EUV light curves from post-flare loops

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C8 flare, 20 Sept 2000, SoHO/SUMER

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FREE-FREE EMISSION IN THE FAR-ULTRAVIOLET SPECTRAL RANGE: A RESOURCE FOR DIAGNOSING SOLAR AND STELLAR FLARE PLASMAS

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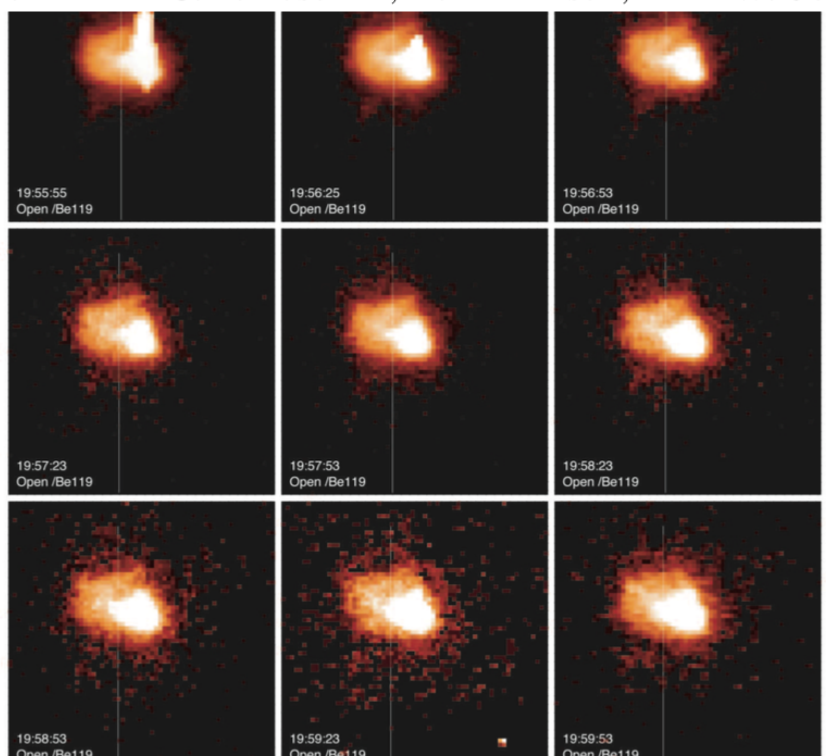
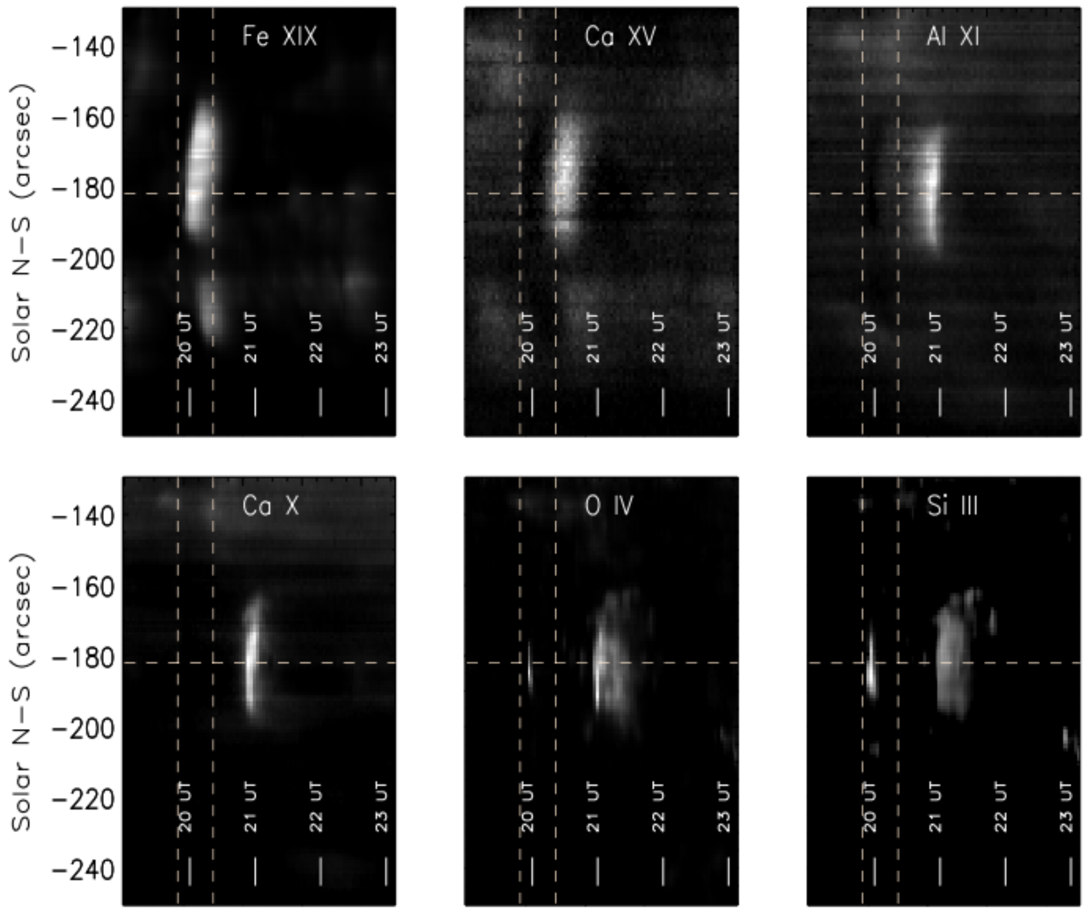
Yohkoh/SXT

Flare at the limb



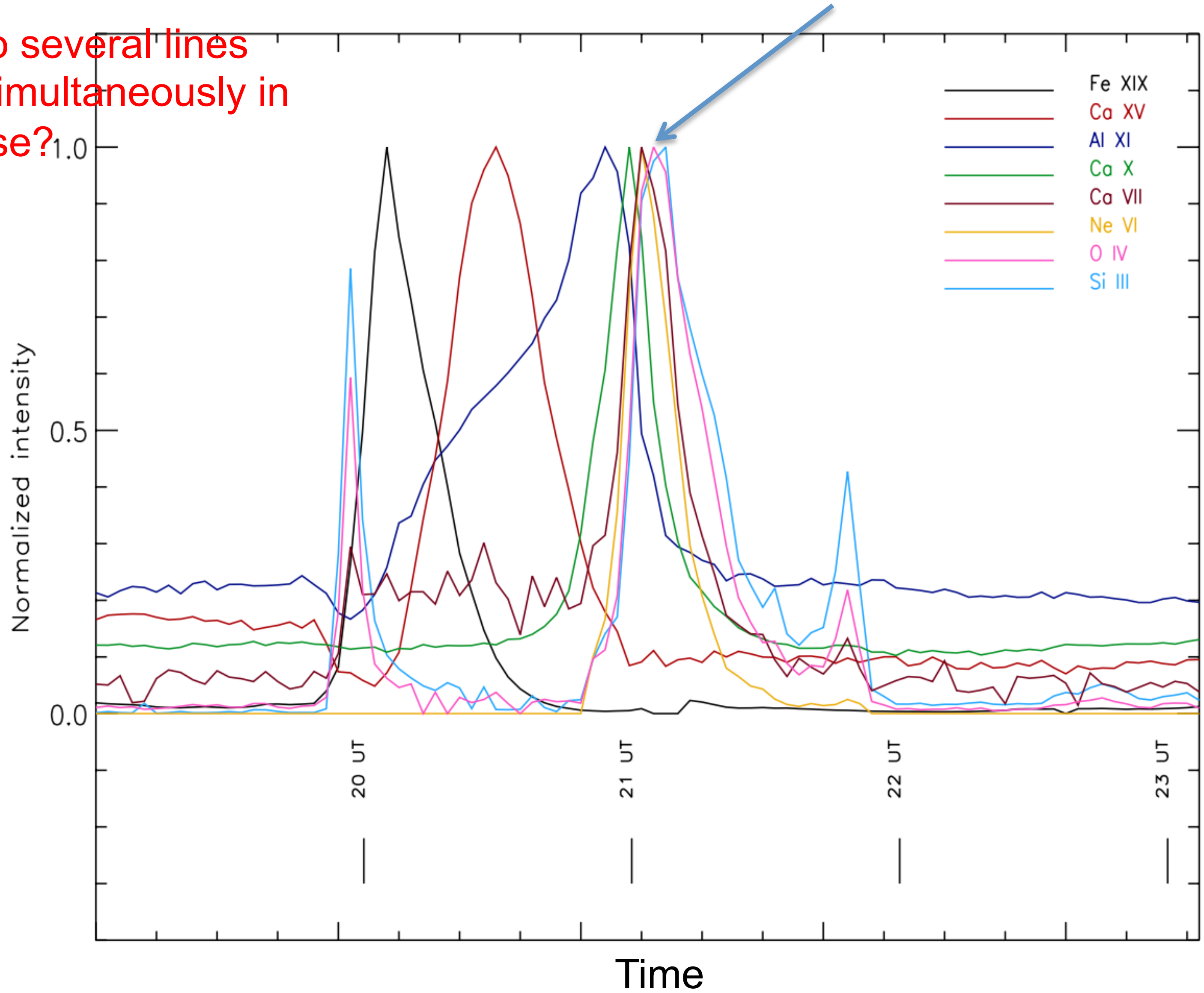
Time intensity plot
(Reale, Landi & Orlando, ApJ, 2012)

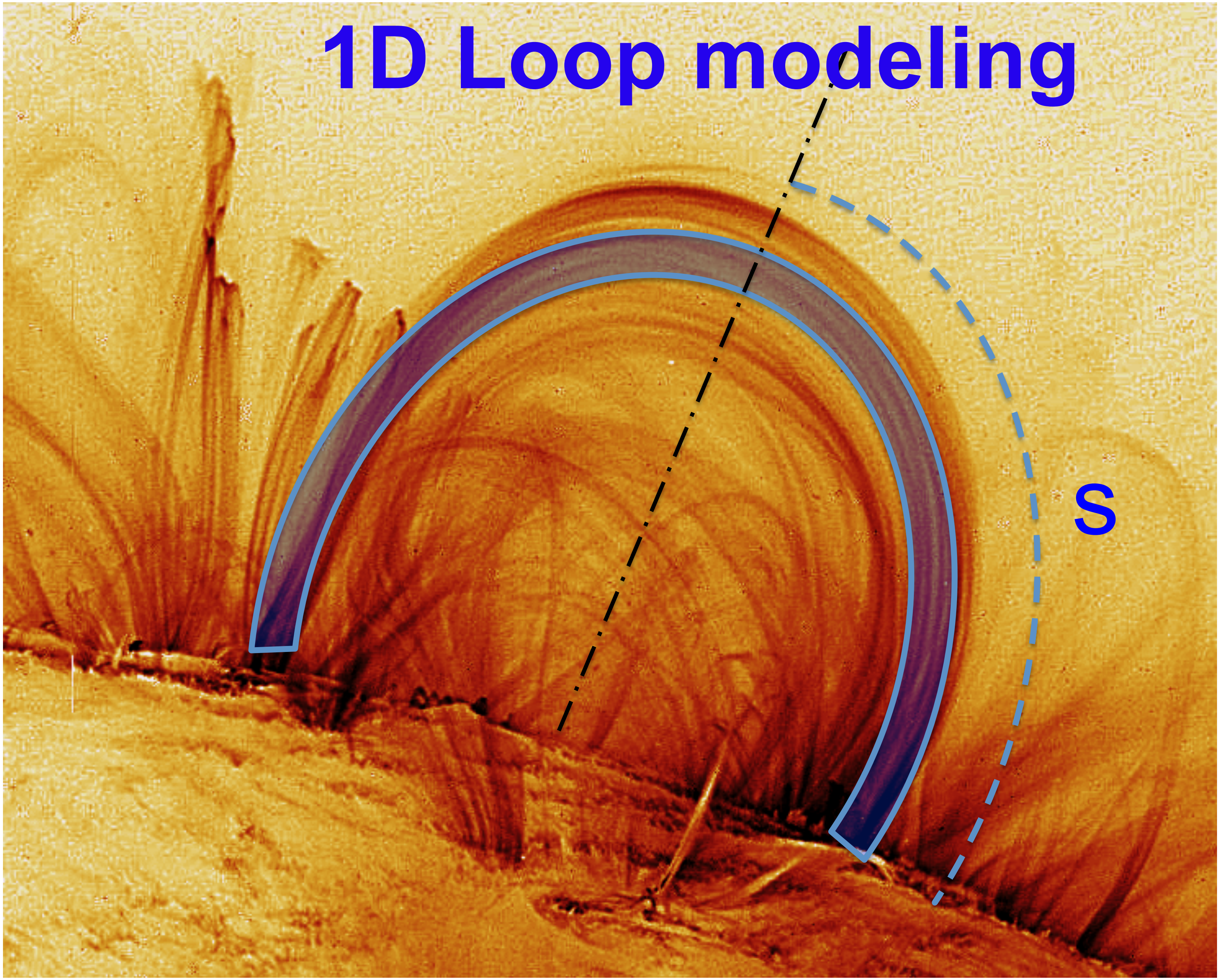
Dashed lines:
GOES flare



SUMER Light curves

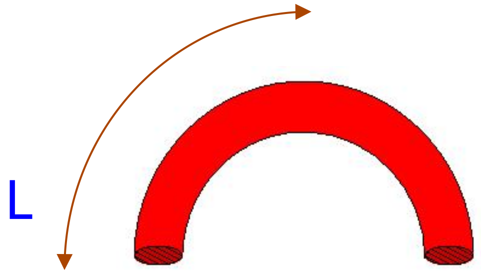
Question: Why do several lines brighten almost simultaneously in the flare late phase?




1D Loop modeling
S

Hydrodynamic equations

- Plasma moves and transports energy along the B-field lines
- Hydrodynamics only (no magnetic forces)



$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial s} = 0$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial (P + \rho u^2)}{\partial s} = \rho g$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial (\rho E + P) u}{\partial s} = \rho u g - \frac{\partial q}{\partial s} + Q(s, t) - n_e n_{\rm H} \Lambda(T),$$

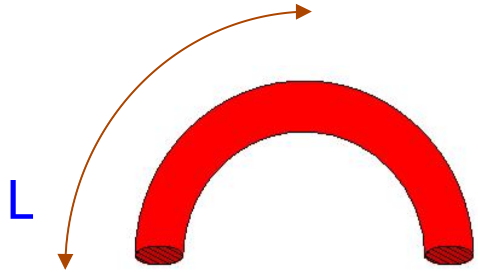
$$\text{where} \quad E = \epsilon + \frac{1}{2} u^2$$

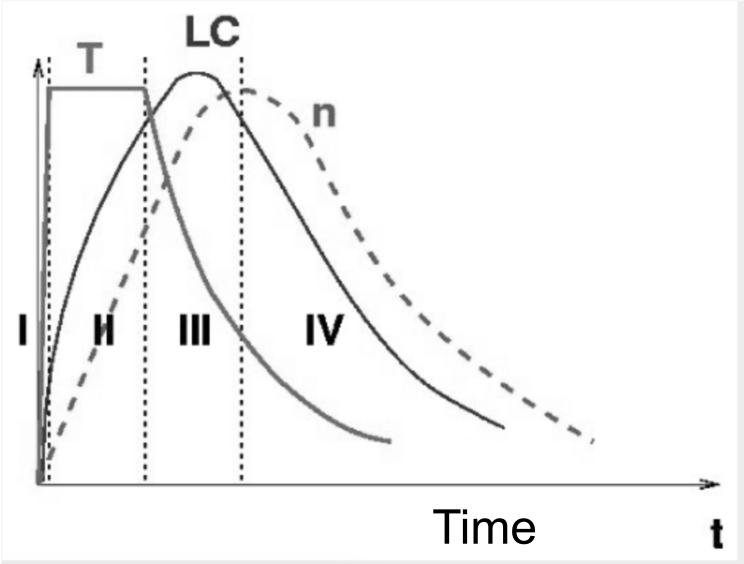
1D flare modeling: extensive literature

These equations can be solved numerically and several specific codes have been used extensively to investigate the physics of coronal loops and of X-ray flares (e.g., Nagai, 1980 ; Peres *et al.*, 1982 ; Doschek *et al.*, 1982; Nagai and Emslie, 1984 ; Fisher *et al.*, 1985a ,a ,a ; MacNeice, 1986 ; Gan *et al.*, 1991; Hansteen, 1993 ; Betta *et al.*, 1997 ; Antiochos *et al.*, 1999 ; Ofman and Wang, 2002; Müller *et al.*, 2003; Bradshaw and Mason, 2003; Sigalotti and Mendoza-Briceño, 2003; Bradshaw and Cargill, 2006).

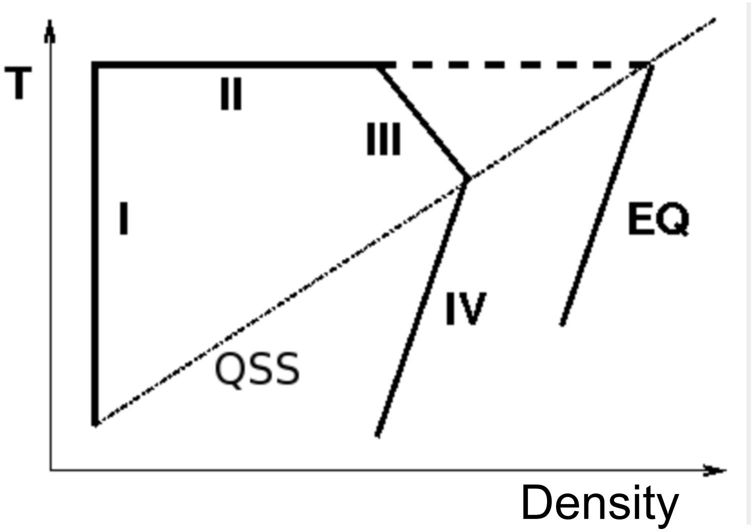
Reale 2014, LRSP

Flare evolution



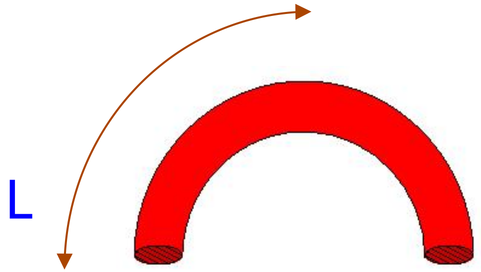


Flare loop phases (Reale 2014)
I: heating
II: evaporation
III: conductive cooling
IV: radiative cooling



Hydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial s} = 0$$



$$\frac{\partial \rho u}{\partial t} + \frac{\partial (P + \rho u^2)}{\partial s} = \rho g$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial (\rho E + P) u}{\partial s} = \rho u g - \frac{\partial q}{\partial s} + Q(s, t) - n_e n_{\mathrm{H}} \Lambda(T),$$

where $E = \epsilon + \frac{1}{2} u^2$

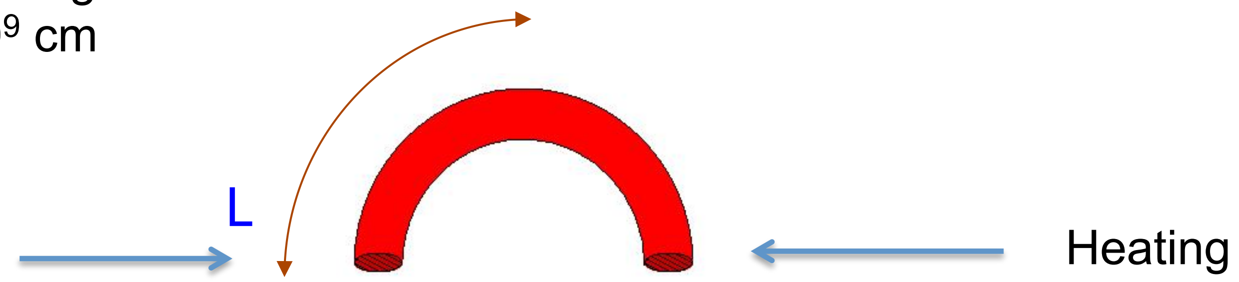
Flare heating

$$Q(s,t) = H_0 \times g(s) \times f(t)$$

$$g(s) = \exp\left[-(s - s_H)^2 / \left(2\sigma_H^2\right) \right]$$

$f(t)$ is a pulse function : 3 min

Loop half-length:
L = 3 x 10^9 cm



Thermal conduction

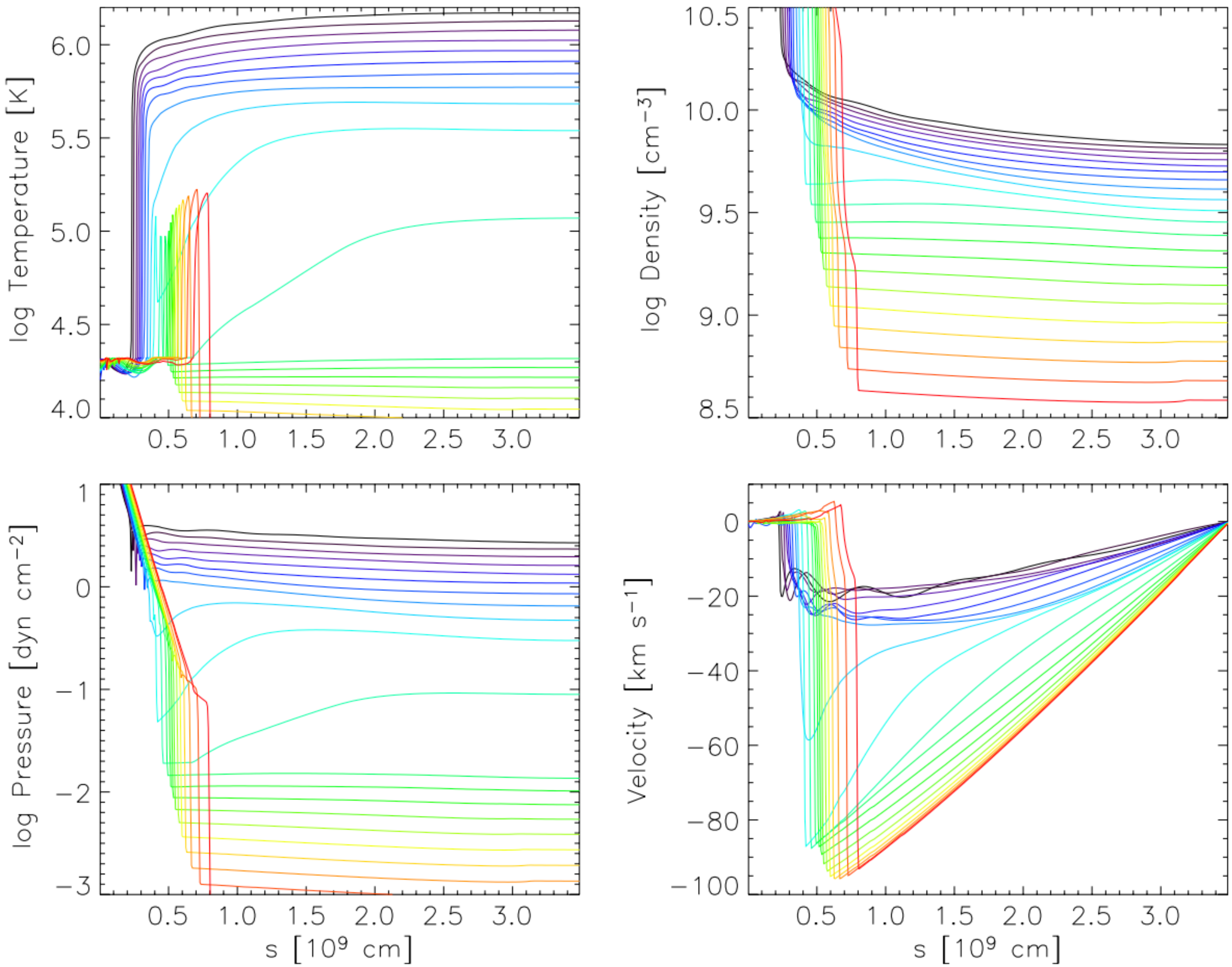
$$q = \left(\frac{1}{q_{\rm spi}} + \frac{1}{q_{\rm sat}}\right)^{-1}$$

$$q_{\rm spi} = -\kappa(T)\nabla T$$

$$\kappa(T) = 9.2 \times 10^{-7} T^{5/2}\ {\rm erg\ s^{-1}\ K^{-1}\ cm^{-1}}$$

$$q_{\rm sat} = -{\rm sign}(\nabla T)\, 5\phi\rho c_{\rm s}^3$$

Late evolution along the loop (30-50 min, 1 min)

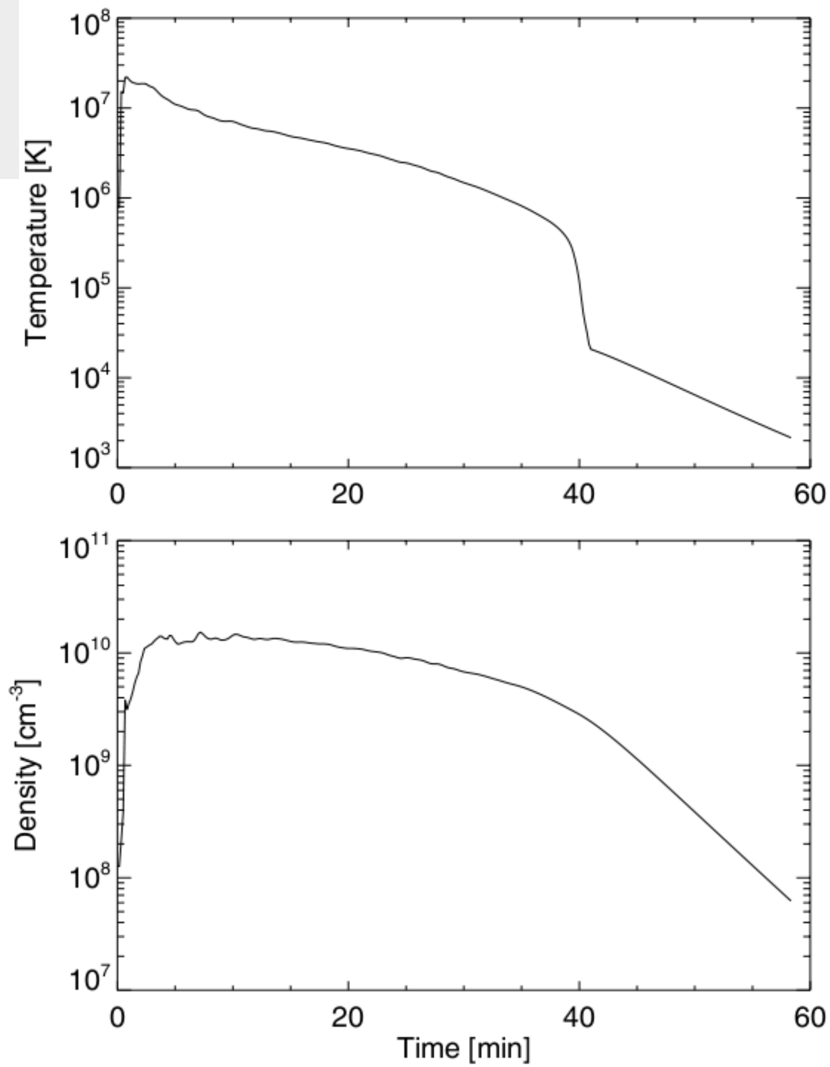


Catastrophic cooling (t ~ 40 min)

$$\tau_c = \frac{3n_c k_B T_0 L^2}{2/7 \kappa T_0^{7/2}} = \frac{10.5 n_c k_B L^2}{\kappa T_0^{5/2}} \approx 1500 \frac{n_9 L_9^2}{T_6^{5/2}} \, ,$$

$$\tau_r = \frac{3k_B T_M}{n_M P(T)} = \frac{3k_B T_M}{b T_M^{\alpha} n_M} \approx 3000 \frac{T_{M,6}^{3/2}}{n_{M,9}} \, ,$$

Cooling times both very long:
“regular” cooling

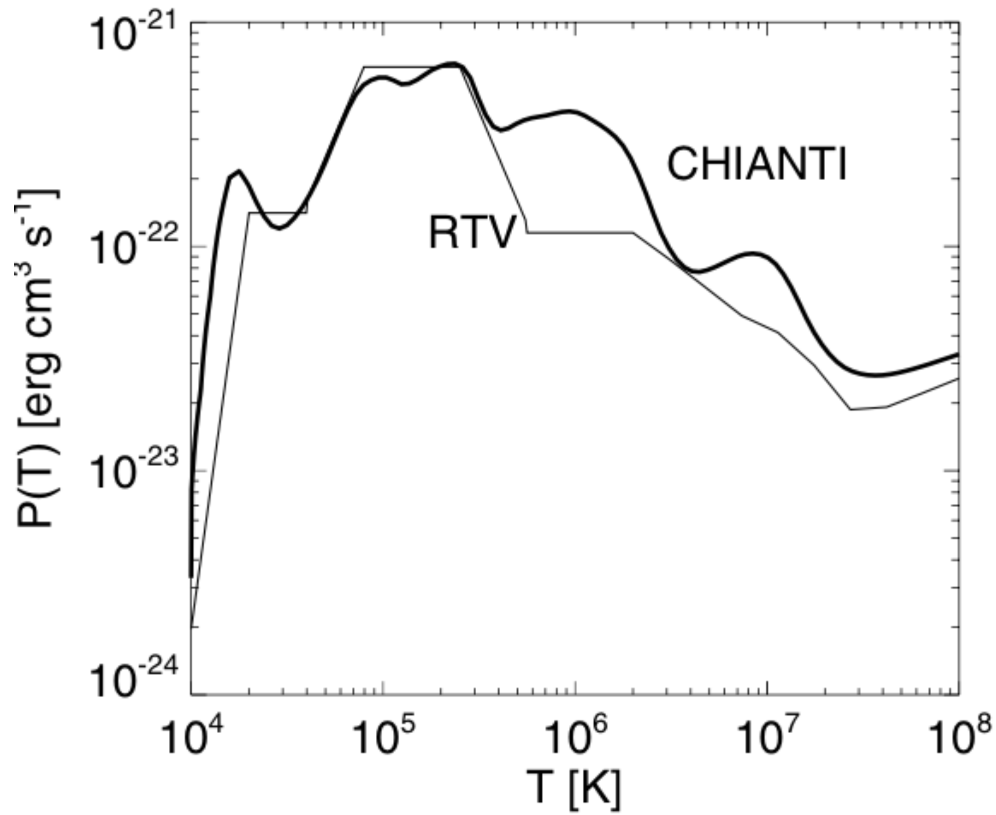


Condition for instability

Combination of radiation and draining: efficient draining (enthalpy flux) inhibits efficient radiative cooling

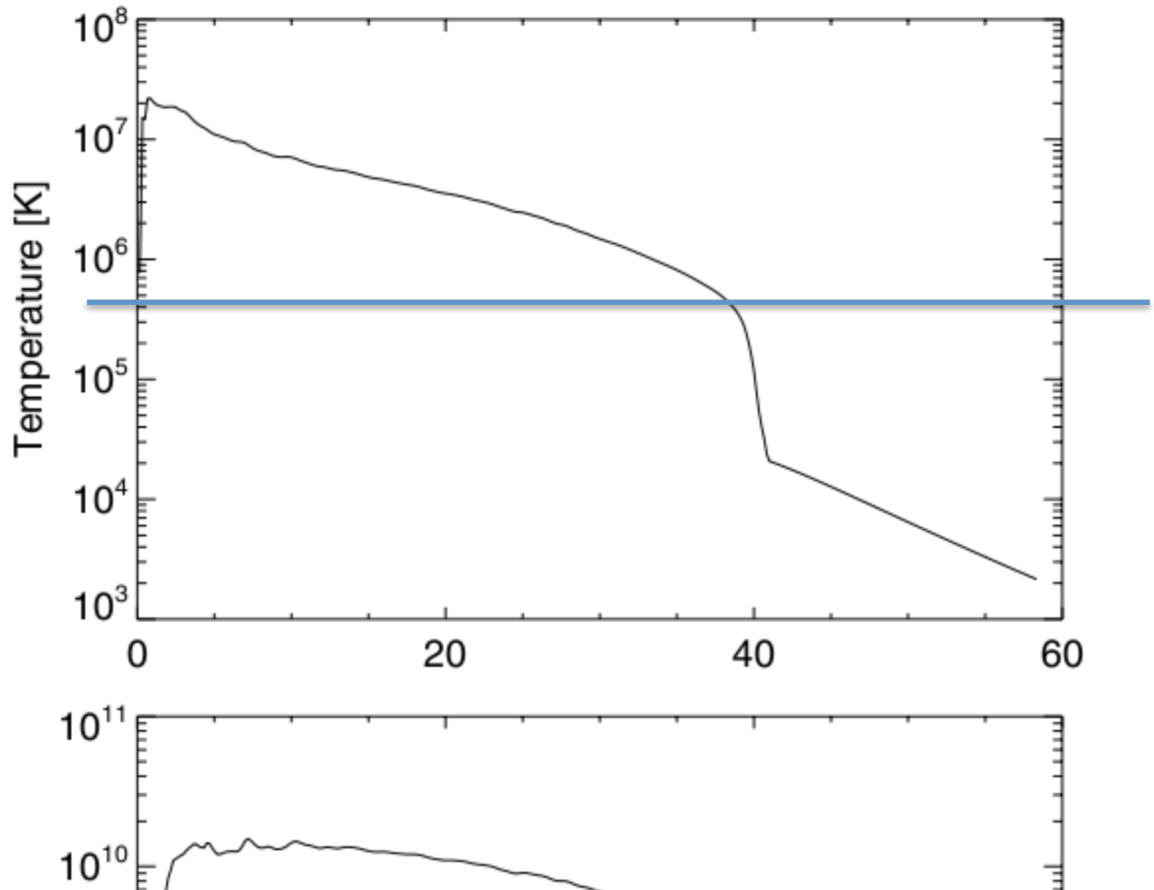
Sound travel time vs radiative cooling time (Cargill & Bradshaw 2013, ApJ):

$$\frac{\tau_s}{\tau_R} = \left(\frac{\tau_{s0}}{\tau_{R0}}\right)\left(\frac{T_0}{T}\right)^{3/2}\left(\frac{n}{n_0}\right)\left(\frac{R_L}{R_{L0}}\right) > 1,$$



Catastrophic cooling
(t ~ 40 min)

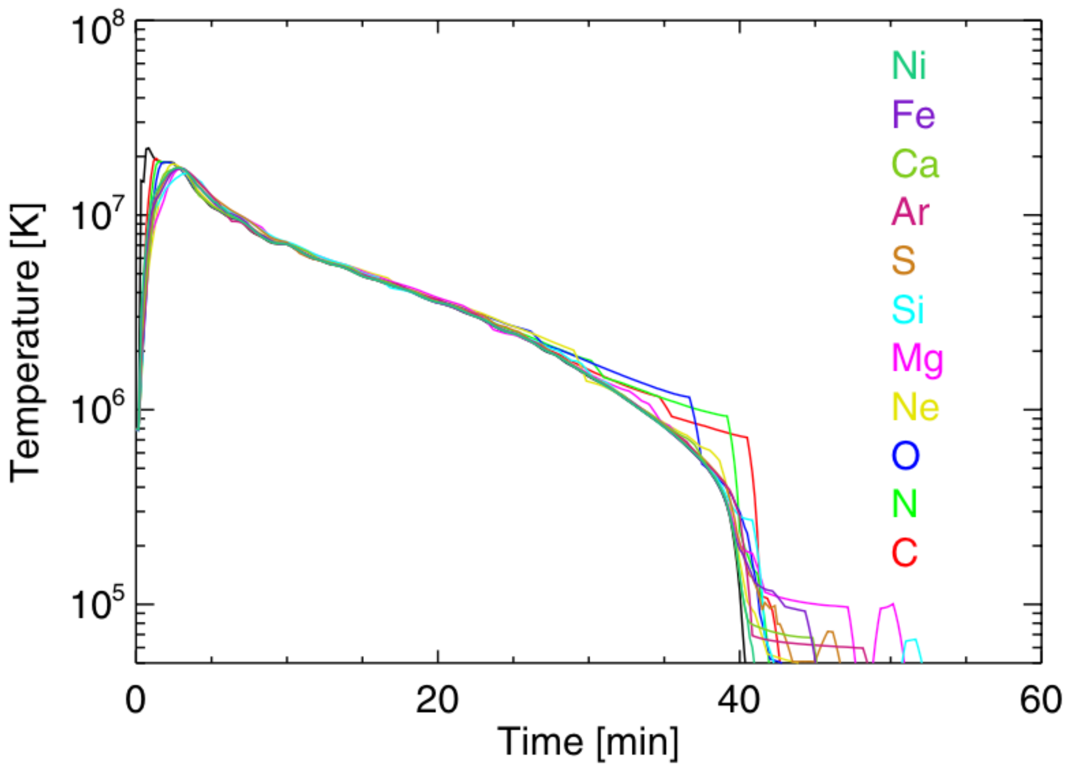
For flaring loops it occurs at T ~ 1 MK (Cargill & Bradshaw 2013)



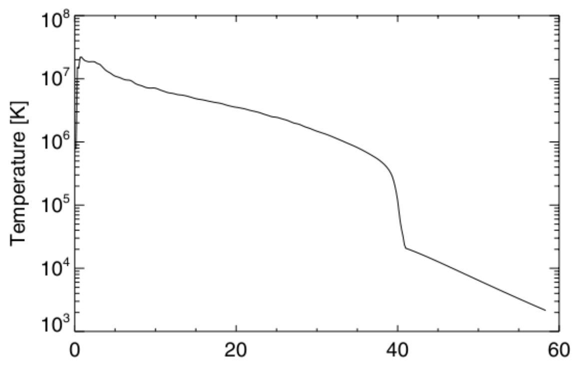
Non-equilibrium of ionization

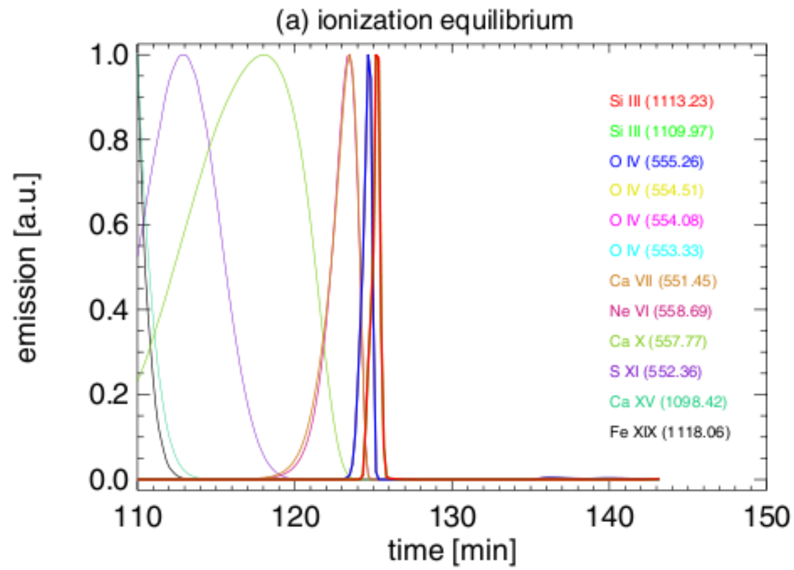
$$\frac{\partial n_i^Z}{\partial t} + \nabla \cdot n_i^Z \mathbf{v} = R_i^Z \quad \begin{matrix} (Z = 1, \ldots, N_{\mathrm{elem}}) \\ (i = 1, \ldots, N_{\mathrm{ion}}^Z) \end{matrix} ,$$

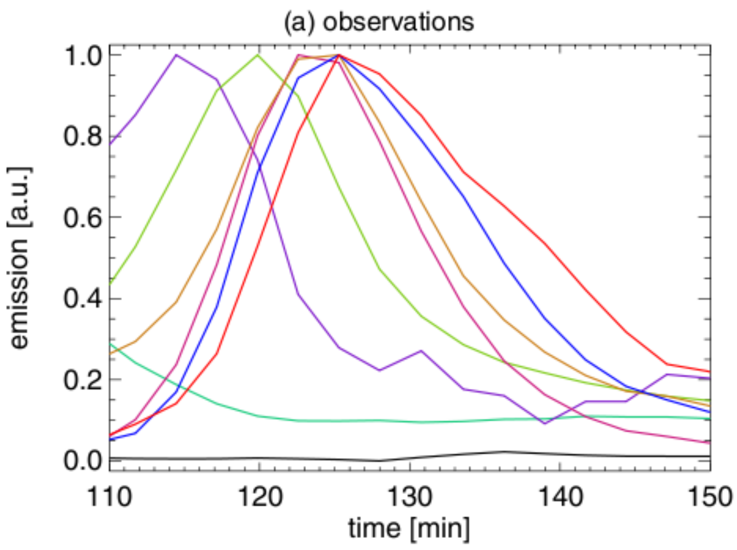
$$R_i^Z = n_e \left[n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z \left(\alpha_i^Z + S_i^Z \right) \right]$$

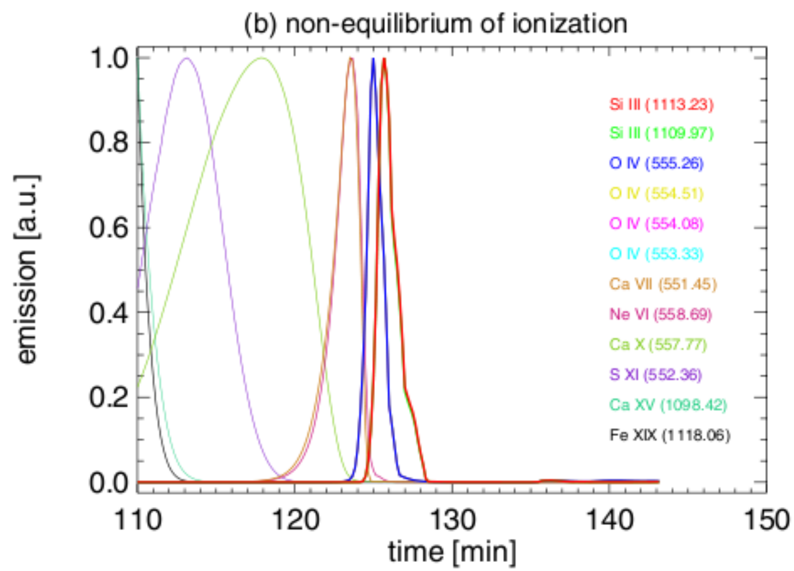


Single loop light curves

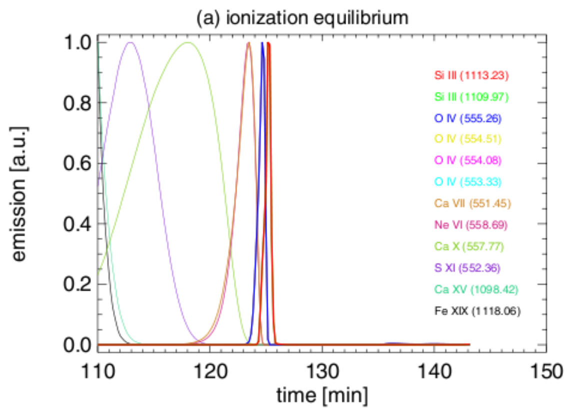








Light curves: multistrand (Gaussian convolution)



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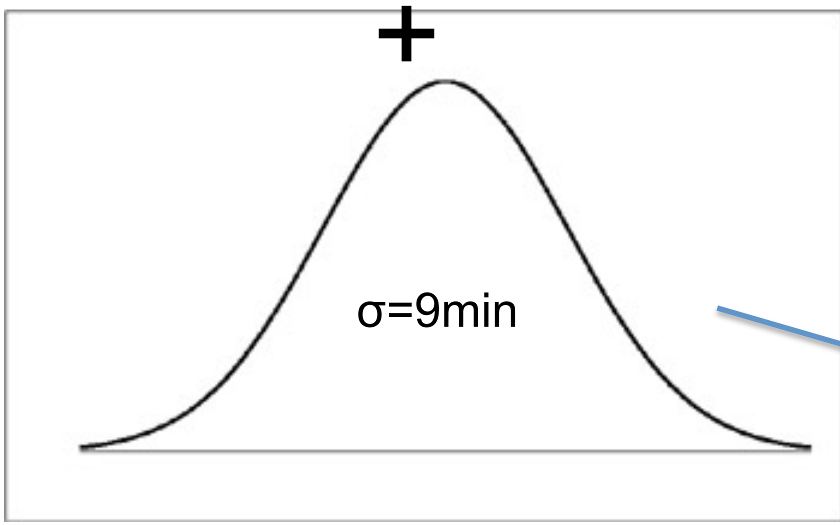

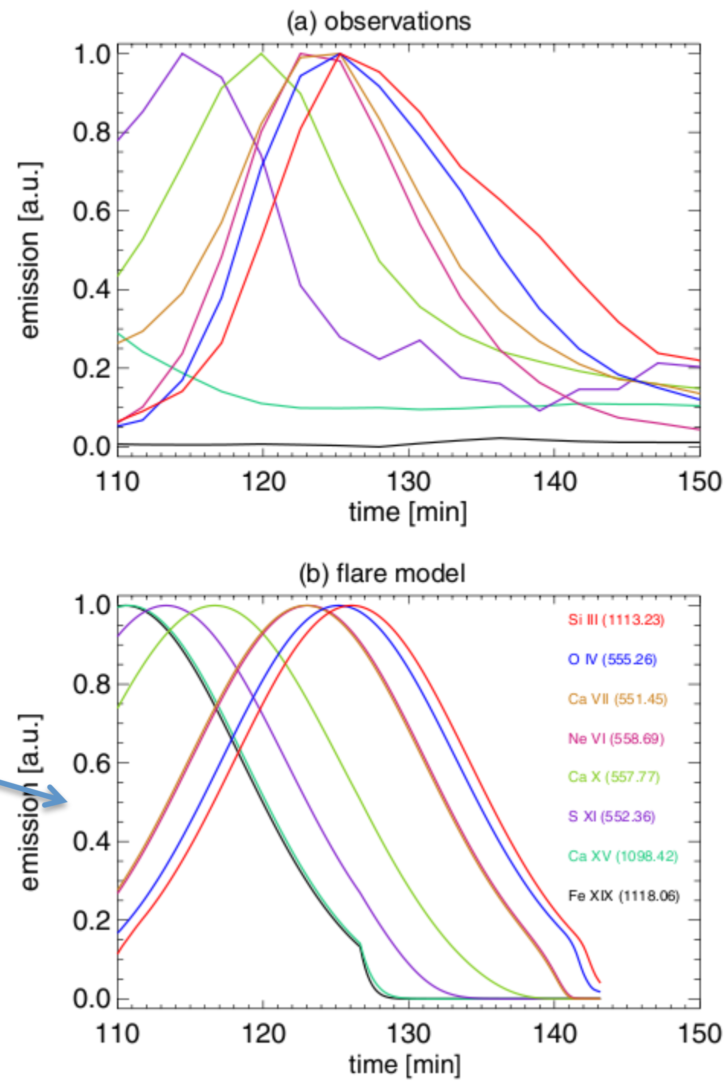

Conclusions

- Catastrophic cooling can explain almost simultaneous brightening of UV lines at different temperature
- Out-of-phase heating can explain broadening of light curves: evidence for multi-stranded loop structure