flux, however modeling suggests that electrons alone do not carry enough energy to produce sunquakes.
- Based on our semi-empirical RADYN models, cooler photospheric conditions may make it more likely for the line to go into emission, however more physically consistent models of particle beams above various photospheric conditions are required.

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