Cosmological Simulations of AGN Feedback in Groups and Clusters: Implementation, Results and Uncertainties

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Introduction

To solve the overcooling flow problem in cosmological simulations:

- SNe heating only (e.g. Borgani, 2004)
- CRs from SNe and structure formation shocks
- thermal conduction (Jubelgas et al. 2006)
- physical viscosity (Sijacki et al. 2007)
- AGN-driven bubbles and winds

Other (related) problems:

1. Scaling relations that deviate from self-similarity
2. Gas radial profiles e.g. temperature, density
3. Metallicity gradients
4. Ages and masses of central cluster galaxies,...

Borgani, 2004
Implementation

Phenomenological BH growth and feedback models in cosmological simulations of galaxy clusters:

I MPA group:

II Leiden group:
Booth & Schaye 2009;

III French-Swiss group:
Teyssier 2011; Dubois 2010
Implementation

MPA group Tree-SPH code GADGET

- BHs: collisionless sink particles
- Black hole seeding with FOF finder on the fly:
  every halo with \( M > M_{\text{thresh}} \) acquires a central BH of mass \( M_{\text{seed}} \)
  typical choices \( M_{\text{thresh}} = 10^{10} M_\odot \) \( M_{\text{seed}} = 10^5 M_\odot \)
- BH growth:
  via mergers with other BHs (within smoothing length & \( V_{\text{rel}} < C_s \))
or via gas accretion (Bondi-like) limited to the Eddington rate

\[
\dot{M}_{\text{BH}} = \frac{4\pi\alpha G^2 M_{\text{BH}}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}} \quad \dot{M}_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_p}{\epsilon_r \sigma_T c}
\]

with \( \alpha = 100 \) volume average of Bondi rates for cold and hot ISM
Implementation

MPA group Tree-SPH code GADGET:

- BH feedback is in two modes (analogous to X-ray binaries):

1. Quasar feedback if BHAR > 0.01 x Eddington rate
   small fraction of bolometric luminosity couples THERMALLY to the surrounding gas

\[ \dot{E}_{\text{feed}} = \epsilon_f L_r = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2 \]

with \( \epsilon_r = 0.1 \) and \( \epsilon_f = 0.05 \)
- BHs are in quasar mode at high redshifts (until \( z \sim 1-2 \)), inhabiting protogroups/clusters and acquire most of their mass (i.e. Soltan's argument)
Implementation

MPA group Tree-SPH code GADGET:

1. Radio feedback if BHAR < 0.01 x Eddington rate
THERMAL bubbles (determined by the BH)

$$E_{bub} = \epsilon_m \epsilon_r c^2 \delta M_{BH}$$

with $\epsilon_r = 0.1$, $\epsilon_m = 0.2$, $\delta_{BH} = 0.01$.

$$R_{bub} = R_{bub,0} \left( \frac{E_{bub}/E_{bub,0}}{\rho_{ICM}/\rho_{ICM,0}} \right)^{1/5}$$

with $R_{bub,0} = 30kpc$, $E_{bub,0} = 10^{55}$erg, $\rho_{ICM,0} = 10^4$Msun/kpc$^3$, and $R_{bub}$ scaling derived from solutions for radio cocoon expansion.

- BHs are in radio mode at low redshifts in massive groups and clusters - "maintenance mode" regulating central gas cooling rate

EXTENSIONS:
1. viscous bubbles
2. CR bubbles
3. BH spins
4. BH recoils
Implementation

Leiden group (Joop Schaye):

Similarities:
1. Based on the same code GADGET
2. Based on the same model for BH growth and feedback

Differences:
1. Due to different EOS Bondi-like prescription has 2 parameters, with $\alpha$ depending on local gas density to some power $\beta$ (no difference in cosmological simulations)
2. Only quasar feedback prescription (no radio mode)
3. Energy in quasar mode not injected continuously but stored until temperature of the surrounding particles can be increased by $10^8 K$
Implementation

French-Swiss group (Roman Teyssier):

Similarities:
1. Based on the same model for BH growth and feedback

Differences:
1. Implemented in grid-based code RAMSES
2. Different seeding prescription (based on gas & stellar density and stellar velocity dispersion)
3. Only quasar feedback prescription (no radio mode) as Schaye

Dubois 2010: AGN feedback is sub-relativistic bipolar outflow - mass, momentum and energy deposition in a small cylinder
Results

MAP OF A GALAXY CLUSTER AT Z = 1 WITH OVERPLOTTED BHs
Results:

Statistical properties

Sijacki et al.

Resimulation at very high resolution of 21
Millennium clusters with gas & BH physics – mass resolution increased by up to 64 times
range of halo masses: $8 \times 10^{12} - 1.5 \times 10^{15}$ Msun/h

TEMPERATURE PROFILES
Results:

Statistical properties


\[ \text{fgas} - T500 \text{ SCALING RELATION} \]

\[ \text{Lx} - T \text{ SCALING RELATION} \]
Results:

BCG, satellites and ICL


BCG LUMINOSITIES

BCG STAR FORMATION EPOCH

DOWN-SIZING
Results:

BCG, satellites and ICL

Puchwein, Springel, Sijacki & Dolag 2010, MNRAS

FRACTION OF IC STARS

TOO MUCH IC STARS:
- AGN feedback not efficient enough in small mass galaxies?
- intracluster star formation within “cold blobs” which are stripped from infalling galaxies?
Results

The cosmological results of all three groups qualitatively agree:

Similarities:
1. AGN feedback is energetic enough to offset overcooling
2. Central gas density is decreased
3. Lower SFR in massive galaxies
4. Stellar mass of the BCG significantly reduced
5. Lower baryon fraction within Rvir

Differences:
1. No significant differences between MPA and Leiden group (not too surprising)
2. Hard to quantify detailed differences between Teyssier's group and others: they have only one high resolution object!
3. But, ...
Results

...There are differences between Teyssier and Dubois AGN feedback implementation (Dubois2011)
Uncertainties in...

...Physical mechanisms that should occur on widely different scales: how to incorporate them faithfully in fully cosmological simulations?

- Sub-grid models need higher level of sophistication
- Much more powerful computing could breach the gap between (some of) these length-scales
Uncertainties in...

...Physical mechanisms that *do probably* occur but we don't know their magnitude/parametrization

Observational multiwavelength input is essential!
- Detailed comparisons with well studied cases
- Statistical comparisons over a range of redshifts

**VISCOSITY**
- Reynolds et al., Ruszkowski et al., Sijacki et al., Dona et al.

**THERMAL CONDUCTION**
- Balbus et al., Jubelgas et al., Parrish et al., Bogdanovic et al.

**BH MERGING - RECOILS**
- Escala et al., Cuadra et al., Merritt et al., Sijacki et al.

**MHD JETS and BUBBLES**
- Xu et al., Ruszkowski et al., O’Neill et al., Robinson et al., Dursi et al.

**COSMIC RAY BUBBLES**
- Guo et al., Sijacki et al., Ruszkowski et al.
Uncertainties in...

...Hydro and gravity solvers of different codes used to simulate galaxy clusters

- Much more careful code comparisons are needed!
- Improvements in basic code solvers

Eulerian mesh-based codes (+ AMR)
- Eulerian mesh-based codes (+ AMR)
- FLASH
- RAMSES
- ART

Lagrangian particle-based Codes (SPH)
- Lagrangian particle-based Codes (SPH)
- HYDRA
- GASOLINE
- GODUNOV SPH
- GADGET
Non-radiative cosmological hydrodynamical simulations

12 codes

SPH simulations: power-law entropy profiles

GRID-based simulations: cored entropy profiles
Discrepancy between SPH and grid entropy profiles

What causes this discrepancy???

- lower effective resolution of grid codes?
- different gravity solvers?
- Galilean non-invariance of grid codes?
- artificial viscosity of SPH codes?
- treatment of fluid instabilities?
- gravitational N-body noise?
- ???

FUNDAMENTAL IMPLICATIONS FOR:
- UNDERSTANDING ASTROPHYSICS OF GALAXY CLUSTERS
- USING GALAXY CLUSTERS AS HIGH-PRECISION COSMOLOGICAL PROBES
Our approach

**GADGET** (Springel et al. 2001, 2005)
Lagrangian method (SPH)
particles act as fluid elements

**AREPO** (Springel et al. 2010)
finite volume method on a moving mesh (Lagrangian nature)

**ADVANTAGES:**
- identical initial conditions
- identical gravity solver

**PHILOSOPHY:**
device as simple as possible numerical tests to isolate different physical/numerical effects and gauge their importance
Inflow of cold gas into a static potential: Strong shock

- NO GAS SELF-GRAVITY, NO COOLING
- STATIC HERNQUIST DM POTENTIAL
- RADIAL INFALL OF COLD GAS

Graph showing the relationship between $S/T/\rho^{2/3}$ and $r$ [kpc].
Infall of two cold gas spheres into a static potential: interacting shocks and fluid mixing

- NO GAS SELF-GRAVITY, NO COOLING
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Infall of two cold gas spheres into a static potential: interacting shocks and fluid mixing

MORE ACCURATE FLUID INSTABILITIES AND MIXING IN AREPO LEAD TO HIGHER CENTRAL ENTROPY
Bow shock in 3D

“BLOB” experiment (Agertz et al. 2007):

- high density blob in pressure equilibrium with surrounding hot medium
- external medium velocity = 1000 km/s

Tests:
- development of dynamical instabilities, such as RT and KH

Implications for:
- survival of satellites in clusters
- mixing of multi-phase medium
- level of turbulence
“Generalized Blob” Test

- ten dense blobs moving through the hot halo atmosphere:
  NO COOLING \[ P_{\text{BLOB}} \sim 0.01 \times \max(P_{\text{ICM}}) \]
  NO ROTATION
“Generalized Blob” Test

- ten dense blobs moving through the hot halo atmosphere:

NO COOLING
NO ROTATION

DIFFERENT STRIPPING IN AREPO LEADS TO DIFFERENT ORBITS OF THE BLOBS AND DIFFERENT DISIPATION DUE TO STIRRING MOTIONS

\[ S \sim T/\rho^{2/3} \]
Inflow of cold gas into a static potential: Strong shock

- NO GAS SELF-GRAVITY, NO COOLING
- STATIC HERNQUIST DM POTENTIAL → LIVE HALO
- RADIAL INFALL OF COLD GAS

GAS DENSITY DIFFERENCE MAP:
LIVE HALO – STATIC HALO
Inflow of cold gas into a static potential: Strong shock

AREPO MUCH MORE AFFECTED BY GRAVITATIONAL N-BODY NOISE, WHICH LEADS TO OVERPRODUCTION OF ENTROPY
**Conclusions**

*AGN are a key ingredient in cosmological structure formation*

- Great progress in the last couple of years in incorporating BH growth and feedback processes in fully cosmological simulations

- Not only galaxy cluster properties with AGN are much more realistic, but also the same models reproduce BH-galaxy scaling laws, BH mass density at $z = 0$, and even brightest quasars at $z = 6$!

- Results of three independent groups in good qualitative agreement: => coherent picture, but detailed understanding still lacking

- For a new breakthrough in the field improved numerical modelling is needed: more sophisticated codes, detailed code comparisons, ambitious simulation programs (exascale!), and careful comparison with observational data