X-ray spectral signatures of the cold, hot, and intermediate phases from a clumpy AGN outflow

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Cloud formation and acceleration in AGN

Governing equations

These are the basic equations of multiphase gas dynamics:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbb{I}) = \mathbf{f}_{rad}, \tag{2}$$

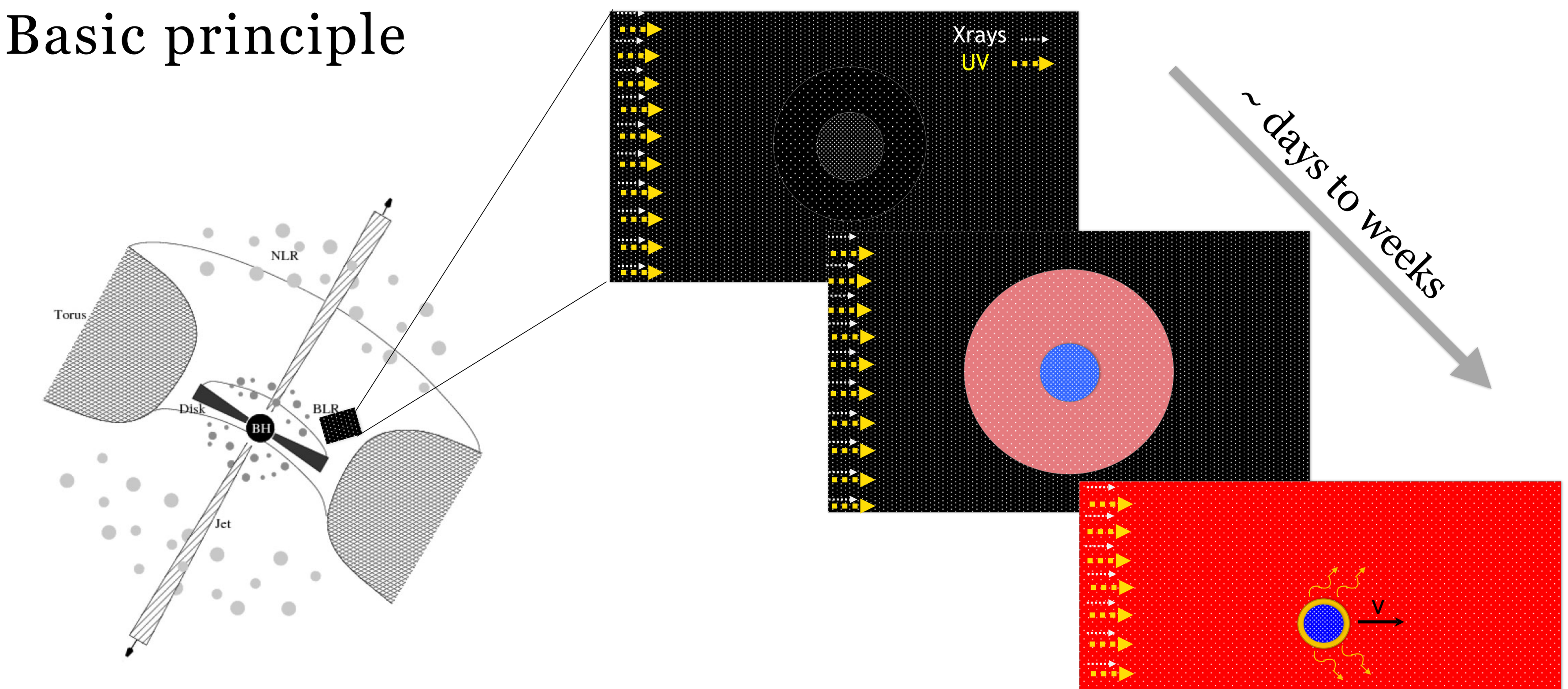
$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+p)\mathbf{v}] = -\rho\mathcal{L} + \kappa_{eq}\nabla^2 T + \mathbf{f}_{rad}\cdot\mathbf{v}. \tag{3}$$

where the radiation force is given by (see Proga & Waters 2015),

$$\mathbf{f}_{rad} = \frac{\rho\sigma_{tot}\mathcal{F}_{tot}}{c}\hat{x} = \frac{\rho\sigma_e\mathcal{F}_X}{c}\left[(1+f_{\rm UV}) + \sigma_X + f_{\rm UV}M_{\rm max}\right]$$

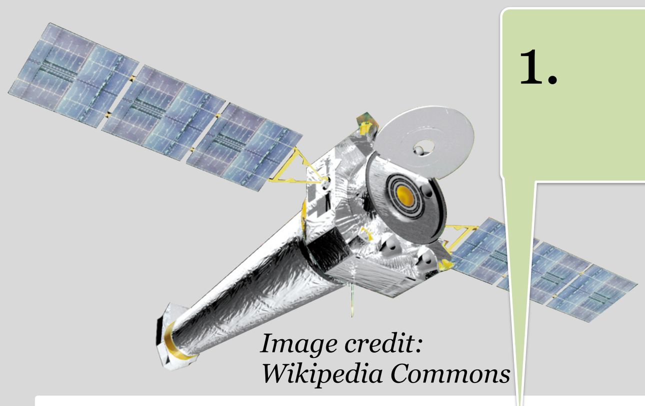
Modeling approach: Local box simulations of UV and X-ray irradiated plasma

Basic principle



Saturation of thermal instability (TI) is a cloud formation process, *but it also naturally leads to cloud acceleration (Proga & Waters 2015).*

Synthetic UV/X-ray absorption lines from 1st principles



1. Observed SEDs

2. Photoionization calculations

3. Hydrodynamical simulations

4. Synthetic absorption lines

Here we show the obscured and unobscured SEDs for NGC 5548 obtained by Mehdipour et al. (2015)

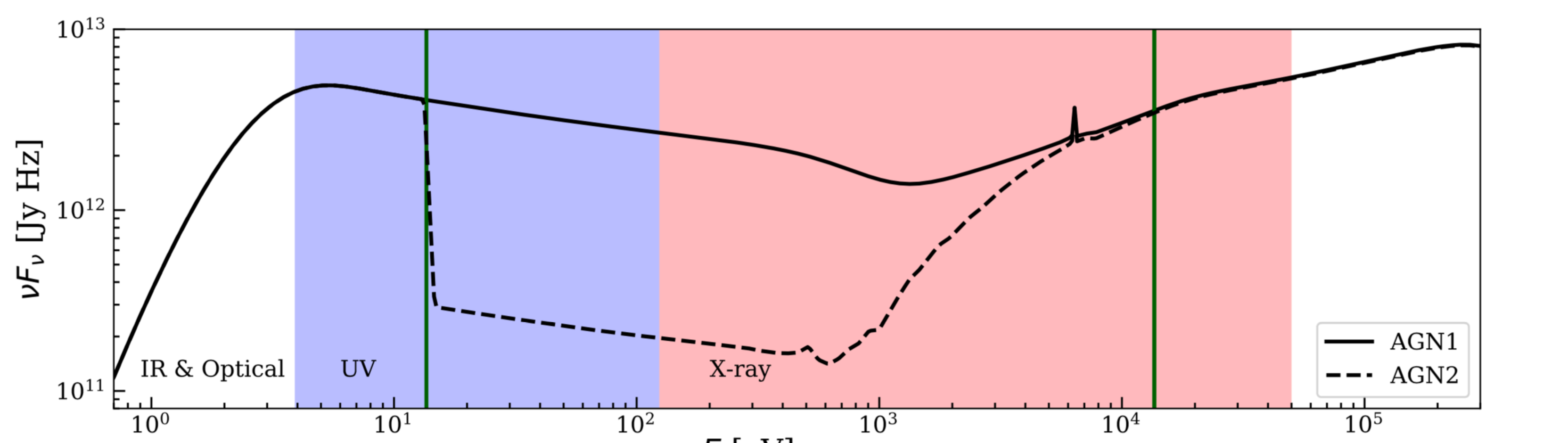
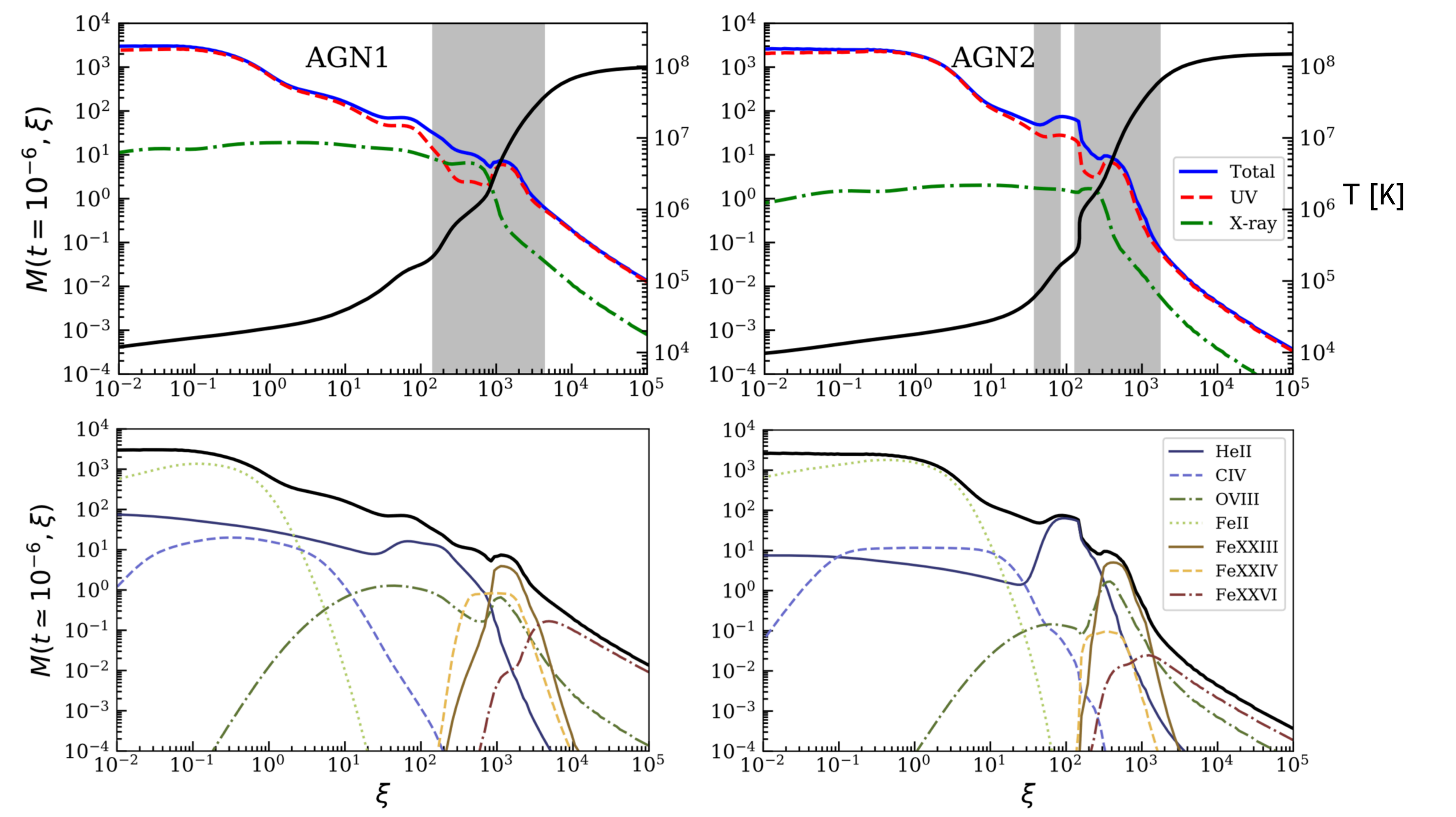


Figure from Dannen et al. (2019)

For these SEDs, we used XSTAR to determine…

i. The heating & cooling rates of the photoionized plasma (see S-curves below)
ii. The opacity to spectral lines, i.e. the force multiplier (blue curves below)

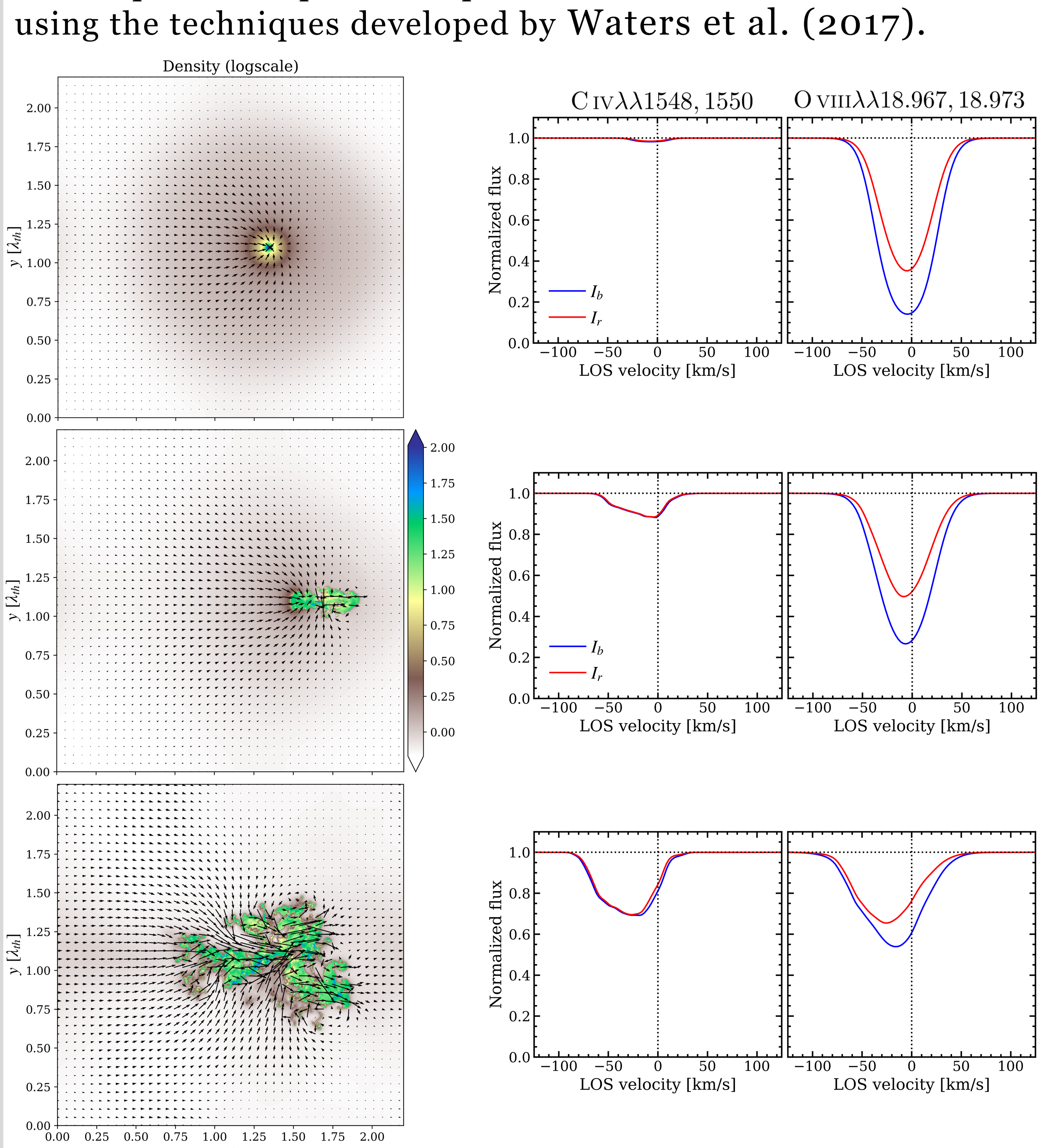


Let us focus on 2 ions in particular

i. CIV - M(t) > 1 for $-1 \lesssim \log\xi \lesssim 1$
ii. OVIII - significant opacity for $0.3 \lesssim \log\xi \lesssim 3.3$

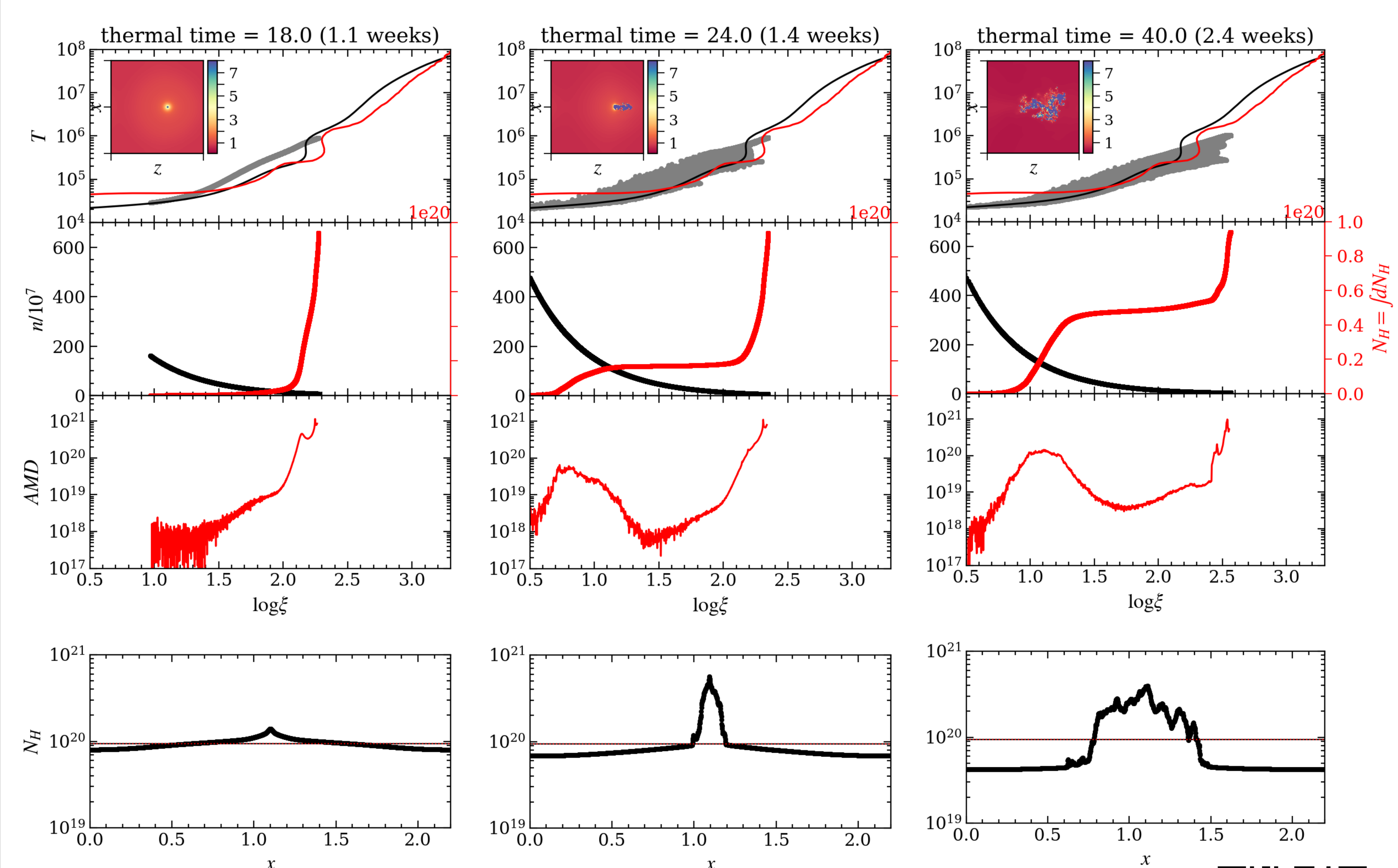
Figure from Dannen et al. (2019)

Using a post-processing routine that again interfaces with XSTAR to compute the opacity of a given ion at every grid zone, we compute absorption line profiles of common doublet lines using the techniques developed by Waters et al. (2017).



Left panels: Density maps with velocity vectors overlaid at times 18, 24, & 40 as before.
Right panels: Synthetic absorption lines. Red and blue colors denote the longer and shorter wavelength components of either doublet line. Due to partial covering, the strength of the C IV lines anti-correlate with those of the O VIII lines as the cloud is disrupted from radiation forces.

Using Athena++, we performed simulations similar to Proga & Waters (2015) but for the SEDs above using a fully self-consistent pipeline.



Upper panels: phase diagram showing a scatter plot of how gas spans the S-curve (top), density and column density (middle), and the absorption measure distribution (AMD; bottom).
Lower panel: column density along the right vertical edge of the domain.

Scan for animation

References

1. Dannen, Proga, Kallman & Waters, Photoionization calculations of the radiation force due to spectral lines in AGNs, 2019, ApJ, 882, 99
2. Dyda, Dannen, Waters, & Proga, Irradiation of Astrophysical Objects: SED and flux effects on thermally driven winds, 2017 MNRAS,467, 4161
3. Mehdipour, M. Kaastra, J.S., Kriss, G.A., et al., Anatomy of the AGN in NGC 5548 I., 2015, A&A, 575, A22
4. Proga & Waters, Cloud Formation and Acceleration in a Radiative Environment, 2015, ApJ, 804, 137
5. Waters, Proga, Dannen, & Kallman, Synthetic Absorption Lines for a Clumpy Medium: a spectral signature for cloud acceleration in AGN?, 2017 MNRAS, 467, 3160

These calculations were performed on the Institutional Computing clusters at Los Alamos National Lab