Resolving Gas Flow within the Bondi Radius of the Supermassive Black Hole in NGC 3115 with Chandra (Wong et al. 2011, 2014)

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Important to study black hole accretion

• Understand black hole (or other compact object) physics

  NASA/Dana Berry, Skyworks Digital

• Impact on large-scale structure formation

  Accretion:
  \[ R_s = \frac{2GM}{c^2} \]
  \[ E \sim PE \sim GM \frac{m}{R_s} \sim 50\% \text{ mc}^2 \]
  10\% feedback efficiency \( \Rightarrow 5\% \text{ mc}^2 \)
  Nuclear fusion: \( \sim 0.7\% \)
  Chemical reaction: \( \sim 10^{-6}\% \)

Perseus cluster;
Radio: NSF/AURA/VLA;
X-ray: NASA/IoA/A. Fabian et al.
How does a black hole accrete?

- The famous standard thin accretion disk model (Shakura & Sunyaev 1973; Novikov & Thorne 1973)
- ?? How successful is thin disk?

Cold accretion models
Geometrically thin
Optically think (~blackbody)
Predicts $L \sim 0.1 \ L_{\text{Eddington}}$
How does a black hole accrete?

- The famous standard thin accretion disk model (Shakura & Sunyaev 1973; Novikov & Thorne 1973)
- ?? How successful is thin disk?

Problems (Narayan):
1. Hard non-thermal state in BH XRBs
2. No Big Blue Bump (disk component) in quiet AGNs
3. Wide varieties of AGNs
4. Cannot explain extremely under-luminous AGNs ($L << L_{\text{Eddington}}$)
Quasars, AGNs, and Quiescent SMBHs

\[ L_{\text{bol}} \sim 10^{46} \text{ erg s}^{-1} \]
\[ \sim 0.1 \, L_{\text{Eddington}} \]
Rare in local universe!

Few percent in current population

\[ L_{\text{bol}} \sim 10^{42} \text{ ergs s}^{-1} \]
\[ \sim 10^{-5} \, L_{\text{Eddington}} \]

\[ L_{\text{bol}} \sim 10^{36} \text{ ergs s}^{-1} \]
\[ \sim 10^{-8} \, L_{\text{Eddington}} \]

Majority of SMBHs

Why are most SMBHs so radiatively inefficient?
Bondi (1952) Accretion Model

- Gravitational energy $\approx$ thermal energy

\[ R_B \approx \frac{2GM}{c_s^2} \]
Gas Capture Rate and Efficiency

Bondi rate = \( \dot{M}_B = 4\pi R_B^2 \rho v \sim 10^{-6} M_\odot \text{yr}^{-1} \) for Sgr A*

\[ v \sim c_s \]

Thin Disk \( \Rightarrow \) predicts \( L_{\text{Bondi}} \sim 10^{41} \text{ergs s}^{-1} \gg 10^{36} \text{observed!} \)

Why is material that is flowing through the Bondi radius only radiating a tiny fraction of its available energy?

Three general solutions:
(1) Material makes it to the event horizon, but energy is advected into the black hole without radiating (ADAF).
(2) Material does not make it to the event horizon, having been removed from the inner flow through either convection or outflow (CDAF, ADIOS).
(3) Radiative efficiency < 0.1 (or < thin disk)

\{ Hot accretion models \\
(Shapiro et al. 1976; Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994; Abramowicz et al. 1995) \}
Cold vs Hot Accretion Models

$T < T_{\text{vir}}$ (cold)
Geometrically thin
Optically thick
$L \sim 0.1 \, L_{\text{Eddington}}$

$T \sim T_{\text{vir}}$ (hot)
Geometrically thick
Optically thin
$L \ll L_{\text{Eddington}}$

http://www.mpa-garching.mpg.de/HIGHLIGHT/2000/highlight0004_e.html

Gas is hot and optically thin, with the ions carrying most of the thermal energy

⇒ gas is too low density to cool efficiently, so gas falls into the BH carrying most of the energy with it without radiating

Pure ADAFs predict:

\[ \dot{M}(R) \propto \text{constant} \quad \text{and} \quad T(R) \propto R^{-1} \quad \text{and} \quad \rho(R) \propto R^{-3/2} \]
Gas is hot and optically thin, with the ions carrying most of the thermal energy \( \Rightarrow \) gas is too low density to cool efficiently, so gas falls into the BH carrying most of the energy with it without radiating.

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\[
\begin{align*}
\dot{M}(R) & \propto \text{constant} \\
T(R) & \propto R^{-1} \\
\rho(R) & \propto R^{-3/2}
\end{align*}
\]
CDAF (Convection Dominated Accretion Flow)
(Narayan et al. 2000; Quataert & Gruzinov 2000; Abramowicz et al. 2002)

Gas circulates in convective eddies, removing gas from the inner accretion flow and redistributes it to larger radii within flow

\[ \dot{M}(R) \propto R \quad \text{and} \quad T(R) \propto R^{-1} \quad \text{and} \quad \rho(R) \propto R^{-1/2} \]
CDAF (Convection Dominated Accretion Flow) ([Narayan et al. 2000; Quataert & Gruzinov 2000; Abramowicz et al. 2002])

Gas circulates in convective eddies, removing gas from the inner accretion flow and redistributes it to larger radii within the flow:

\[ T(R) \propto R^{-1} \]
\[ \rho(R) \propto R^{-1/2} \]

ADIOS (Advection Dominated Inflow Outflow Solution) ([Blandford & Begelman 1999])

Strong wind carries away gas and energy, completely removing it from flow:

\[ \dot{M}(R) \propto R^p \quad \text{and} \quad T(R) \propto R^{-1} \quad \text{and} \quad \rho(R) \propto R^{-3/2+p} \quad \text{or} \quad R^{-s} \]

\[ p = 0-1 \quad \text{or} \quad s = 0.5-1.5 \]
Realistic Numerical Simulations

Magnetically Arrested Accretion; Tchekhovskoy et al. 2011

3D GR Radiation MHD; McKinney et al. 2013 submitted
Summary of Accretion Flow Solutions

Recent work has focused on including effects of magnetic fields, gas cooling, conduction, rotation to make flows more realistic.

Yuan, Wu, & Bu (2012) summarized the current state of simulations among various groups. They find in general:

- $\dot{M}(R) \propto R^p$, where $p \neq 0$ (at least beyond $\sim 100 \ R_g$)
- $\rho(R) \propto R^{-3/2+p}$ or $R^{-s}$ where $s = 0.65 - 0.85$

Yuan et al. (2012) simulations go out to $40,000 \ R_g$

$\Rightarrow$ close to area of flow that can realistically be probed by X-ray observations:

$\rho(R) \propto R^{-0.65}$ for $\alpha=0.001$    $\rho(R) \propto R^{-0.85}$ for $\alpha=0.01$
Can we constrain accretion models observationally?

Simulations converging on agreement that:

- $T(R) \propto R^{-1}$
- $\rho(R) \propto R^{-s}$ where $s = 0.65 - 0.85$

Can we spatially resolve the hot gas within the Bondi radius of a SMBH to derive $T(R)$ and $\rho(R)$ profiles?

Since $R_{\text{Bondi}} \propto \frac{M_{\text{BH}}}{kT_{\text{gas}}}$, need systems that have:

- large black hole mass
- cool ISM temperature
- small distance
Chandra X-ray Observatory

0.3 – 10 keV energy range

0.5” spatial resolution

Goal is to measure the radial temperature (and density) profiles of hot gas in the Bondi region of a SMBH from X-ray spectra.
Black holes with Bondi Radius extend large enough to be resolved by Chandra:

- M31* Chandra PI: Michael Garcia
- Sgr A* Chandra XVP PI: Frederick Baganoff; (D. Wang et al. 2013)
- N3115 Chandra XVP PI: Jimmy Irwin

Garcia et al. 2010
+1 Ms Chandra XVP data
0.5–1.0 keV

155 ks Chandra data
0.3–6.0 keV

$R_B = 5$ arcsec

dark/blue = faint, yellow/red = bright
$+1 \text{ Ms Chandra XVP data}$

$0.5-1.0 \text{ keV}$

$>2 \text{ arcsec}, \text{ gas dominates the diffused emission}$

$2.0-6.0 \text{ keV}$

Low Mass X-ray Binaries (LMXB)

$R_B = 5 \text{ arcsec}$

dark/blue = faint, yellow/red = bright
+1 Ms Chandra XVP data

Divide data into annuli:
0–1”, 1–2”, 2–3”, 3–4”, etc

dark/blue = faint, yellow/red = bright
$\Gamma_{\text{LMXB}} \approx 1.6$
$2-4$ arcsec

$CV/AB$

$L_X \propto L_K$
GAS thermal (APEC)
Data before 2011
Chandra XVP data  (1-3 arcsec)

APEC model: Optically thin thermal plasma model
Temperature Profile (pre-XVP in 2011)

$R_B \approx 4'' - 5''$

(188–235 pc)

Wong et al. 2011
For the first time, temperature profile has been spatially resolved within $R_B$!

$R_B \approx 4'' - 5''$

(188–235 pc)

Wong et al. 2011
Temperature Profile (XVP data)

1-temperature thermal model

The clearest and the only spatially well resolved gas temperature profile inside $R_B$ today!

$1'' = 47$ pc @9.7 Mpc

Wong et al. 2014
Temperature Profile (XVP data)

1-temperature thermal model

Inner 3" shows a decline, unlike an expected $T(R) \propto R^{-1}$ profile predicted by hot accretion models.

90% confidence error bars

$1" = 47 \text{ pc \, @9.7 Mpc}$
Temperature Profile (XVP data)

1-temperature thermal model

2-temperature thermal model

Use two thermal models for inner 2-3 spatial bins

$1'' = 47 \text{ pc } @ 9.7 \text{ Mpc}$
Cool gas (brown/green data points) represents about 75% of the total 0.5-1.0 keV flux within 3”, and has a temperature of ~0.3 keV.

Could cooler gas from larger radii projected in front of/behind the inner two bins be responsible for cooler component?
Projection from Outer Cooler Gas?

Considered:

1) Spherical distribution of 0.3 keV gas beyond 5”

2) Oblate spheroid model for 0.3 keV gas with ellipticity matching optical contours

3) A thick circular disk of uniform 0.3 keV gas with thickness 6” and an outer radius of 40” aligned along optical axis

These projection models account < 25% of cooler gas within 3”
Tidally stripped giant cores?

Tidal stripping rate is too small to leave enough cores for the observed soft X-ray emission.
Multi-Phase Gas?

Recent realistic models by Gaspari et al. (2013):

- Hot gas is thermally unstable to cooling if $t_{\text{cool}} \leq 10 t_{\text{freefall}}$
- Cold and chaotic accretion in this model
- Periodic outbursts as cold gas is accreted in clumps

Gaspari et al. (2013)

See also other simulations by, e.g., Barai, Proga, Nagamine 2012; Gaspari et al. 2015
Cold & Chaotic Accretion

Recent realistic models by Gaspari et al. (2013) indicate that hot gas is thermally unstable to cooling if $t_{\text{cool}} \leq 10 \ t_{\text{freefall}}$

Predicts multi-phase gas, and cold mode accretion.

For NGC 3115, globally $t_{\text{cool}} \sim 100 \ t_{\text{freefall}}$ (Shcherbakov et al. 2013). Perhaps $t_{\text{cool}} \leq 10 \ t_{\text{freefall}}$ locally? New physics?

Emission-weighted temperature profile as a function of time with cooling/turbulence (Gaspari et al. 2013)
Deprojected Density Profile

Emission measure at each radius:
\[ \text{EM} = \int n_e n_H \, dV / 4\pi D^2 \]
\[ \Rightarrow \text{density } n_e \text{ profile} \]

From 5”-40” (outside \( R_B \))
\[ \rho(R) \propto R^{-s}, \quad s = 1.34^{+0.20}_{-0.25} \]

Within 5” Bondi radius \( R_B \)
\[ \rho(R) \propto R^{-s}, \quad s = 0.89^{+0.35}_{-0.45} \]
\[ \Rightarrow \text{ADIOS (outflow)} \]
(Yuan et al. 2012: \( s = 0.65-0.85 \) )

\( n_e \) only depends weakly on assumed temperature
Other Bondi Regions?

- Sgr A* (supermassive black hole in our Milky Way)
  - Another Chandra X-ray Visionary Project
    PI: Fredrick Baganoff
  - $R_B \sim 1.5$ arcsec, a bit too small for spatial information
  - But bright enough to get excellent spectral information

By assuming $T \sim R^{-1}$, Daniel Wang et al. 2013 get
\[ \rho(R) \propto R^{-s}, \quad s = 1.0^{+0.3}_{-0.2} \]
Consistent with NGC 3115
M87*  

- \( R_B = 1.5 \text{-} 2.8 \) arcsec  
- Very bright AGN / knob, contaminating \( R_B \)!  
- Fortunately, turning down since 2010

By Russell et al. 2015
Testing models

Wong et al. 2014
Summary

Our Megasecond *Chandra* observation of the Bondi region of the $1-2 \times 10^9 M_\odot$ SMBH of NGC3115 has so far revealed:

1) Most detailed spatially resolved temperature/density profile of hot gas within the Bondi radius of a supermassive black hole.

2) Evidence that temperature increases inside Bondi radius, as expected, but also a cooler component inside 3”.

3) Density profile within 5”: $\rho(R) \propto R^{-s}$, $s = 0.89^{+0.35}_{-0.45}$, in line with many simulations and a few other LLAGNs.
Multi-phase Accretion?

- Can we study other phase with multi-wavelength observations? E.g., M87 Virgo Cluster?

H-alpha image, 0.5 keV X-ray contours
Note the scale of the image is $>> R_B$

Russell et al. 2015

Werner et al. 2010
Other Directions

- Angular variation? Need much longer (3X) observation!

Gaspari et al. (2013)
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$$\rho(R) \propto R^{-s}, \quad s = 1.0^{+0.3}_{-0.2}$$

Consistent with NGC 3115
Other Bondi Regions?

- **Sgr A*** (supermasive black hole in our Milky Way)
  - Another Chandra X-ray Visionary Project
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  - But bright enough to get excellent spectral information

- **M31***
  - Long Chandra observation
  - PI: Michael Garcia
  - $R_B \sim 5$ arcsec, very faint
  - May get surface brightness but not temperature

- **NGC4649*** (in Virgo Cluster, $R_B \sim 1.5$ arcsec)

- **NGC4887*** (in Coma Cluster, $R_B \sim 1.5$ arcsec)
The X-ray Surveyor

Future mission: SMART-X

- Square Meter Arcsecond Resolution X-ray Telescope (SMART-X)
- Chandra’s angular resolution (0.5 arcsec)
- 30–50 times Chandra effective area
  - much more photons to study smaller spatial structure
  - test accretion model beyond spherical symmetry
  - fainter targets such as M31*
- 20-1000 times current CCD spectral resolution
  - thermal dynamic and ionization states of hot plasma
    (constrain micro-physical processes, e.g., cooling, conduction)
  - metallicity of hot gas (constrain stellar feedback)

http://hea-www.cfa.harvard.edu/SMARTX/
Theoretical models

- Stellar wind feedback (Hillel & Soker 2013)
Theoretical models

- Stellar feedback conduction inflow-outflow solution (Shcherbakov, Wong, Irwin, & Reynolds 2014)

Electron heat conduction

Stellar feedback

Conductive heat flux

The outer flow gets unbound

Original: NASA/Dana Berry
Theoretical models

- Stellar feedback conduction inflow-outflow solution
  (Shcherbakov, Wong, Irwin, & Reynolds 2014)
Theoretical models

- State-of-the-art accretion spectral model (multi-wavelength fitting)

Theoretical models

- 2D or 3D numerical simulations include:
  - 1) rotation
  - 2) galactic potential
  - 3) stellar feedback
  - 4) cooling
  - 5) magnetic field?
  - 6) conduction?