The characteristic sizes of individual broad and narrow line region clouds

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Outline

• Review of thermal instability (TI) as the basic mechanism to form AGN clouds

• Distinguishing the isobaric and non-isobaric regimes of TI
  \[ \lambda_F < d_c < \lambda_{th} \quad \text{vs.} \quad \lambda_{th} < d_c < \lambda_J \]

• The crucial role played by turbulence in determining the final characteristic cloud sizes

from Berton et al. (2017)
Review of TI: the linear isobaric regime

Saturation of TI is a cloud formation process, but it also naturally leads to cloud acceleration (PW15).
Review of TI: the linear isobaric regime

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AGN H/C rates and radiation forces

Start with the best-fit SED. Here is NGC 5548’s (Mehdipour et al. 2015):

Fig. 1 of Dannen et al. (submitted)
AGN H/C rates and radiation forces

Use XSTAR/CLOUDY/etc. to calculate the photoionization balance and evaluate **force multipliers** (the biggest contributor to M are lines of iron and helium).
AGN H/C rates and radiation forces

Use XSTAR/ CLOUDY/etc. to calculate the photoionization balance and evaluate optically thin heating and cooling rates and thermal instability.

From Dannen et al. (submitted)
Local cloud formation and acceleration simulations

To view animation please visit http://www.physics.unlv.edu/~twaters/simulations.html
classical evaporation (Cowie & McKee 1977)

Conductive interface

e- e- e-

Steady state configuration:
line cooling balances conductive heating

Begelman & McKee (1990)

\[ \tau_{\text{evap}} \]

Intercloud medium

Cloud core

\[ c_s t_{\text{cool}} \]

Non-isobaric

isobaric

\[ \lambda_F = 2\pi \sqrt{\frac{\kappa_{\text{eq}} T_{\text{eq}}}{\rho_{\text{eq}} \Lambda_{\text{eq}}}} \]

Steady state configuration:
line cooling balances conductive heating
Begelman & McKee (1990)
Non-isobaric TI simulations
- Larger clouds undergo increasingly larger damped oscillations

To view animation please visit http://www.physics.unlv.edu/astro/wp18sims.html
Table 1 in Waters & Proga (2018; submitted)

<table>
<thead>
<tr>
<th>Rate dependence</th>
<th>Wavelength dependence</th>
<th>Mode Type &amp; Stability</th>
<th>Mode</th>
<th>$n_R t_{cool} (\lambda \to \infty)$</th>
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<tbody>
<tr>
<td>$R &lt; 0$ $(N_p &lt; 0)$</td>
<td>$\lambda &lt; \lambda_c$</td>
<td>condensation</td>
<td>E</td>
<td>$k' \sqrt{-R}$</td>
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Splattering can occur during cloud formation in isochorically unstable plasmas

**Cloud splattering:**
A new phenomenon that can turn stationary gas into high velocity blobs!

**Linearized solutions**

to non-adiabatic gas dynamics:

\[
\begin{align*}
\rho(x, t) &= \rho_0 + A\rho_0 e^{nRt} \cos(k \cdot x) \\
v(x, t) &= -A \left(\frac{nR}{k} \right) e^{nRt} \sin(k \cdot x) \\
p(x, t) &= p_0 - A\rho_0 \left(\frac{nR}{k} \right)^2 e^{nRt} \cos(k \cdot x)
\end{align*}
\]

Notice that for large enough wavelengths (small k), linear theory predicts supersonic motions during cloud formation!
The snag encountered when deriving characteristic cloud sizes...

What is the characteristic size of a newly condensed clump?

By mass conservation:

$$\rho_{eq} \lambda^3 \approx \rho_c \frac{4}{3} \pi R_c^3$$

$$R_c \sim \frac{\lambda}{(\rho_c/\rho_{eq})^{1/3}}$$

But we don’t know the characteristic size of a perturbation in AGN.

And even if we did, there as a bigger problem...
Cloud complexes are dynamically unstable.

Clouds tend to coalesce!

Safe to try at home: start with perfect spherical clouds in pressure equilibrium, add the necessary physics described above (i.e. optically thin cooling and thermal conduction, needed to form interfaces) and then evolve.

To view animation please visit http://www.physics.unlv.edu/astro/wp19sims.html

Athena++ simulation by Tim Waters (LANL)
Turbulence to the rescue

Hypothesis: turbulence should favor clump sizes corresponding to wavelengths with maximum linear growth rates of TI:

\[ R_c \sim \frac{\lambda_{\text{max}}}{(\rho_c/\rho_{eq})^{1/3}} \]
Turbulent flow can suppress coalescence

The essence of turbulence…
“Big whirls have little whirls,  
That feed on their velocity;  
And little whirls have lesser whirls,  
And so on to viscosity.” -Richardson

Why invoke turbulence? Otherwise…
“Small clumps merge with big clumps,  
Enhancing their advective velocity;  
And big clumps join even bigger clumps,  
And so on to self-gravity.”
The clumpy outflow paradigm implies turbulent flow

-standard (triply periodic) driven turbulence simulations is likely an appropriate framework for studying the local multiphase gas dynamics

\[ \text{Re} \equiv \frac{v L}{\nu} \approx \frac{10^2 \text{ km s}^{-1} L_{\text{th}}}{c_s \lambda_{\text{mfp}}} \approx 10 \left( \frac{L_{\text{th}}}{\lambda_{\text{mfp}}} \right) \approx 10^7 \]

\[ \frac{\partial \omega}{\partial t} + \nabla \times (\omega \times \mathbf{v}) = \frac{\nabla \rho \times \nabla p}{\rho^2} + \sum_i \nabla \times \mathbf{f}_i \]
BLR/NLR cloud sizes at last

\[
\frac{\lambda_{th}}{\lambda_F} = 7.2 \left( \frac{T}{10^5 \text{ K}} \right)^{-1/4} \left( \frac{L}{10^{-23} \text{ erg cm}^3 \text{ s}^{-1}} \right)^{-1/2}
\]

This ratio does not depend on density!
- Begelman & McKee (1990);
see also Waters & Proga (2018)

From Dannen et al. (submitted)
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Summary
(bolded: suitable for 3-year olds)

• AGN clouds get happier as they grow bigger - they bounce up and down more (i.e. larger non-isobaric clouds undergo stronger thermal response oscillations)

• AGN clouds are a loving family - they like to kiss and hug (i.e. they are dynamically unstable to coalescence)

• Most AGN clouds die whenever they are pushed around. Only the fastest growing clouds can avoid death. That is, turbulence picks out a preferred size corresponding to the fastest growing TI modes.

• Sometimes AGN clouds go splat! (‘splattering’ should occur in isochorically unstable plasmas according to linear theory)