Kinetic versus Thermal AGN Feedback in Galaxy Evolution Simulations

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AGN

• Active galaxy ⇒ Central region radiates huge amounts of energy

• Release of gravitational energy by accretion of gas onto a supermassive black hole: $M_{BH} > 10^6 M_{\odot}$

• Observe
  – Radio loud: Jets & Lobes
  – Outflows: BAL, NAL, warm absorbers

In Hydrodynamical Simulations

• Crucial ingredient in galaxy formation studies
SMBHs affect their host galaxies & the large-scale environment

- Central BH - host galaxy correlations
  - $M_{BH} - \sigma, M_{BH} - M_{bulge}$

- Impact SF in galaxies
  - Quench SF by heating up or expelling gas
  - Trigger SF by compressing cold clouds in multiphase ISM

- Sharp cutoff at the bright end of galaxy luminosity function (high-mass end of mass function)

- Galaxy - BH coevolution (self-regulated BH growth) : cosmic SFR & AGN number density both peaks at similar epoch ($z \sim 2 - 3$)

- Galaxy cluster
  - Heat up the cooling-flow
  - Pre-heating (entropy floor in cool-core clusters)

- Enrich the IGM and ICM with metals
The Feedback Loop (or not)

Gas accretion (during galaxy formation) & cooling

Trigger star-formation & AGN activity in galaxy

AGN Duty-cycle

Mergers

AGN Feedback

Shut-down star-formation & AGN

Gas of galaxy heated up &/or expelled

Self-Regulation
Challenging Problem

Small-scale sim
(e.g: Proga, Ostriker & Kurosawa 2008)

Cosmological sim
(e.g: Di Matteo, Springel & Hernquist 2005)

Large dynamic range of length scales

BH accretion:

\[ M_{\text{BH}} = 10^8 M_{\text{sun}} : R_{\text{Sch}} \sim 10^5 \text{pc} \# \quad R_{\text{sonic}} \sim 1 \quad 10\text{s pc} \# \quad R_{\text{gal}} \sim 10^3 \quad 10^6 \text{pc} \]

- Cosmological galaxy simulations cannot resolve the Sonic or Bondi radius of BH accretion flow
- Implemented as subgrid (sub-resolution) models

(10's Mpc)^3 box:
Resolution \sim 10^6 M_{\text{Sun}}, 1 \text{kpc}
Modeling AGN Feedback in (cosmological hydrodynamical) Galaxy Formation Simulations: the sub-grid physics

• Generation of seed BH, create BH particle at:
  – Center of galaxy (above limiting mass)
  – Density peak, minimum gravitational potential
  – Metal-poor environment

• BH growth
  – Accrete gas from surroundings
  – Merger with other BHs

• Feedback
  – Transfer of energy (thermal, kinetic), momentum, … from BH to surrounding gas

• BH advection
  – With time, does BH remain at the center of halo?
Accretion & Energy Feedback

- Fraction of the accreted mass energy is radiated away

\[ \dot{M}_{BH} = \frac{dM_{BH}}{dt} \] = Mass Accretion rate onto BH

\[ L_r = \varepsilon_r M_{BH} c^2 \]
\[ \varepsilon_r = 0.1 \]


- Some of the radiated energy is fed back & coupled to the surroundings

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BH Accretion Subgrid Models

- Bondi-Hoyle-Lyttleton rate
  \[
  \dot{M}_{\text{Bondi}} = \alpha \left( \frac{4 \pi G^2}{c_s^2 + v^2} \right)^{3/2} \frac{M_{\text{BH}}^2 \rho}{(c_s^2 + v^2)^{3/2}}
  \]
  \(\alpha = 100\)

- Limited to the Eddington rate
  \(\dot{M}_{\text{Edd}} = \frac{c_s^2}{\Omega} \frac{\dot{M}_{\text{vis}}}{\dot{M}_{\text{vis}}}
  \)
  \(\dot{M}_{\text{vis}} = 3 \pi \alpha \frac{c_s^2}{\Omega}
  \)

- Viscous transport of angular momentum

- Accretion disc particle method

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Figure 1. The Accretion Disc Particle Method. The accretion disc particle is a collisionless sink particle that consists of...
Energy Feedback

• Fraction of radiated energy is fed back

• Thermal feedback (Springel, Di Matteo et al. 2005, 2008)
  – Energy is coupled thermally to heat up the surrounding gas
  – Excess thermal energy decays to attain effective EOS energy
    (multiphase SF model of Springel & Hernquist 2003) on a relaxation timescale
    \[ \tau_h = \frac{t_s \rho_h}{\beta (A + 1) \rho_c} \]
  – "Quasar-mode" feedback

• Kinetic Feedback
  – Impart K.E. (Velocity kick) to gas
  – Recently implemented in Gadget-3 code
  – "Radio-mode" feedback
Kinetic Feedback

- Energy-driven wind:
  \[
  \frac{1}{2} M_w v_w^2 = \frac{\dot{E}_{\text{feed}}}{c^2} \\
  M_w = 2 \varepsilon_f \varepsilon_r \frac{c^2}{v_w^2} M_{BH}
  \]

- Momentum-driven wind:
  \[
  p_w = M_w v_w = \frac{\dot{E}_{\text{feed}}}{c} \\
  M_w = \varepsilon_f \varepsilon_r \frac{c}{v_w} M_{BH}
  \]

Free Parameters: \( \varepsilon_f \)

\( v_w = \) Wind Velocity = (2.5, 5, 10) \( \times 10^3 \) km/s

- Probabilistic method for kicking gas particles around BH

- New particle velocity
  - Along rotation axis
    \[
    \hat{n} = \hat{v} \times \vec{\nabla} \phi
    \]

- Wind particles always coupled to hydrodynamic interactions
Calibrate Model Parameters: Match \([M_{BH} - \sigma_*]\) with Observations

**Figure 1.** Black hole mass versus galaxy stellar velocity dispersion along line-of-sight. The single isolated galaxy models, shown at resolution time of 2 Gyr, are in the left panel. The merger simulations, shown at an evolution time of 2.5 Gyr, are in the right panel. Different colors and plotting symbols distinguish the AGN models as labeled in each panel. Each of the four broad categories of feedback denoted by a different color: \([th1 \ldots th3]\) thermal - red, \([kinE1 \ldots kinE3]\) kinetic EDW with \(v_w = 5000 \text{ km/s}\) - blue, \([kinE4 \ldots kinL]\) kinetic EDW with \(v_w = 10000 \text{ km/s}\) - cyan, \([kinM1 \ldots kinM4]\) kinetic MDW - green. The parameter choices are represented by plotting symbols; \(\epsilon_s = 0.002\) - asterisk, \(\epsilon_s = 0.01\) - triangle, \(\epsilon_s = 0.05\) - filled circle, \(\epsilon_s = 0.25\) - open square, \(\epsilon_p = 0.25\) - open circle, \(\epsilon_p = 1\) - open triangle.
SF-only:
Stellar Evol, Enrichment

BH Kinetic Feedback
MDW

BH Thermal Feedback

Isolated
Radial Profiles of Gas Properties in Isolated Galaxy
Merger: Kinetic Feedback, Energy-driven Wind

\[ \alpha = 100 \]
\[ \varepsilon_f = 0.25 \]
\[ v_w = 5000 \text{ km/s} \]
Radial Profiles of Gas Properties in Galaxy Merger
Mass Evolution of BH & Gas Components in Isolated Galaxy & Merger

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Summary

• Implemented BH kinetic feedback in Gadget-3 code

• Issues, possible numerical problems
  – Thermal feedback is not effective, no effect by heating the gas
    • Alternate numerical scheme needed
  – Effect by depletion of gas (creation of Hole) due to accreting into BH or ejected out by feedback
    • Impact enhanced in rotationally-supported disk galaxies, much less in cosmological simulations

Future

• Cosmological simulations
  – Include kinetic BH feedback in Cluster simulations
  – Thermal feedback in Quasar-mode & Kinetic feedback in Radio-mode

• Implement Cold Accretion (Gaspari et al. 2013)
  – BH mass accretion rate $\propto$ Cooling rate of gas (instead of Bondi rate)
Kinetic Feedback MDW: Run16-IC_vel300-KinM-v2.5k-e1.0

Higher-mass galaxy. BH kinetic feedback drives intermittent jet-like, fast outflows.

$v_w = 2500 \text{ km/s}$

$\varepsilon_f = 1.0$
Thermal Feedback:
Run15-IC_vel300-Thermal-e0.01

\[ \varepsilon_f = 0.01 \]

Higher-mass galaxy. BH thermal feedback drives slow outflows, some gas falls back.
SF-only: Stellar Evol, Enrichment

Merger

BH Kinetic Feedback

EDW

BH Thermal Feedback
Kinetic Feedback EDW: Run03-KinEnrg-v5k-e0.25

$v_w = 5000 \text{ km/s}$
$\varepsilon_f = 0.25$

Fiducial-mass galaxy. BH kinetic feedback distorts galaxies more.
SF-only: Stellar evolution, Chemical enrichment (No-BH)

Isolated Galaxy
Gas-Internal-Energy

Note outflow at t = 1.7 time units, caused by SNIa feedback in stellar evolution model of Tornatore et al. (2007)
Note multiple cold outflows (t = 1.2, 1.7 units), caused by SN feedback in stellar evolution model.
Fiducial-mass galaxy. Same SN-driven outflows visible in BH thermal feedback run.