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Using Intensity/Duration Correlations in Solar and Stellar Flares to Improve Models of Irradiance Variability

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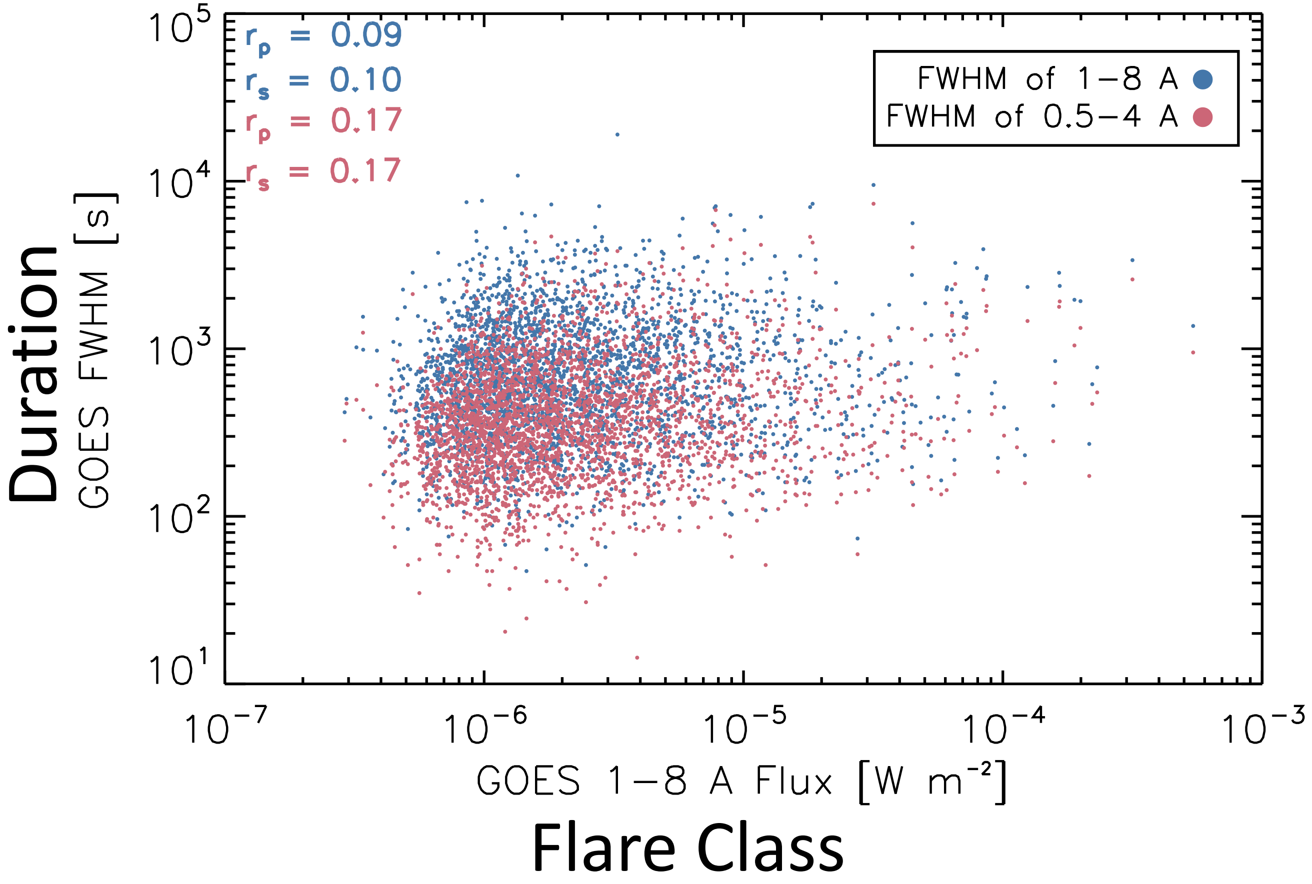
ORCiD

Soft X-ray (SXR) flare duration not correlated with flare class

Reep et al



Not correlated!

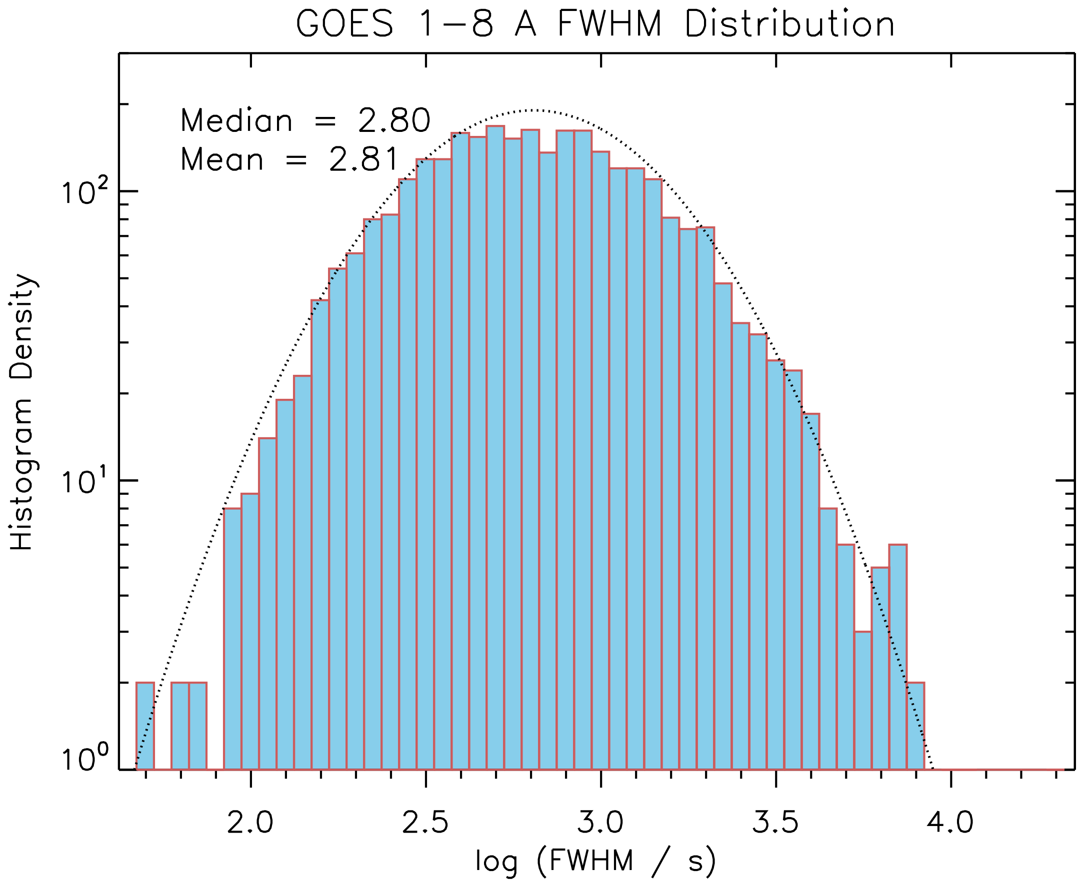
Duration also not correlated with physical volume, temperature, density, total energy release, or magnetic field strength

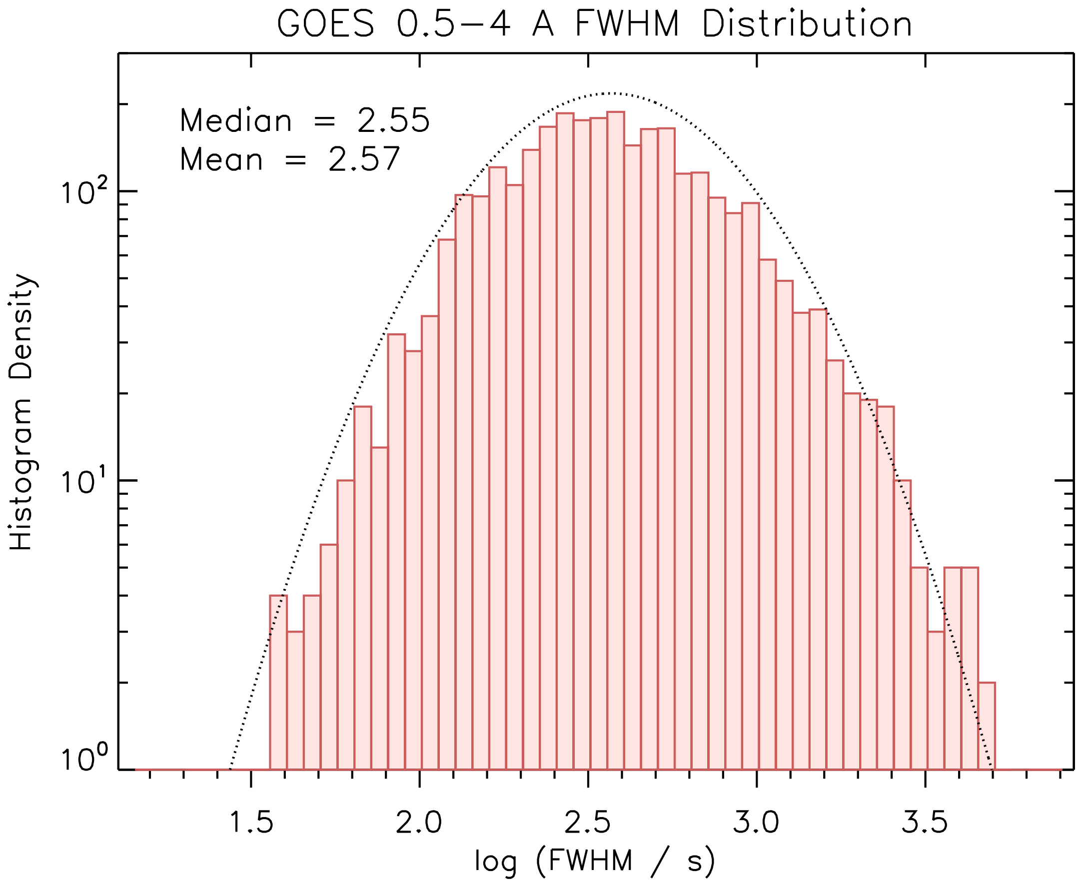
Reference(s): Reep & Knizhnik 2019, ApJ, 874, 157

Distribution of SXR flare durations (FWHM)

Reep et al.

Log-normal Distributions, dependent on wavelength

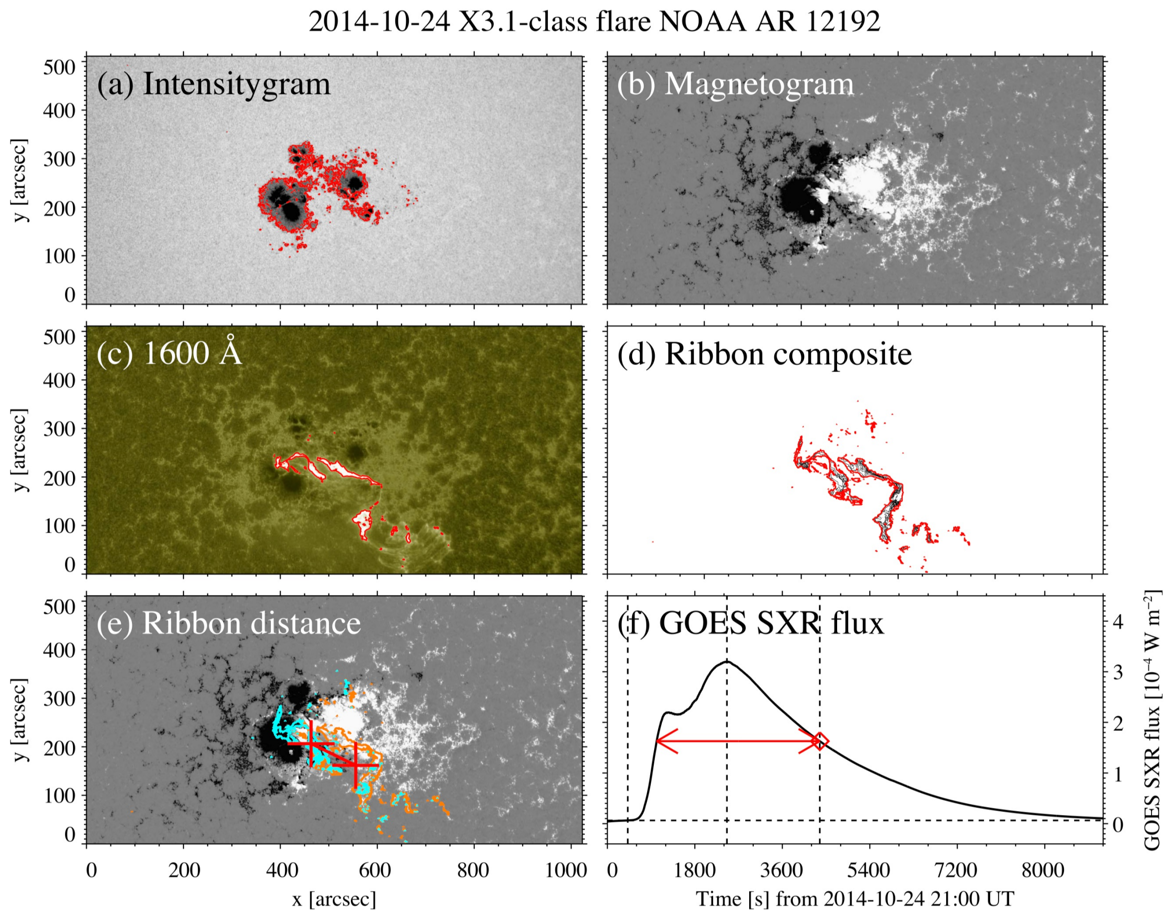




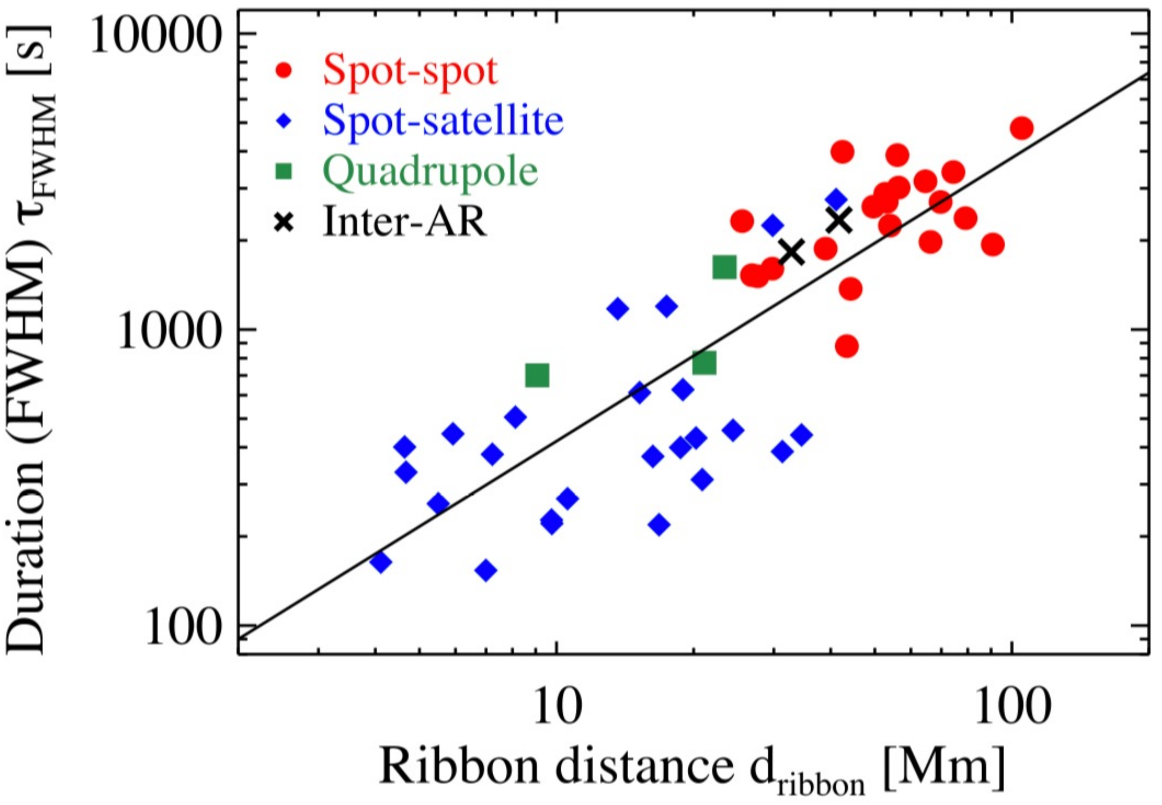
Reference: Reep & Knizhnik 2019, ApJ, 874, 157

SXR duration correlated with ribbon separation

Reep et al.



Ribbon separation correlated with flare duration

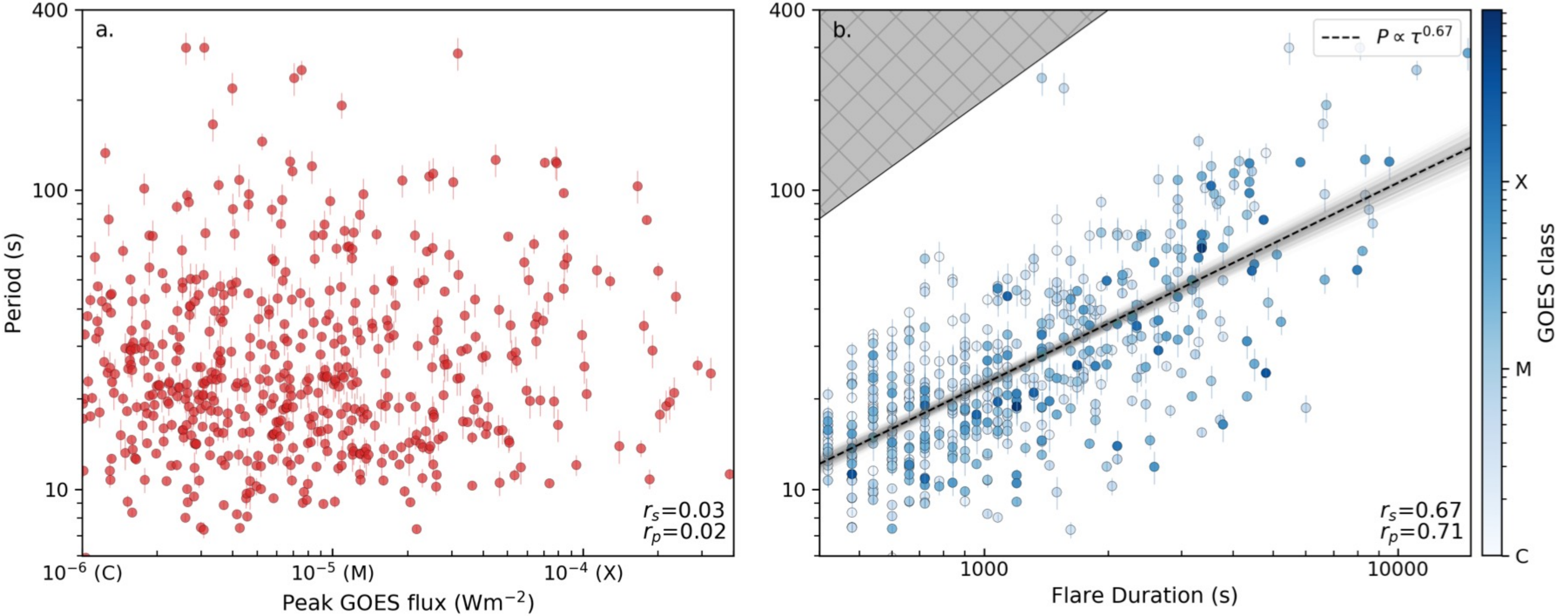


References: Toriumi et al 2017, ApJ, 834, 56

QPP period related to SXR duration, but not class

Reep et al.

QPP Period



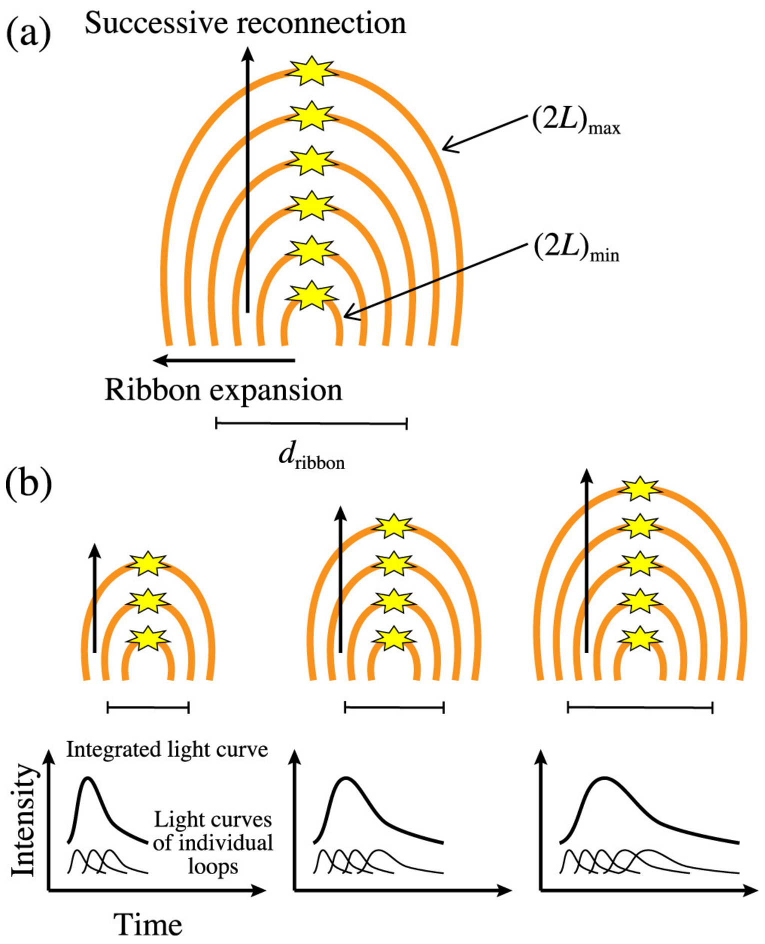
GOES Class

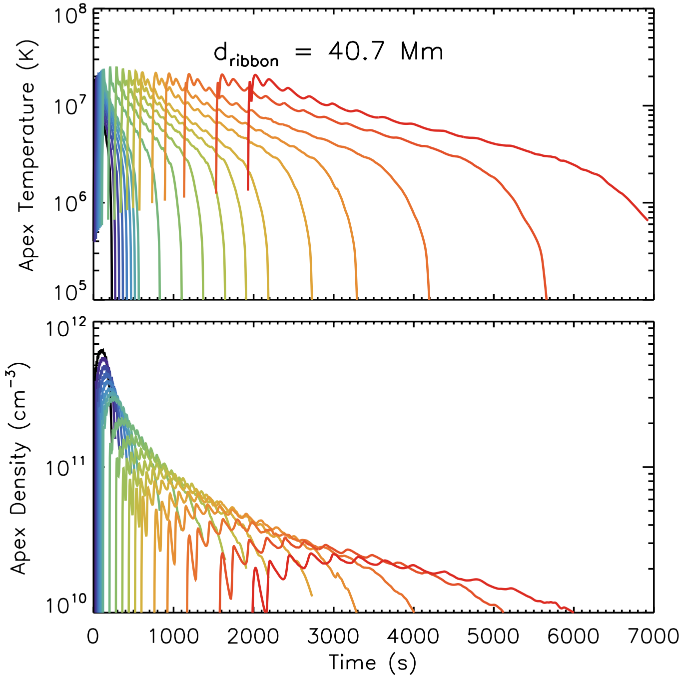
GOES Duration

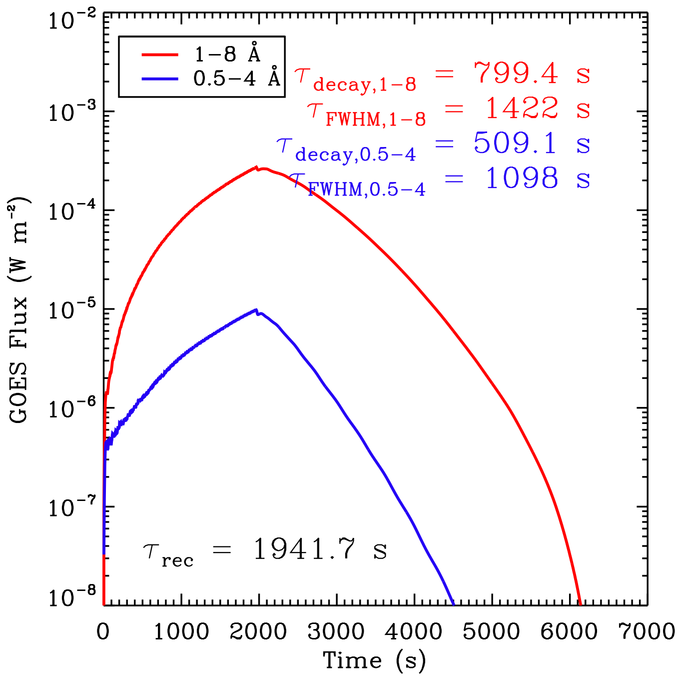
References: Hayes et al 2020, ApJ, 895, 50

Testing the relation between SXR duration and ribbon separation

Reep et al





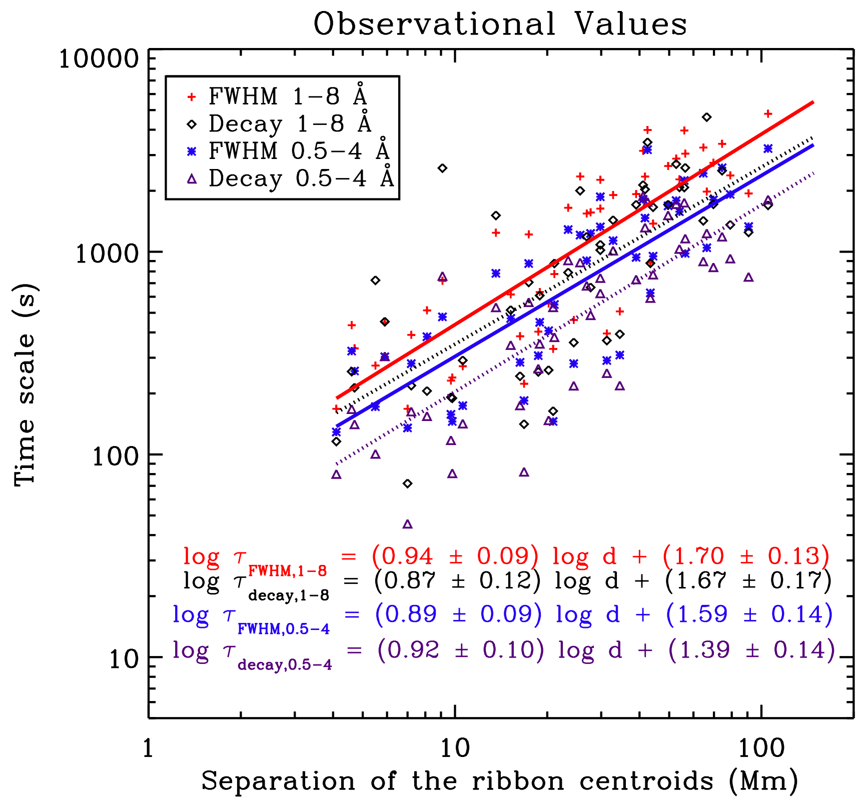


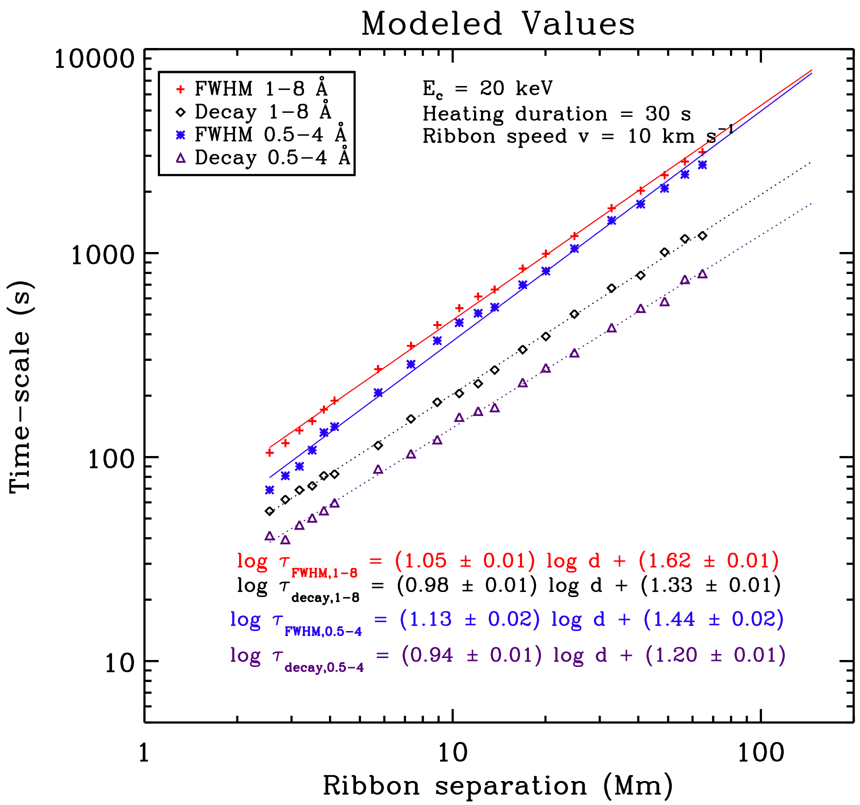
Construct a multithreaded flare model to test the relation

Reference(s): Reep & Toriumi 2017, ApJ, 851, 4

τ - d Relation Reproduced

Reep et al.





Reconnection duration can explain the relation between SXR duration and ribbon separation

Reference: Reep & Toriumi 2017, ApJ, 851, 4

Duration from conversion of magnetic flux

Reep et al.

Likely explanation is that the duration of a flare is simply a measure of the time to convert the magnetic flux to thermal energy

- More flux, longer time reconnecting to longer and longer loops
- QPP period tied to loop length (~ L/v_A)

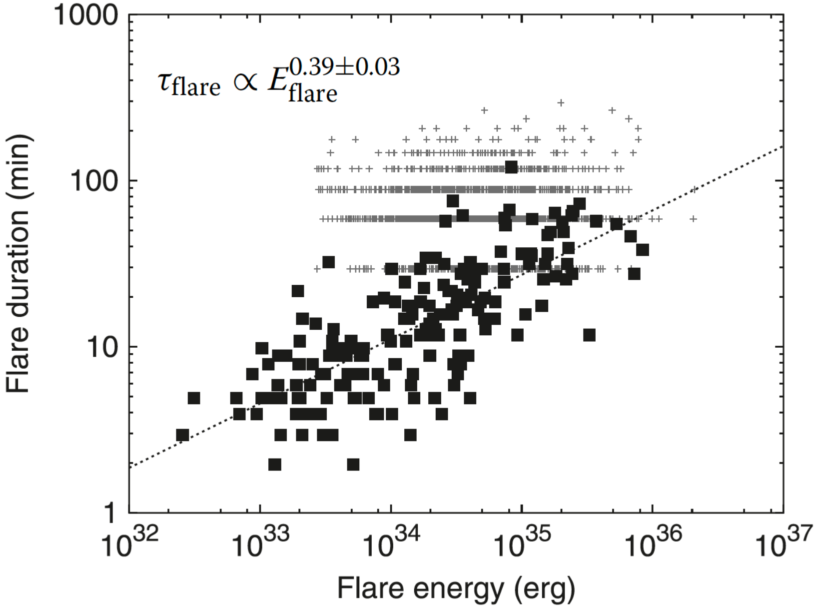
Are we done?

Reference(s): Toriumi et al 2017, ApJ, 834, 56

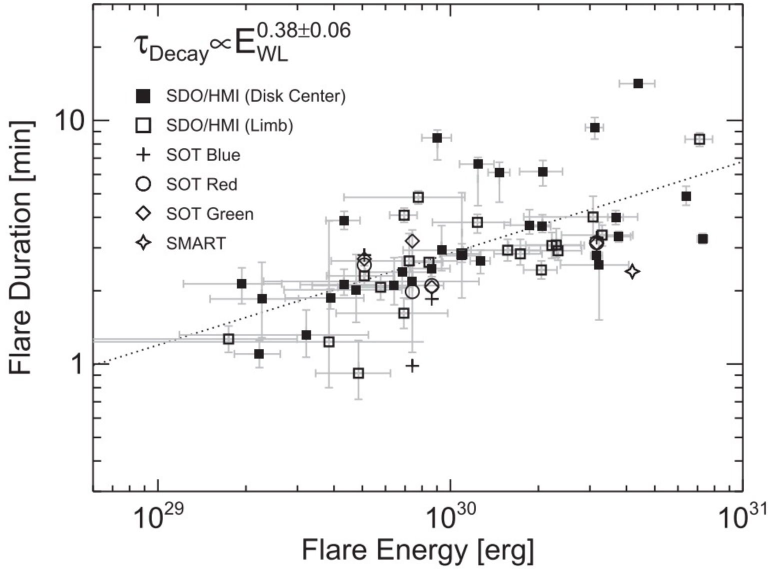
White Light Duration

Reep et al.

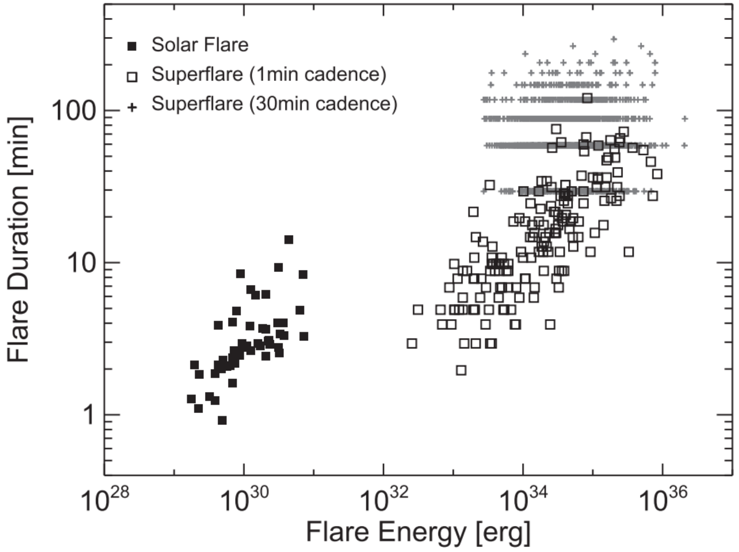
Stellar flares observed by Kepler



Solar flares observed by HMI and SOT



Both

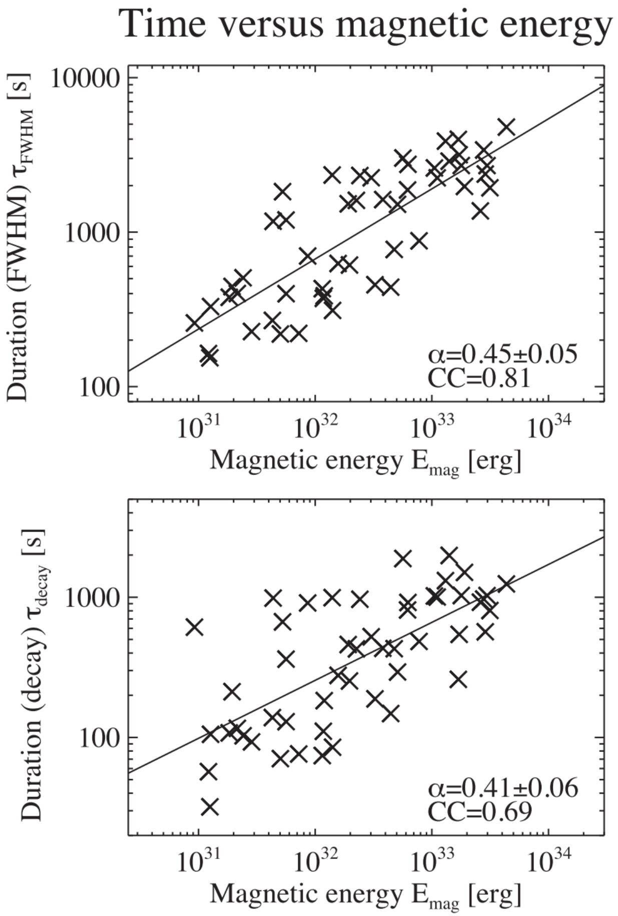


- Both solar and stellar flares show the same relation between white light duration and flare energy
- Stellar flares are longer duration, possibly because of higher field strengths (longer magnetic dissipation)

Reference(s): Maehara et al 2015; Namekata et al 2017

A spanner in the works

Reep et al.



SXR duration ***is*** correlated with magnetic energy of the event

→ There is some sort of disconnect between magnetic energy and emergent X-ray intensity

Reference(s): Toriumi et al 2017, ApJ, 834, 56

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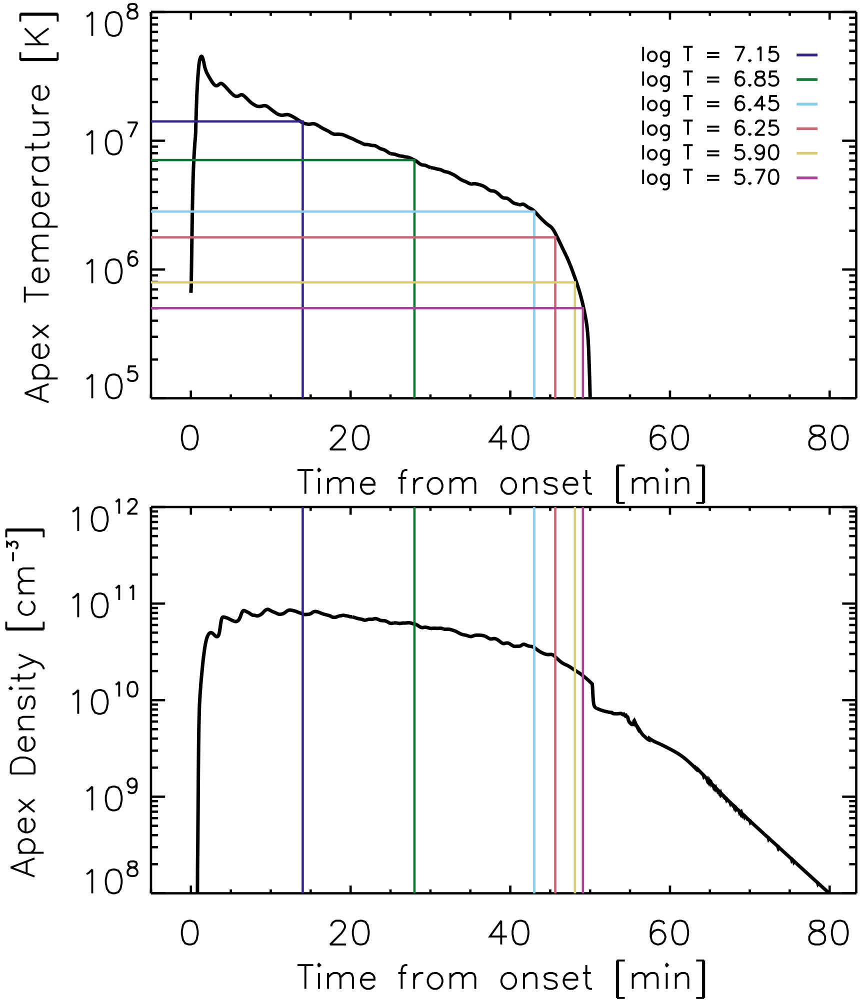
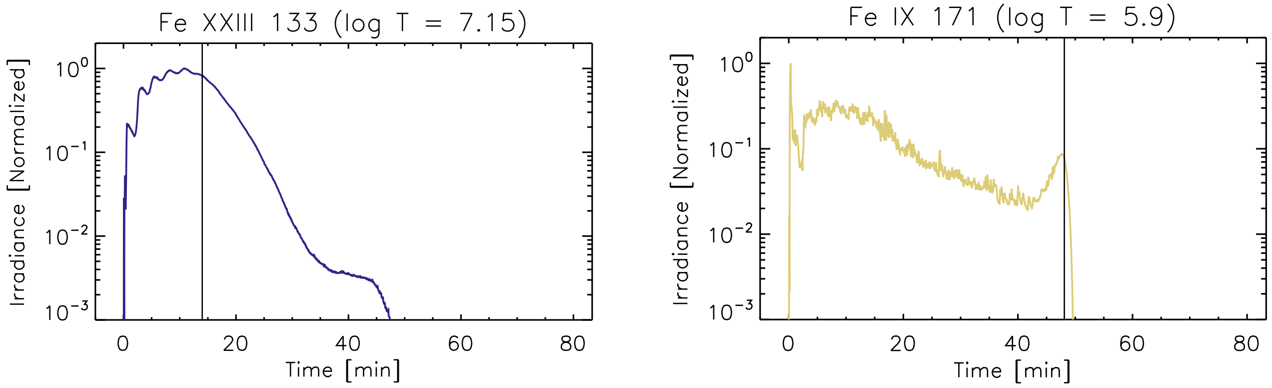
Irradiance time series at different temperatures

1. Uniform, laminar loop

Reep et al.

$$\tau_{cool} \propto \frac{L^{5/6}}{(nT)^{1/6}}$$





In a ”typical” flaring loop, emission forming at hot and cool temperatures have a distinct time evolution

→ The duration of emission in a given wavelength depends on where it forms in the atmosphere

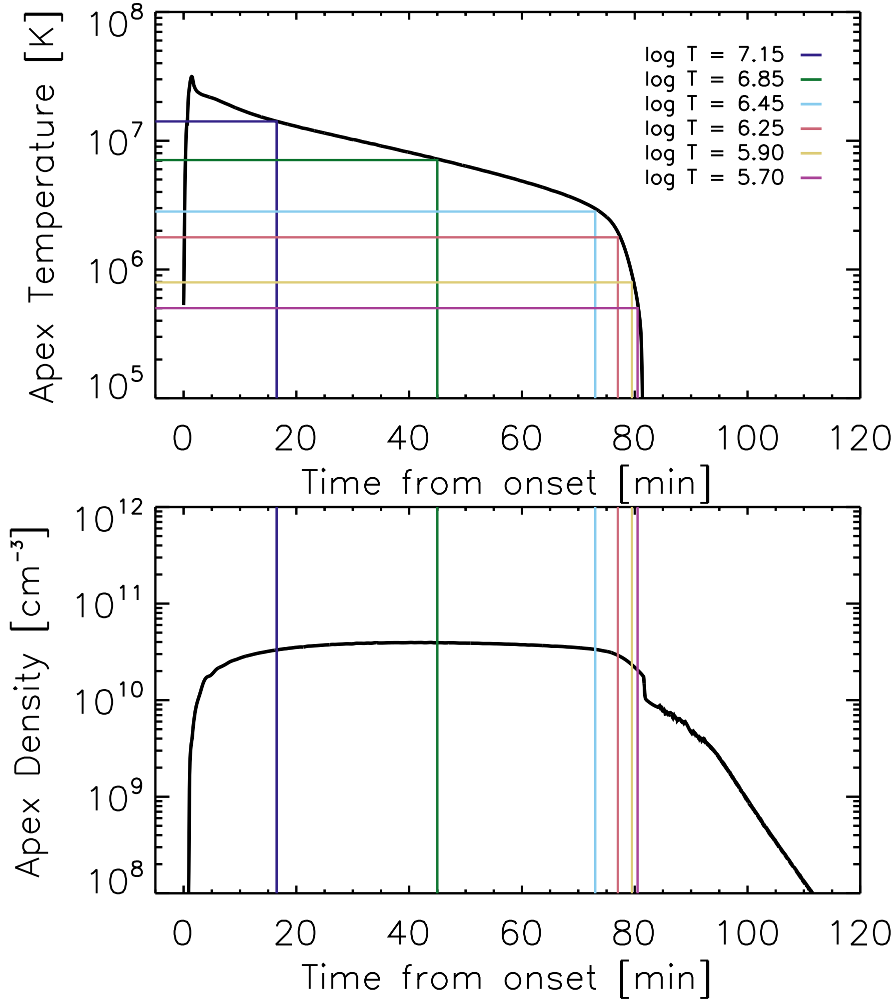
Reference(s): Reep & Airapetian, submitted to ApJ

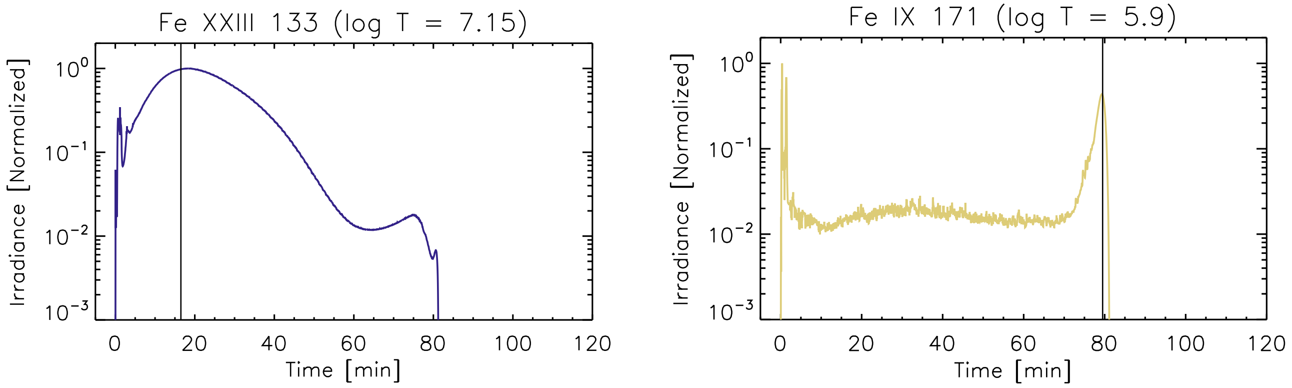
Irradiance time series at different temperatures

2. Expanding, laminar loop

Reep et al.

$\tau_{cool} \propto ?$





With area expansion, the cooling time is lengthened, and draining is suppressed which causes light curves to track ionization fractions

→ The duration of emission depends on the change in magnetic topology (equivalently, field strength)

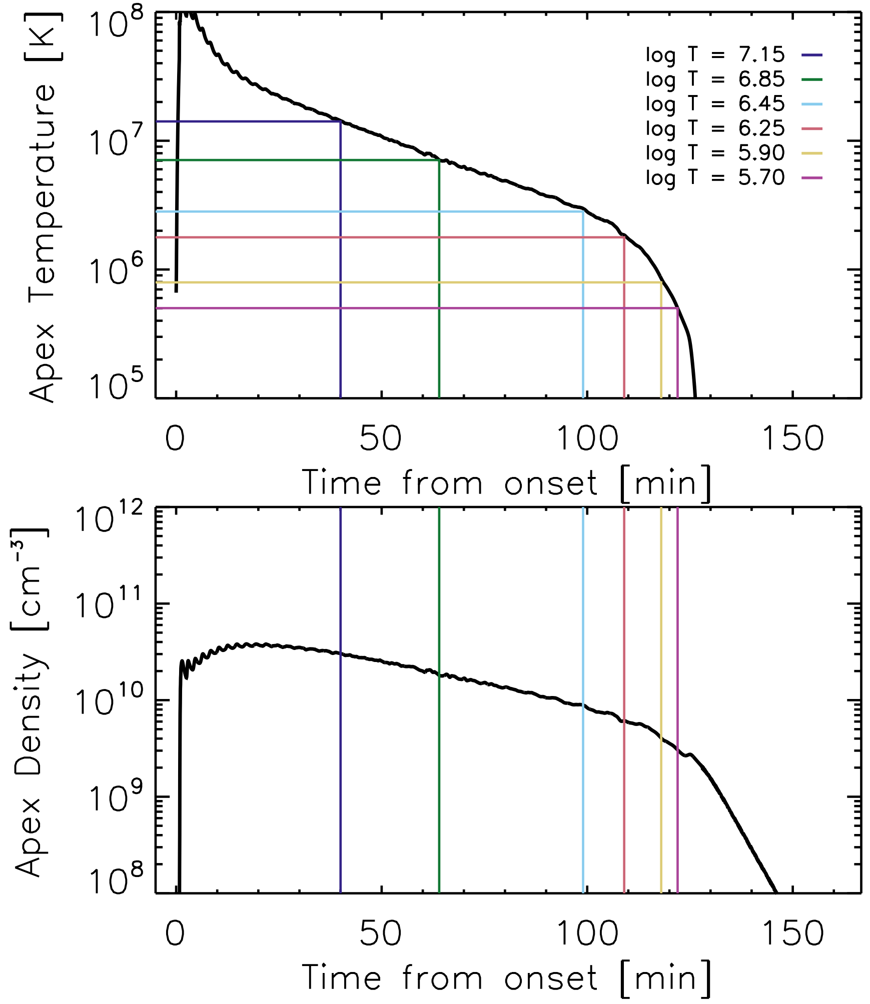
Reference(s): Reep & Airapetian, submitted to ApJ

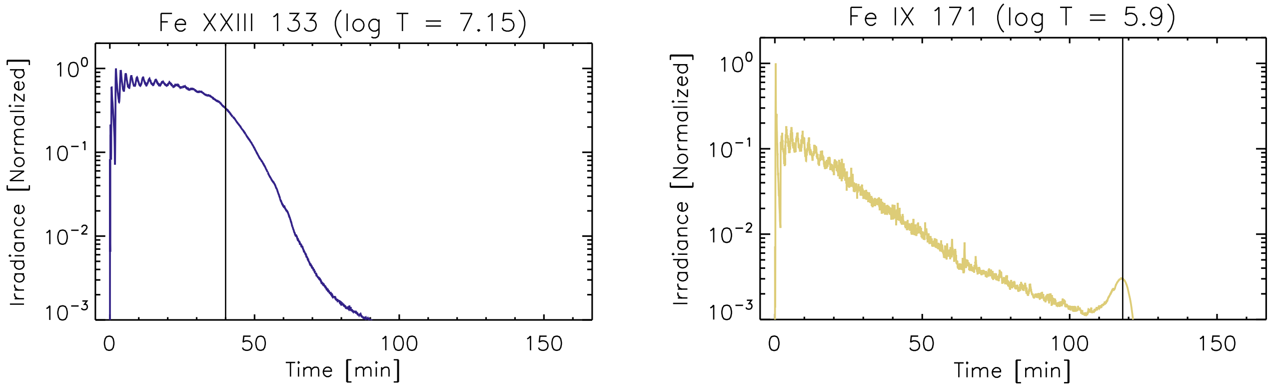
Irradiance time series at different temperatures

3. Uniform, turbulent loop

Reep et al.

$$\tau_{cool} \propto \frac{T^{2/3} L^{5/6}}{\lambda_T \; n^{7/12}}$$





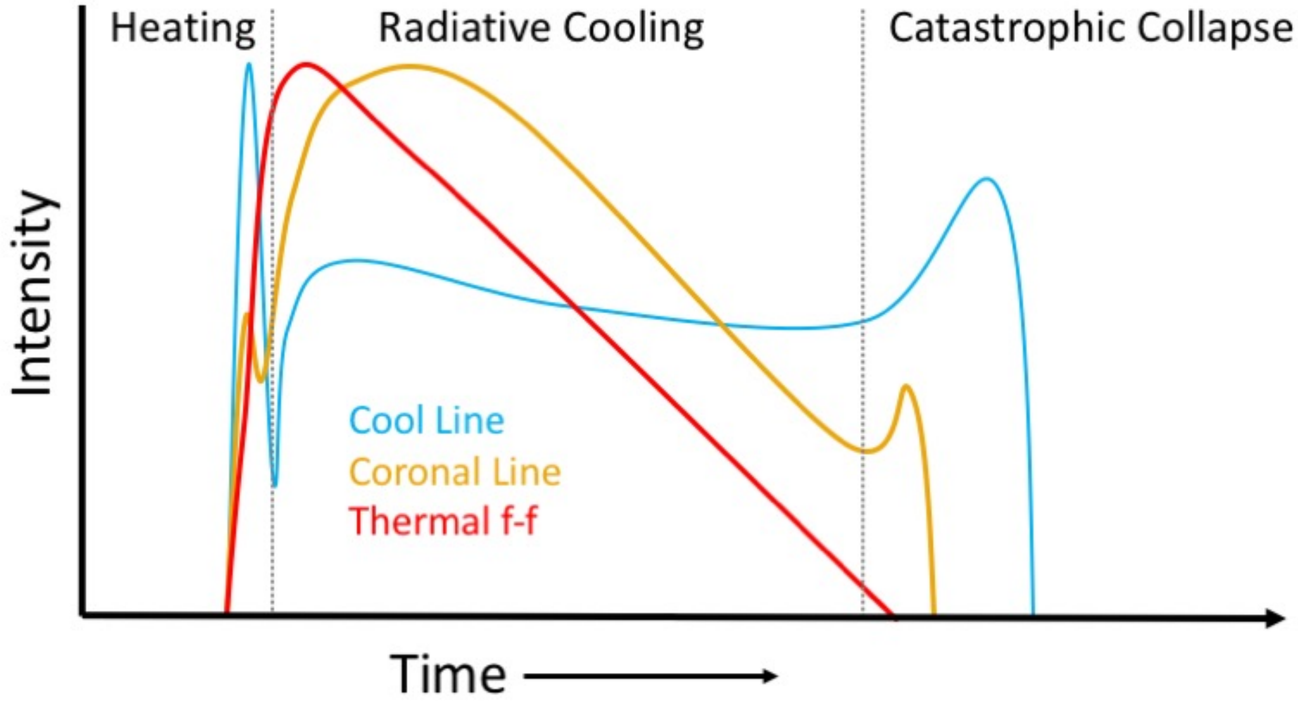
With turbulence, the cooling time is significantly lengthened, and the loop steadily drains. Light curves slowly decrease with time.

→ The duration of emission depends on how turbulent the plasma is

Reference(s): Reep & Airapetian, submitted to ApJ

Cartoon Description of Time Evolution of Irradiance from a Loop

Reep et al.



Three distinct phases:

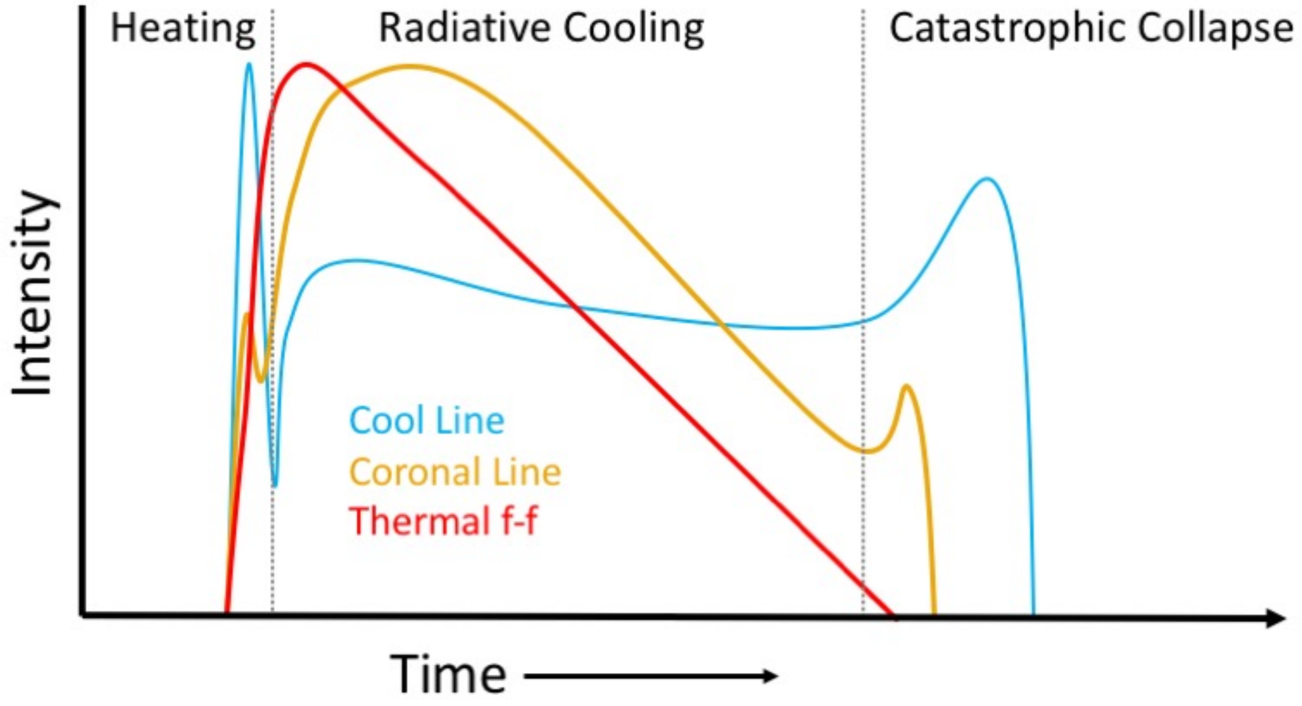
1. Heating phase, where all emission rises in step with the heating. Cool emission spikes strongly, as the transition region is lowered in height to higher densities.

(We saw in Harry's talk yesterday that Ly-α spiked simultaneously with HXRs, for example)

Reference(s): Reep & Airapetian, submitted to ApJ

Cartoon Description of Time Evolution of Irradiance from a Loop

Reep et al.



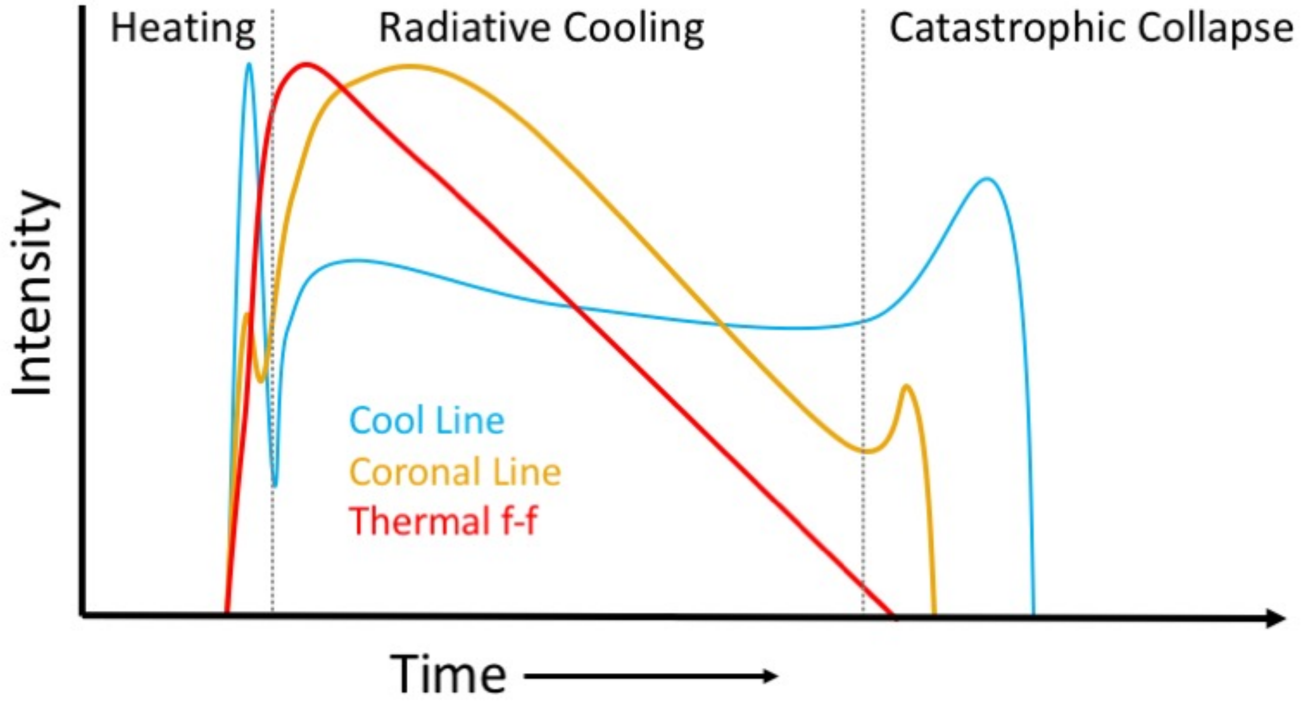
Three distinct phases:

2. Radiative cooling phase, where the density of the corona peaks due to evaporation, while the temperature starts to fall. Cooler emission, forming in the TR or chromosphere, is mostly steady during this time. Hotter emission, forming in the corona, decays as the temperature falls.

Reference(s): Reep & Airapetian, submitted to ApJ

Cartoon Description of Time Evolution of Irradiance from a Loop

Reep et al.



Three distinct phases:

3. Catastrophic collapse, when the coronal temperatures plummets to chromospheric values, and the density quickly drains. Individual lines spike in intensity when the coronal portion of the loop reaches their peak formation temperature, but then fade away almost instantly.

Reference(s): Reep & Airapetian, submitted to ApJ

The Neupert Effect

Reep et al.

There is an obvious distinction between the behavior of cool and hot emission, and this stems from the so-called Neupert effect, originally a relation found between thermal SXR emission and non-thermal microwave or hard X-ray emission:

$$I_{\mathrm{SXR}} \propto \int I_{\mathrm{HXR}}\, dt$$

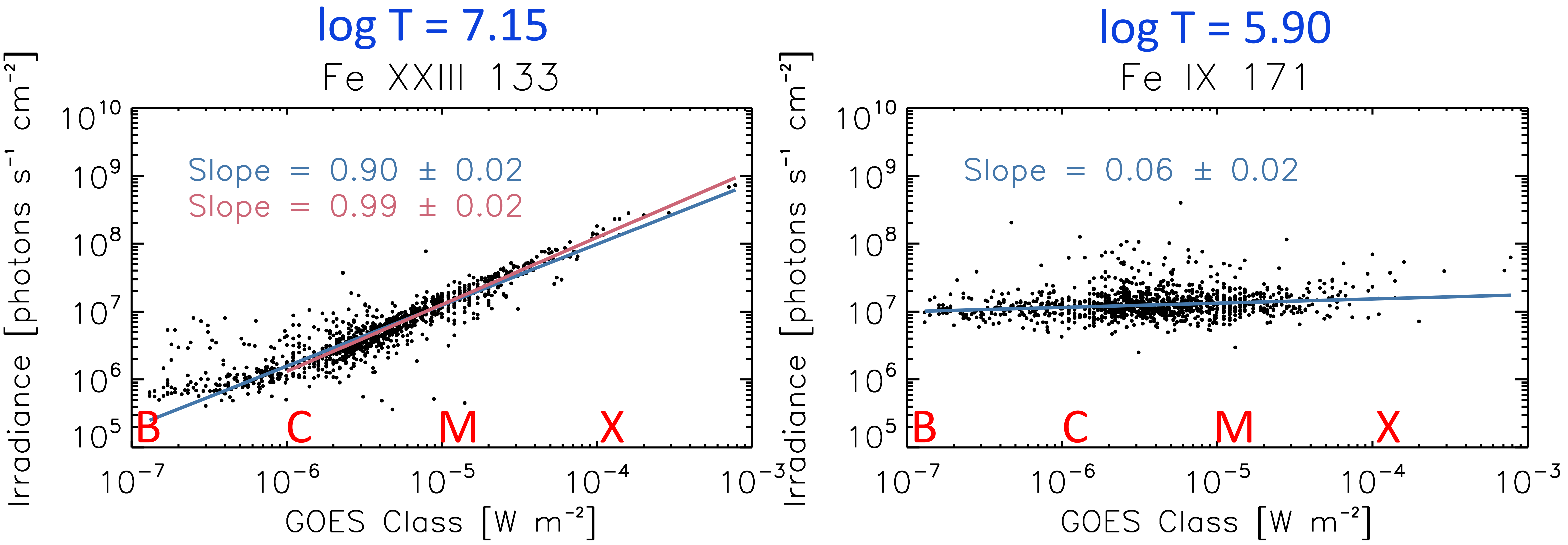
$$I_{\mathrm{HXR}} \propto \frac{d}{dt}\left(I_{\mathrm{SXR}}\right)$$

The relation is more general. Emission forming in the low atmosphere (chromosphere, TR) responds directly to heating as the TR is pushed to lower heights and higher densities. Emission forming in the corona increases with chromospheric evaporation, that is, indirectly to heating.

Reference(s): Neupert 1968, ApJL, 153, L59

Intensity also impacted!

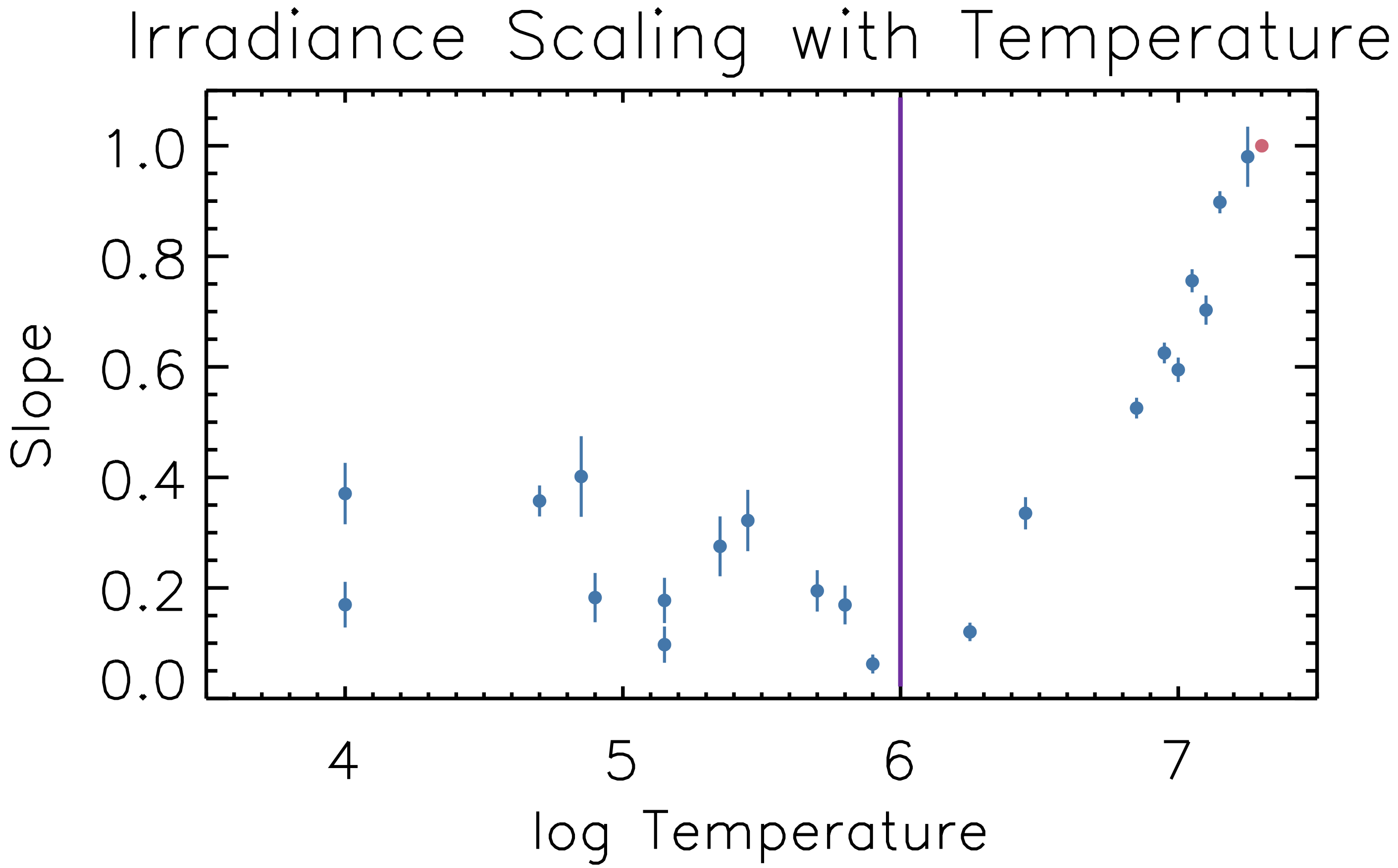
Reep et al.



Reference(s): Reep et al 2022, ApJ, 927, 103

Irradiance Scaling with Temperature

Reep et al.



Hot lines scale ~ linearly

Cooler lines scale sublinearly

Slope decreases with temperature until about log T = 6

Reference(s): Reep et al 2022, ApJ, 927, 103

Conclusions

Reep et al.

The behavior of emission that responds directly to heating behaves differently to emission that responds indirectly (a general Neupert effect). SXR intensity is disconnected from the flare duration because it responds indirectly, brightening after the onset of chromospheric evaporation.

To improve models of irradiance, we need to:

- Understand the magnetic topology from the chromosphere through the corona
- Quantify the level of turbulence across the atmosphere

Acknowledgements

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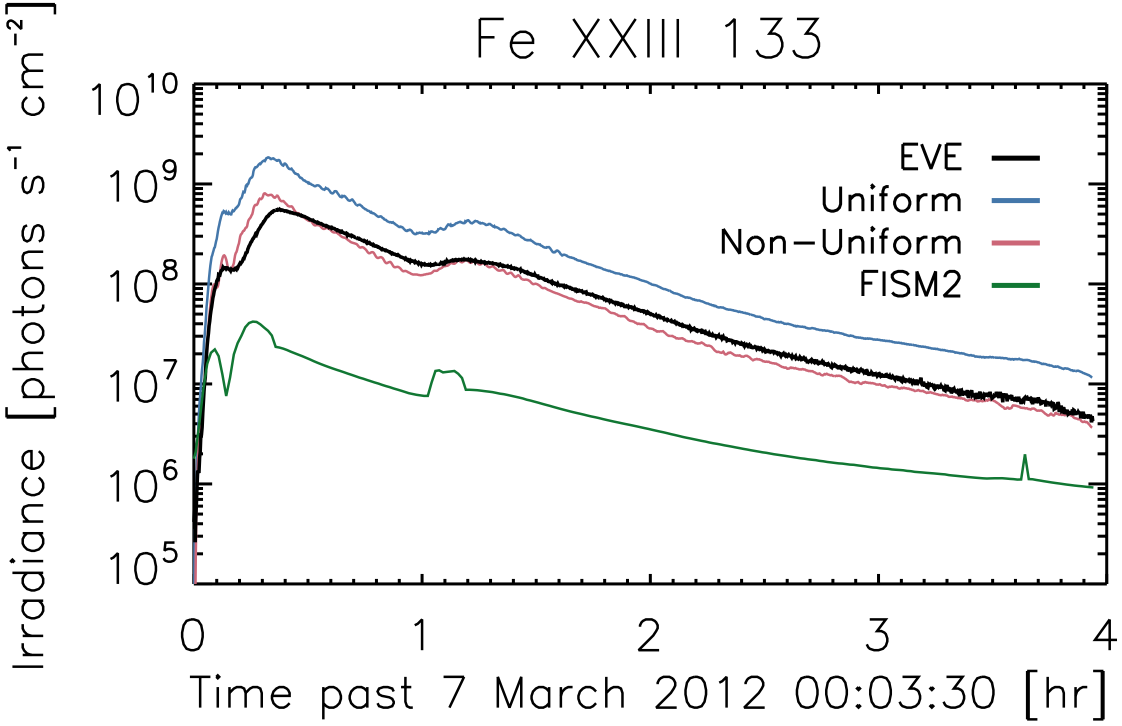
Supplementary Slides

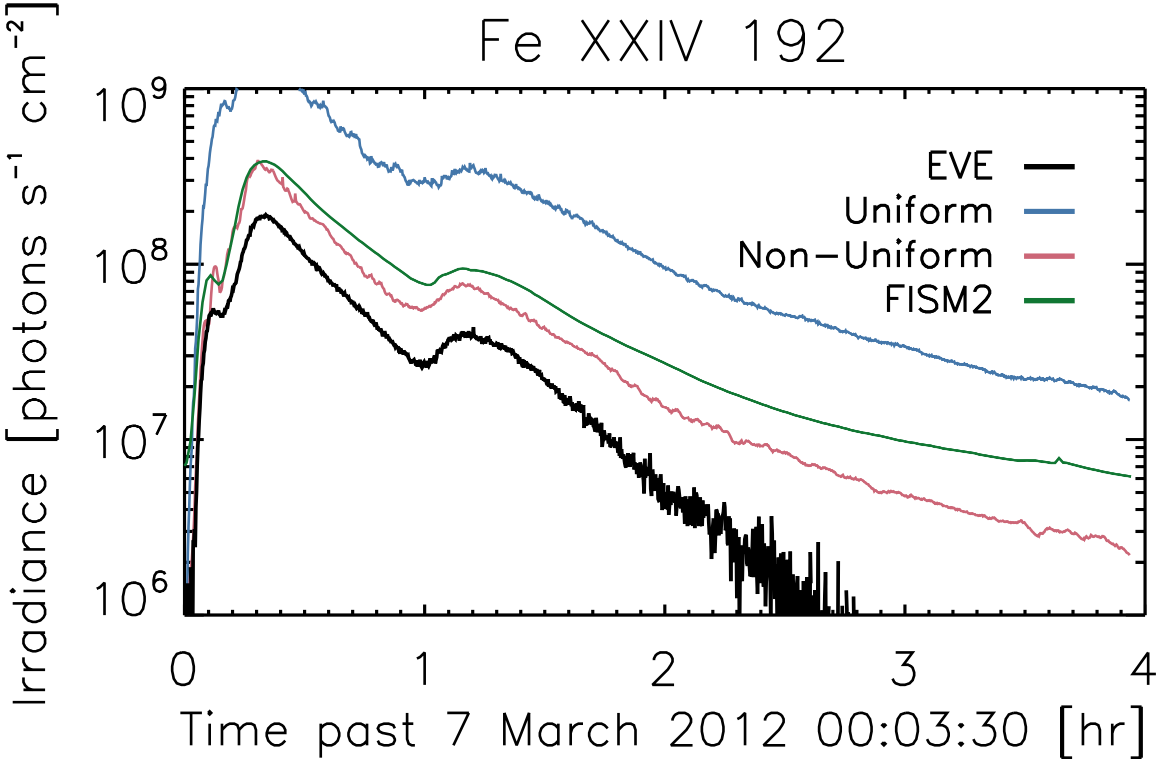
Observations vs Models – Light Curves

Reep et al.

07-Mar-2012 UT 00:03 X7.8 Flare



log T = 7.15

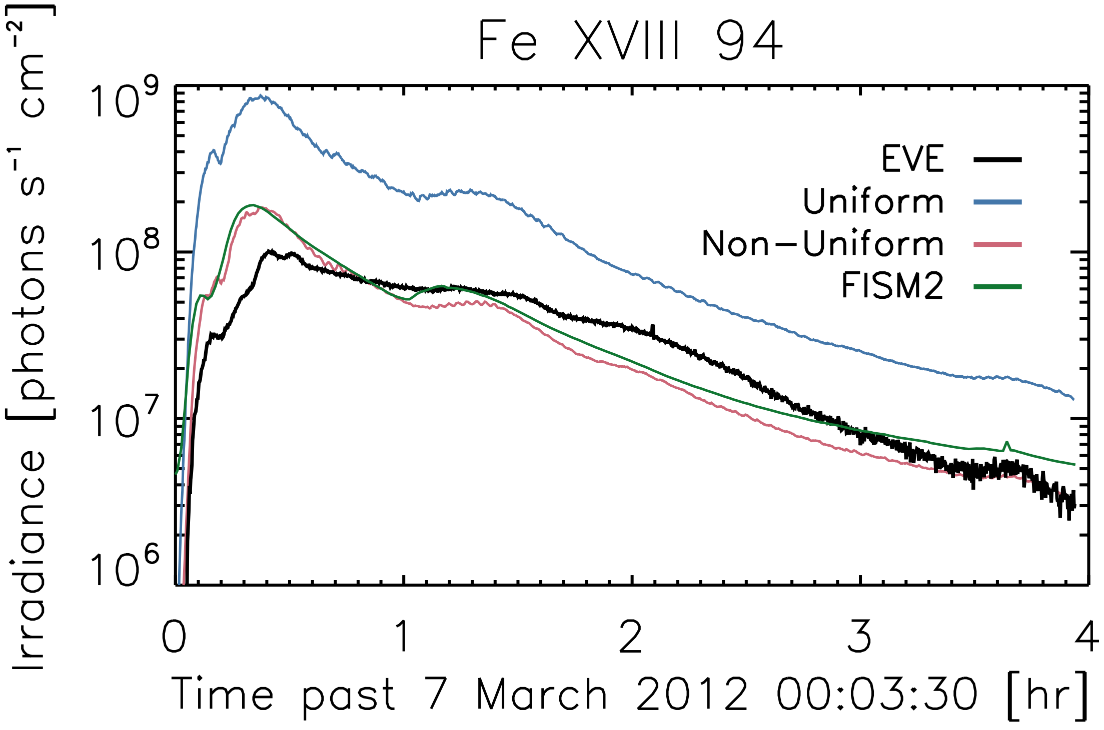


log T = 7.25

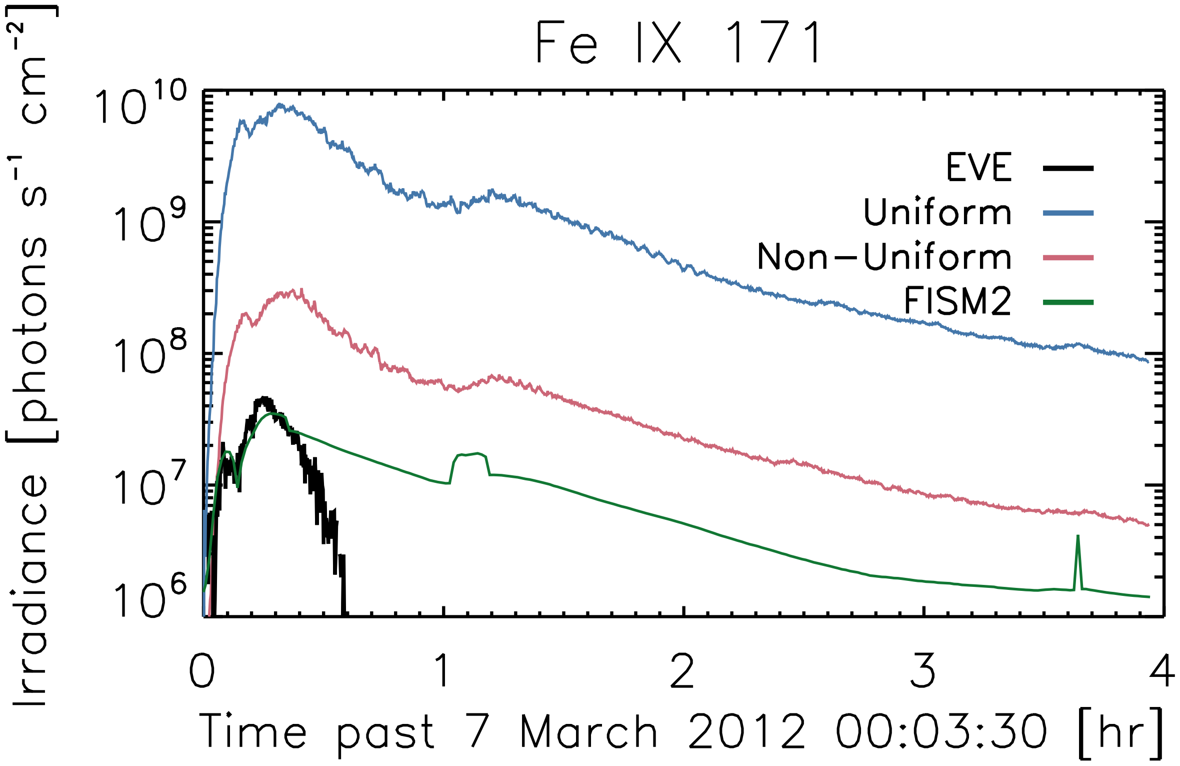
Observations vs Models – Light Curves

Reep et al.

07-Mar-2012 UT 00:03 X7.8 Flare



log T = 6.85

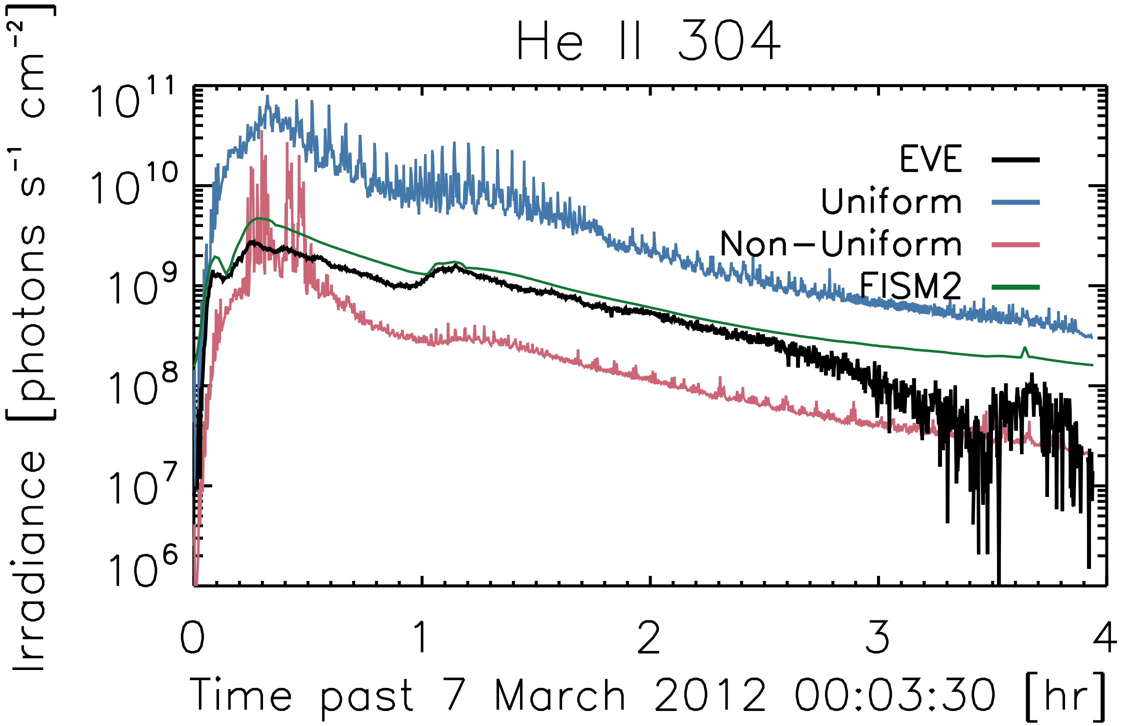


log T = 5.90

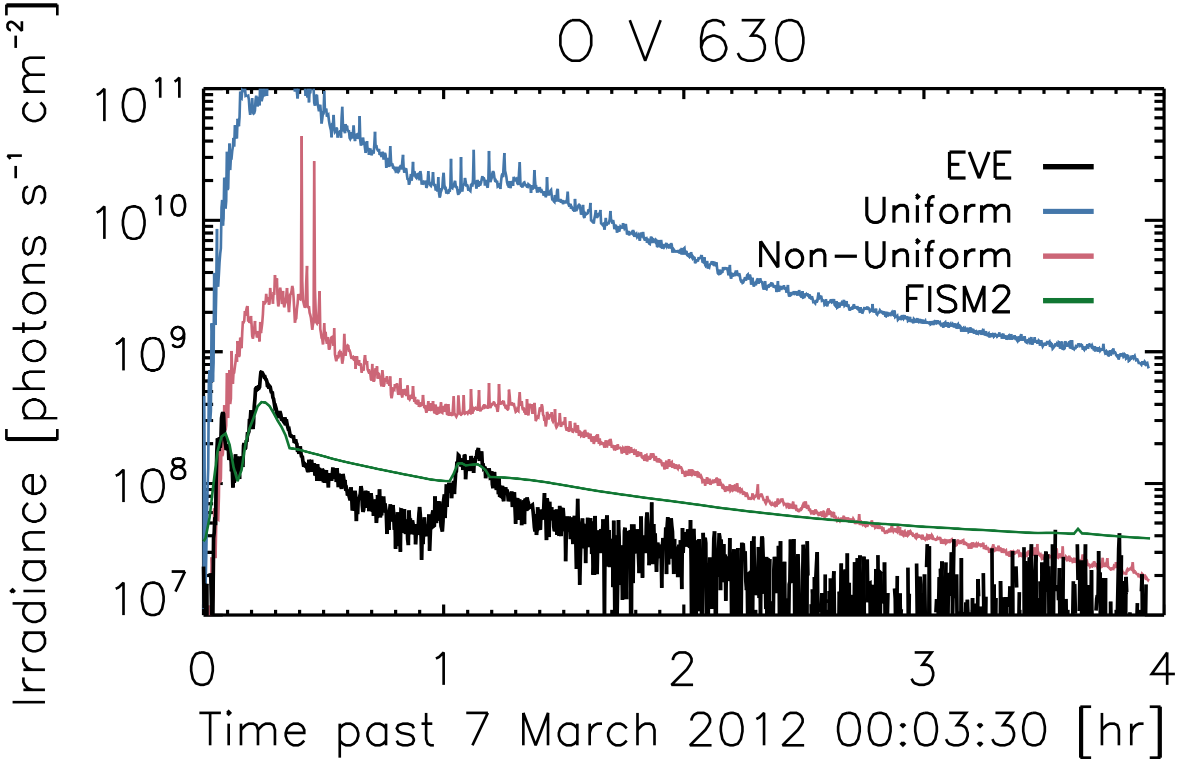
Observations vs Models – Light Curves

Reep et al.

07-Mar-2012 UT 00:03 X7.8 Flare



log T = 4.70



log T = 5.35

Reference(s):