Gas Accretion onto a Supermassive Black Hole: a step to modeling AGN feedback in cosmological simulations

Ken Nagamine
Univ. of Nevada, Las Vegas (UNLV)

Collaborators: Paramita Barai (UNLV / INAF Trieste) Daniel Proga (UNLV)
Outline

• Intro / Motivation
• The simplest case: spherical Bondi accretion
• Include radiative cooling / heating -- radiative feedback by X-rays
• Non-spherical accretion flow, fragmentation due to thermal instability
  Barai, Proga, KN, 2011, in prep. (Paper II)
• Conclusions
Motivation

Small-scale sims

Cosmological sims

Still a large gap btw small-scale sims & cosmological sims. 

• Cosmo sims uses ad-hoc AGN accretion models as “sub-grid” physics.
• How well can a cosmological SPH code (e.g. GADGET) handle accretion onto a SMBH?
The Bondi Accretion Problem

- Spherically symmetric accretion onto a central mass (Bondi 1952)
- Gas is at rest at infinity, with \( \rho_\infty \) & \( p_\infty \). Increase in the central mass is ignored.
- Two equations are solved:

\[
\dot{M} = -4\pi r^2 \rho v = \text{constant.} \quad \text{(Continuity Eq.)}
\]

\[
\frac{v^2}{2} + \left( \frac{\gamma}{\gamma - 1} \right) \frac{p_\infty}{\rho_\infty} \left[ \left( \frac{\rho}{\rho_\infty} \right)^{\gamma^{-1}} - 1 \right] = \frac{GM_{BH}}{r}, \quad \text{(Bernoulli’s Eq.)}
\]

- One of the solutions:

\[
\dot{M}_B = 4\pi \lambda_c \frac{(GM_{BH})^2}{c_{s,\infty}^3} \rho_\infty, \quad \lambda_c = \left( \frac{1}{2} \right)^{\frac{(\gamma+1)}{2(\gamma-1)}} \left( \frac{5 - 3\gamma}{4} \right)^{\frac{(3\gamma-5)}{2(\gamma-1)}}.
\]

- Characteristic scales:

\[
\text{Bondi radius: } \quad R_B = \frac{GM_{BH}}{c_{s,\infty}^2}.
\]

\[
\text{Sonic radius: } \quad R_s = \left( \frac{5 - 3\gamma}{4} \right) R_B.
\]

\[
\text{Bondi time: } \quad t_B = \frac{R_B}{c_s} = \frac{GM_{BH}}{c_{s,\infty}^3}.
\]
**Simplest Case: Spherical Bondi Accretion Flow onto a SMBH**

- **GADGET-3**: 3-d cosmological SPH/N-body code (Springel '05)
- **Central SMBH** $10^8 \, M_\odot$ represented by a pseudo-Newtonian Paczynsky & Wiita (1980) potential
- $r_{\text{out}}=5-20 \, \text{pc}$, $N_{\text{ptcl}}=64^3-128^3$
- Set IC to uniform/spherical Bondi flow w/ $\gamma=1.01$, $\rho_\infty=10^{-19} \, \text{g/cm}^3$, $T_\infty=10^7 \, \text{K}$, $T_{\text{init}}=T_\infty$
- Corresponding Bondi solution: $R_B=3 \, \text{pc}$, $R_{\text{sonic}}=1.5 \, \text{pc}$, $t_B=7.9 \times 10^3 \, \text{yr}$
- All runs: $r_{\text{in}}=0.1 \, \text{pc}$, $\gamma=1.01$

### 3-d spherical volume, vacuum boundary condition

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$r_{\text{out}}$ [pc]</th>
<th>$N$ $^b$</th>
<th>IC</th>
<th>$M_{\text{tot,IC}}$ $^c$ [$M_\odot$]</th>
<th>$M_{\text{part}}$ $^d$ [$M_\odot$]</th>
<th>$t_{\text{end}}$ $^e$ [10$^4$ yr]</th>
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<td>29.75</td>
<td>8</td>
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Example: Properties of Particles

Run 7:

- $r_{\text{out}}=20$ pc, $N_{\text{ptcl}}=128^3$
- Snap at $t=2t_B=1.6 \times 10^4$ yr
- Follows the Bondi solution (red curve) well except the very inner part
- Inner part: supersonic ($M \sim 6$), outer part: subsonic

![Graphs showing radial velocity, temperature, density, Mach number, acceleration, and smoothing length as functions of radius for Run 7.](image)

- Radial velocity
- Temperature: almost isothermal ($\gamma = 1.01$)
- Density: $\rho_B$
- Mach number: $M_B$ near $v_r=0$ and $M=1$
- Acceleration
- Smoothing length $h_{\text{Smoothing}}$

$Rs \sim 1.5$ pc
$h_{\text{min}} \sim 0.15$ pc

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Mass Inflow Rates at $r_{in}$

- the larger $r_{out}$, the longer duration of Bondi inflow rate
- If started from a Bondi flow, Bondi rate is achieved quickly.
- After a while, the inflow rate decreases due to the artificial outflow at the outer boundary.
- Greater sim. volume reduces this effect on mass inflow.

reproducing Bondi rate well.

due to outflow problem at outer BC
Radiative Heating & Cooling

- X-ray emitting corona irradiates the accretion flow

\[ L_X = f X \ L_{\text{Edd}}, \quad L_{\text{Edd}} = \frac{4\pi c G m_p M_{\text{BH}}}{\sigma_e}, \quad \text{Flux:} \quad F_X = \frac{L_X}{4\pi r^2}. \]

- Approx. analytic heating/cooling rates from Blondin '94; opt-thin gas illuminated by a 10 keV bremsstrahlung.

**net rate:** \[ \rho \dot{L} = n^2 (G_{\text{Compton}} + G_X - L_{b,l}) \quad [\text{erg cm}^{-3} \text{ s}^{-1}], \]

**Compton h/c rate:** \[ G_{\text{Compton}} = 8.9 \times 10^{-36} \xi (T_X - 4T) \quad [\text{erg cm}^3 \text{ s}^{-1}]. \]

**Net X-ray photoionization heating and recombination cooling rate:** \[ G_X = 1.5 \times 10^{-21} \xi^{1/4} T^{-1/2} \left(1 - \frac{T}{T_X}\right) \quad [\text{erg cm}^3 \text{ s}^{-1}]. \]

**Brems. and line cooling rate:**

\[ L_{b,l} = 3.3 \times 10^{-27} T^{1/2} \]
\[ + \left[1.7 \times 10^{-18} \exp \left(-1.3 \times 10^5 / T\right) \xi^{-1} T^{-1/2} + 10^{-24}\right] \delta \quad [\text{erg cm}^3 \text{ s}^{-1}]. \]

\[ T_X = 1.16 \times 10^8 \text{ K} \quad (=10 \text{ keV, Blondin '94}) \]
### Runs with radiative cooling/heating

| Run No. | \( r_{\text{out}} \) [pc] | \( N \) | \( M_{\text{tot,IC}} [M_\odot] \) | \( M_{\text{part}} [M_\odot] \) | \( \gamma_{\text{init}} \) | \( T_\infty [\text{K}] \) | \( R_B [\text{pc}] \) | \( \rho_\infty [\text{g/cm}^3] \) | \( T_{\text{init}} \) \( L_X [L_{\text{Edd}}] \) | \( t_{\text{end}} [10^5 \text{ yr}] \) |
|---------|-----------------|-----|-----------------|-----------------|---------|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 13      | 20              | \( 128^3 \) | \( 5.81 \times 10^5 \) | 0.277          | 1.4    | \( 10^7 \)     | 2.19        | \( 10^{-21} \)  | \( T_\infty \)  | 0.5             | 1.0             |
| 14      | 50              | \( 128^3 \) | \( 8.23 \times 10^6 \) | 3.92           | 1.4    | \( 10^7 \)     | 2.19        | \( 10^{-21} \)  | \( T_\infty \)  | 0.5             | 2.9             |
| 15      | 20              | \( 128^3 \) | \( 5.81 \times 10^{-1} \) | 2.77 \( \times 10^{-7} \) | 1.4    | \( 10^7 \)     | 2.19        | \( 10^{-27} \)  | \( T_\infty \)  | 0.5             | 1.0             |
| 16      | 20              | \( 256^3 \) | \( 5.81 \times 10^{-1} \) | 3.46 \( \times 10^{-8} \) | 1.4    | \( 10^7 \)     | 2.19        | \( 10^{-27} \)  | \( T_\infty \)  | 5 \( \times 10^{-4} \) | 1.9             |
| 17      | 20              | \( 128^3 \) | \( 5.81 \times 10^5 \) | 0.277          | 1.4    | \( 10^7 \)     | 2.19        | \( 10^{-21} \)  | \( T_{\text{rad}} \) b | 5 \( \times 10^{-4} \) | 2.9             |
| 18      | 20              | \( 128^3 \) | \( 5.65 \times 10^5 \) | 0.269          | 5/3    | \( 10^7 \)     | 1.84        | \( 10^{-21} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 3.0             |
| 19      | 20              | \( 128^3 \) | \( 1.47 \times 10^7 \) | 7.0            | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-21} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 1.5             |
| 20      | 200             | \( 256^3 \) | \( 1.33 \times 10^9 \) | 79.09          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-21} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 6.5             |
| 21      | 200             | \( 256^3 \) | \( 4.95 \times 10^8 \) | 29.50          | 5/3    | \( 10^7 \)     | 1.84        | \( 10^{-21} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 8.7             |
| 22      | 200             | \( 128^3 \) | \( 1.33 \times 10^7 \) | 6.33           | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 70              |
| 23      | 200             | \( 256^3 \) | \( 1.33 \times 10^7 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{rad}} \) | 5 \( \times 10^{-4} \) | 20              |
| 24 c    | 200             | \( 1.24 \times 10^7 \) | \( 9.77 \times 10^6 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{Run23}} \) | 5 \( \times 10^{-5} \) | 19              |
| 25      | 200             | \( 1.24 \times 10^7 \) | \( 9.77 \times 10^6 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{Run23}} \) | 5 \( \times 10^{-3} \) | 21              |
| 26      | 200             | \( 1.24 \times 10^7 \) | \( 9.77 \times 10^6 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{Run23}} \) | 1 \( \times 10^{-2} \) | 22              |
| 27      | 200             | \( 1.24 \times 10^7 \) | \( 9.77 \times 10^6 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{Run23}} \) | 2 \( \times 10^{-2} \) | 25              |
| 28      | 200             | \( 1.24 \times 10^7 \) | \( 9.77 \times 10^6 \) | 0.791          | 5/3    | \( 10^5 \)     | 183.9       | \( 10^{-23} \)  | \( T_{\text{Run23}} \) | 5 \( \times 10^{-2} \) | 50              |
Ptcl properties **w/ radiative heating & cooling**

**Representative run:**

- **red:** free-fall scaling
- **blue:** ZEUS-2d result
- Near the inner radius, excess heating by artificial viscosity is seen.
- Inflow rate is enhanced above Bondi rate, due to lower gas temp: $T(r_{out}) < 10^5$ K, $T_\infty = 10^5$ K

- **green:** free-fall scaling w/ only adiabatic term
- $T_{ff,ar}$: solving internal energy eq. w/ both radiative & adiabatic term

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### Run #23: $t=1$ Myr, $L_x=5e-4L_{Edd}$, $\gamma=5/3$

- $r_{out}=200$ pc, 256³ ptcls

---

**Left:**

- **Run 23:** $t=1$ Myr, $L_x=5e-4L_{Edd}$, $\gamma=5/3$
- $r_{out}=200$ pc, 256³ ptcls
- Inflow rate is enhanced above Bondi rate, due to lower gas temp: $T(r_{out}) < 10^5$ K, $T_\infty = 10^5$ K

**Right:**

- $T_{ff,ar}$: solving internal energy eq. w/ both radiative & adiabatic term
- $T_{ff,ar}$: solving internal energy eq. w/ both radiative & adiabatic term
Impact of varying $L_x$ on inflow rates

- Restart Run #23 at $t=1.4$ Myr, $L_x/L_{Edd}=5e-4$ orig.
- Runs 24-28: increase $L_x$
- Dramatic decrease in $\dot{M}_{in}$ at $L_x/L_{Edd}>0.01$ --- transition from net inflow to net outflow

**Thermal instability due to rad. feedback**

Impact of varying $L_x$ on inflow rates

```
Restart Run #23 at t=1.4 Myr, Lx/L_{Edd}=5e-4 orig.
Runs 24-28: increase Lx
Dramatic decrease in $\dot{M}_{in}$ at Lx/L_{Edd}>0.01 --- transition from net inflow to net outflow
```

**Thermal instability due to rad. feedback**

Net outflow; non-spherical fragmentation observed.
Non-spherical outflow: due to rad. feedback

Run 26: $r_{out}=200\text{pc}$, $Lx/L_{Edd}=0.01$

Temperature

Density

inner ±40pc

inner ±4pc

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Run 26: \( r_{\text{out}} = 200\text{pc}, \quad \frac{L_x}{L_{\text{Edd}}} = 0.01, \quad t = 2.0\ \text{Myr} \)

Large scatter due to thermal instability --- cold inflow and hot outflow

Energy feedback parameter:

\[
\xi \equiv \frac{4\pi F_X}{n} = \frac{L_X}{r^2n},
\]

\( F_X \) is the X-ray luminosity, which irradiates the accretion flow. The X-ray luminosity, \( L_x \), is expressed as

\[
L_x \approx 4\pi F_X \rho c^2 \Omega^2 R^3\left(\frac{M}{M_\odot}\right)^{-0.5} T_x^3.5
\]

where each of the components are formulated below. The heating-cooling function is parametrised in terms of the X-ray luminosity, \( L_x \)

\[
\frac{d\xi}{dt} = \frac{1}{r^2} \left[ \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} \right] - \frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]

\[
\xi = \frac{4\pi F_X}{m_H n} = \frac{L_X}{r^2 m_H n}
\]

In the equation of state, the non-radiative terms are integrated in an explicit fashion using the simulation timestep, \( \Delta t \)

\[
\rho \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} = -\frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]

\[
\frac{d\xi}{dt} = \frac{4\pi F_X}{m_H n} - \frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]

\[
\frac{d\xi}{dt} = \frac{4\pi F_X}{m_H n} - \frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]

\[
\frac{d\xi}{dt} = \frac{4\pi F_X}{m_H n} - \frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]

\[
\frac{d\xi}{dt} = \frac{4\pi F_X}{m_H n} - \frac{L_x}{\rho} \frac{d\xi}{dt} + \frac{1}{\rho} \frac{d\rho}{dt} + \frac{\dot{M}}{\rho} - \frac{L_x}{\rho} \frac{d\xi}{dt}
\]
Run 26: $r_{\text{out}}=200$ pc, \(L_x/L_{\text{Edd}}=0.01\), \(t=2.0\) Myr

- Start (triangle): \(r=53\) pc, \(t=1.4\) Myr
- End (square): \(r=1\) pc, \(t=1.8\) Myr
- + symbol: \(dt=0.004\) Myr

**Figure 4.** Time evolution of a single particle in Run 26 as it moves inward. The starting point, from the initial condition at \(t=1.4\) Myr when it is at \(r=53\) pc, is denoted by the triangle in each panel. The end point at \(t=1.8\) Myr when it is at \(r=0.99\) pc is denoted by the square in each panel. The plus signs denote the relevant quantity in uniform intervals of 
\(0.004\) Myr, except the last two points (inner-most in \(r\)) which are separated by \(\sim 0.001\) Myr. The top two rows show four radial properties: radial and angular velocities, density, temperature and entropy. The bottom row plots the evolution in the temperature vs. photo- and pressure-ionization parameter planes, where the direction of progress of time is indicated by arrows. The slopes of three characteristic processes are shown as the blue lines in the bottom row: adiabatic free-fall (\(T\sim\xi^2\), and \(T\sim\Xi^{-2}\)) as the solid line, constant-pressure (\(T\sim\xi\), and \(\Xi=\text{constant}\)) as the dashed line, and constant-density (\(\xi=\text{constant}\), and \(T\sim\Xi^{-1}\)) as the dash-dotted line. These slopes are used to describe $T$ in §3.1.1.
**Non-spherical outflow:** due to rad. feedback

Run 27: $r_{\text{out}} = 200\,\text{pc}$, $L_x/L_{\text{Edd}} = 0.02$

![Temperature](image1)

$\pm 200\,\text{pc}$

![Density](image2)

inner $\pm 60\,\text{pc}$

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Ptcl Properties: impact of rad feedback

Run 27: $r_{\text{out}}=200\text{pc}$, $L_x/L_{\text{Edd}}=0.02$
Non-spherical outflow: due to rad. feedback

Run 28: $r_{\text{out}}=200\text{pc}$, $L_x/L_{\text{Edd}}=0.05$

Temperature

Density

\[\pm 200\text{pc}\]
Figure 8. Time evolution of gas in Run 28 ($L_X/L_{Edd}=0.05$) showing the whole computational volume 200 pc of the $y-z$ plane through $x=0$. The gas density is in the left panel, temperature in the right panel, overplotted with the velocity vector arrows. Rows correspond to the times: $t=1.8$ Myr (top) and $t=3.0$ Myr (bottom). The gas is outflowing mainly over the whole volume, except near the very center toward the right in the plotted plane. A hot, less-dense bubble is well-formed and buoyantly rises from the center along the negative $z$-axis. The rest of the gas outflow remains spherically symmetric.
Conclusions

- GADGET-3 SPH code can reproduce the spherical Bondi accretion rate properly, but with some limitations.
- Spurious heating by *Artificial Viscosity* near \( r_{\text{in}} \) & artificial outflow at \( r_{\text{out}} \) due to outer BC are problems for SPH.
- Non-spherical in/outflow develops due to *rad. feedback* via *thermal instability*, even in the simplest situation that we studied --- connection with NLR? (Paper II)
- Future work: include *rad. pressure*, rotation, diff geometry, comparison w/ NLR obs, connect with cosmological sim
Run 26: $r_{out}=200$ pc, $L_x/L_{Edd}=0.01$ ± 30 pc range (t = 2.047 Myr)

The gas density is in the top-left panel, temperature in the top-right, photoionization parameter in the bottom-left, and Mach number in the bottom-right, overplotted with the velocity vector arrows. It shows colder, denser filament-like structures, with hotter, less-dense gas in between, both components accreting in (with the colder phase moving in faster), all of which has been caused by non-spherical cooling and fragmentation. This and all the other cross-section images in this paper have been generated using SPLASH (Price 2007).

colder, denser filament-like structures due to non-spherical fragmentation.
Run 26: \( r_{\text{out}} = 200 \text{pc} \), \( \frac{L_x}{L_{\text{Edd}}} = 0.01 \)

**Zoom-in: inner 4 pc**

The panels represent gas density in the top-left, temperature in the top-right, photoionization parameter in the bottom-left, and Mach number in the bottom-right. It shows stretching of the colder clumps as they fall into the center. The remaining dense, however, get heated up at \( r < 1 \text{pc} \), mostly by adiabatic compression.

Note that the color scheme in this cross-section has been changed and it has been plotted without the velocity vectors, in order to show the small-scale features clearly.
Run 27

$r_{\text{out}}=200\text{pc}, \quad L_x/L_{\text{Edd}}=0.02$

t=1.86 Myr

$t=2.12 \text{ Myr}$

$t=2.46 \text{ Myr}$