Hydrodynamic Models of AGN Feedback in Cooling Core Clusters

Dissertation Defense

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05/15/2008

Outline

- The Cooling Problem in Clusters
  - AGN Feedback
- Three Sets of Simulations:
  1. Parameter Survey of Jets
  2. The Failure of Simple Feedback Models
  3. Precessing Jet Models
- Conclusions/Future Directions

Background

- The Intracluster Medium (ICM) in rich relaxed clusters is cooling, primarily in X-ray.
- Central cooling times shorter than the age of the cluster, but strong observational limits on the amount of cool gas.
- Nothing below $\sim \frac{1}{3} T_{virial}$ (from XMM-Newton observations).
- This is the Cooling Flow Problem.
- Together, these observations suggest the need for a heating source.

Formation Processes

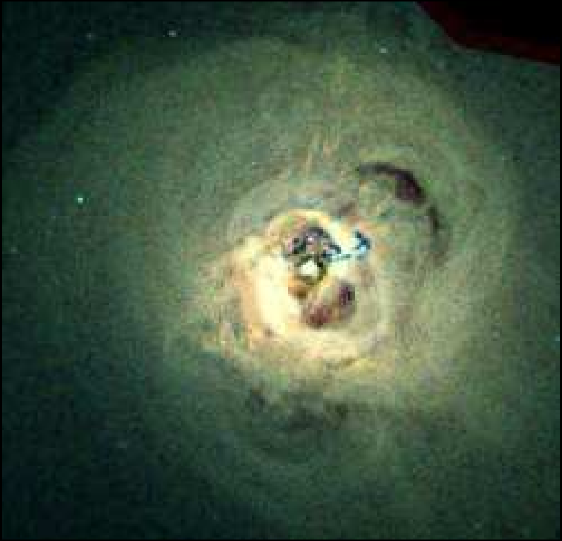
This appears to be a way that Black Holes can affect their environment on very large scales.

- In the standard picture, "cold" baryonic gas should follow the developing dark matter halo of the cluster.
- The cutoff in the high end of the galaxy luminosity function shows this is not the case.
- Can feedback from a central supermassive black hole account for this?

Background – AGN jets

- Powerful, with right energy to balance cooling (but see Bîrzan et al. 2004 for possible problems with this idea).
- Often in cluster centers, just where heating is needed.
- But how exactly does this heating work?
- Is the efficiency enough and is the heating spatially distributed properly?

AGN Impact on the ICM



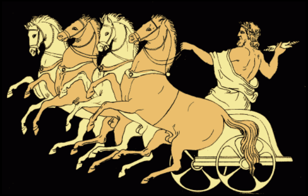
Perseus A, Fabian et al. 2005

Our Models

A series of models to assess the efficiency and spatial distribution of heating from AGN jets under the assumption of ideal hydrodynamics.

- Initially cluster is spherically symmetric, isothermal, and hydrostatic.
- β-model atmosphere with static potential.
- Supersonic, underdense jet injected on the inner boundary.
- Radiative Cooling.

Modified Public Hydro Code



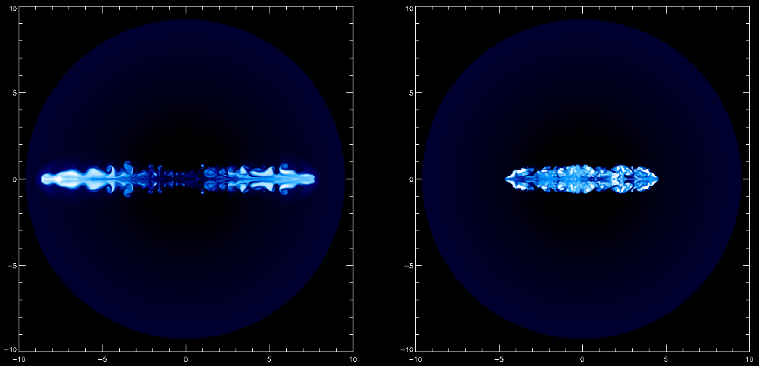
- Modified and updated version of FORTRAN 77 NCSA release.
- ZEUS-MP v1.5.13
- `http://www.astro.umd.edu/~vernaleo/zeusmp.html`

1. Parameter Survey of Jets

We can cheaply study a wide range of jet parameters in 2D (axisymmetric) models.

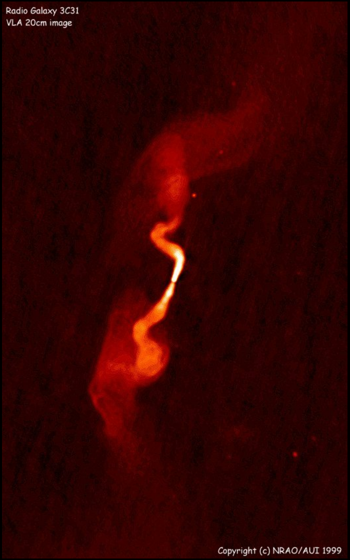
- High resolution.
- Can compare evolution of jet inflated structures ("cocoons") and energetics with jet parameters.

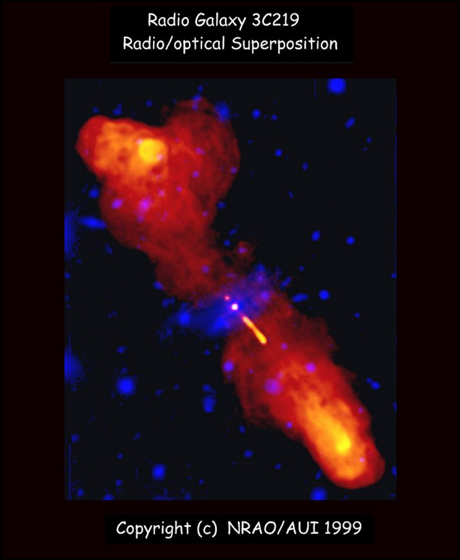
Non-Cocoon or Cocoon?



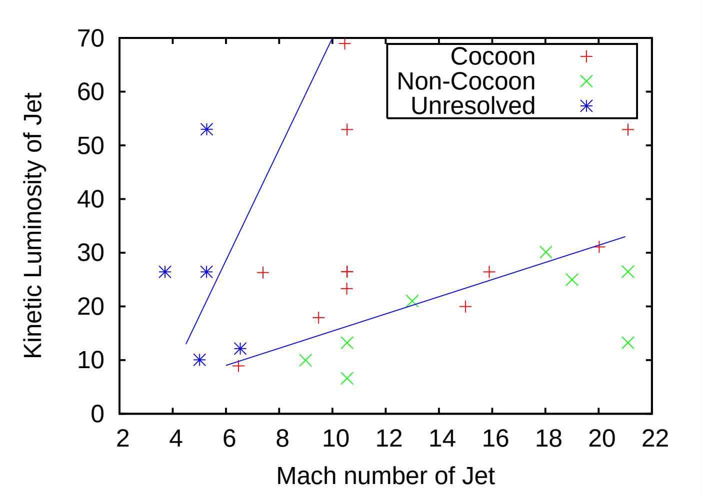
Entropy Maps

FR I and FR II radio galaxies

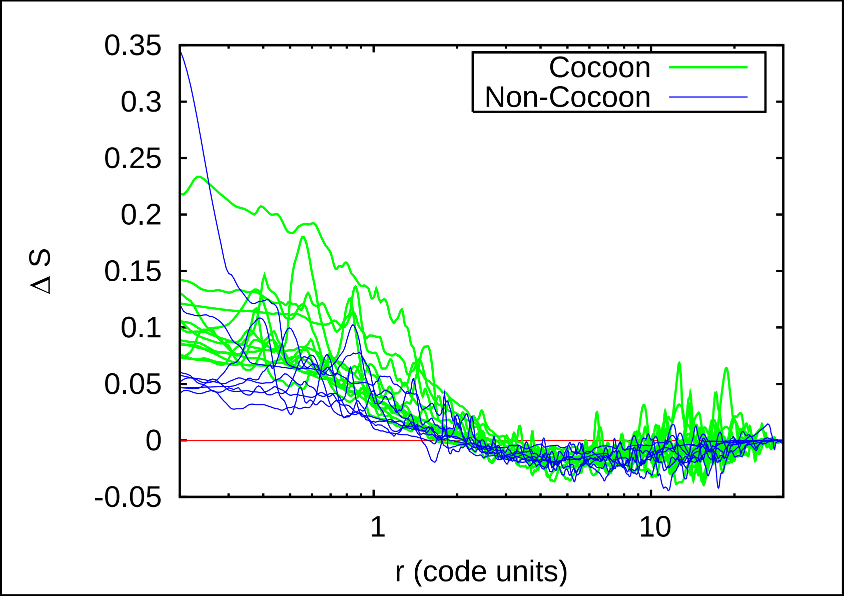




Separate Regions of Parameter Space



Total Entropy Change vs. Radius



Summary of Parameter Survey

- Jet inflated structures fall into two morphological classes.
- Connection to FR I/II divide?
- Cocoons efficient at changing central entropy.
- Jets efficient at thermalizing energy, but it mostly goes into potential.

2. Feedback Models

How does the AGN know how powerful to be? Can we couple the jets to the cooling ICM and close the feedback loop?

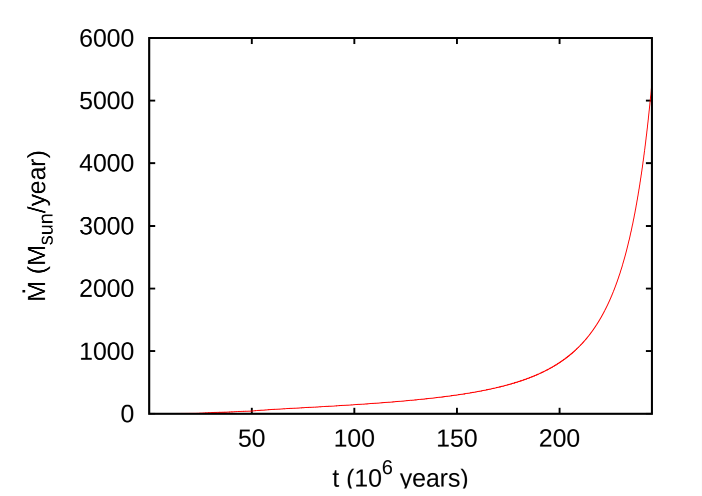
- Single Jet.
- Inject a jet with $L_{kin} \propto \dot{M}$.
- Delayed Feedback.
- Simplest way to connect ICM to jet power with minimal assumptions.

Delayed Feedback

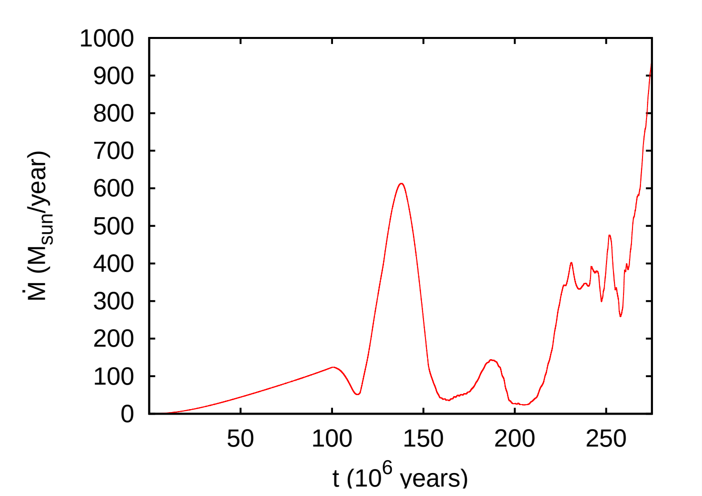
$$v_{jet} = \left(\frac{2\eta \dot{M} c^2}{A\rho} \right)^{\frac{1}{3}}$$

We introduce a delay (100 Myrs which is the dynamical time of the cluster center) between v_{jet} and $\dot{M}$.

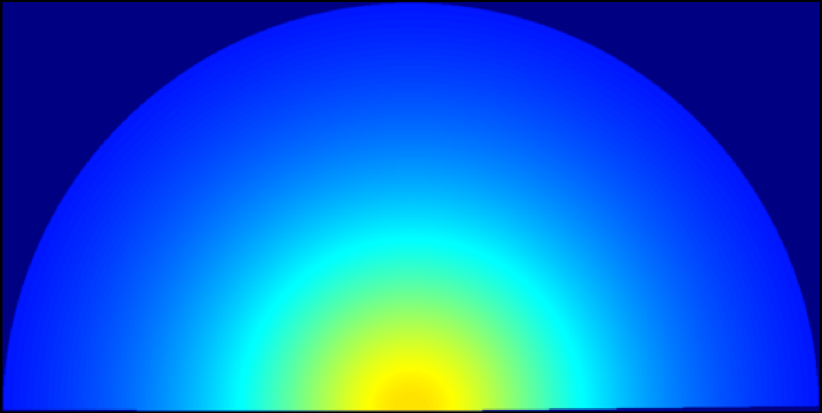
Pure Cooling – Mass accretion on inner boundary



Delayed Feedback – Mass accretion on inner boundary



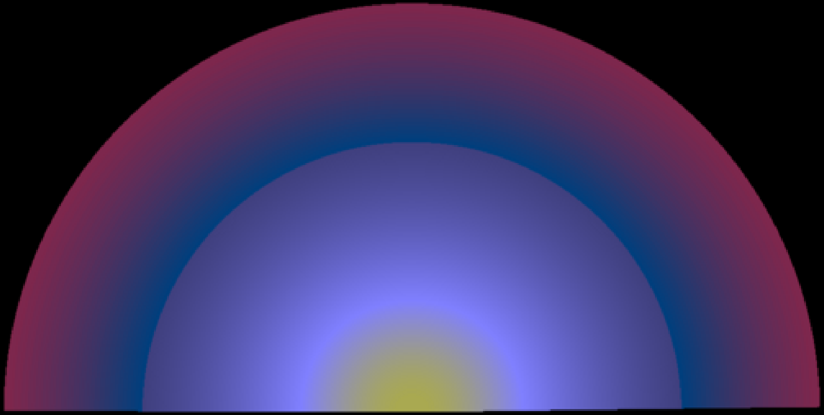
Channel Formation and the Failure Mode of Feedback Models



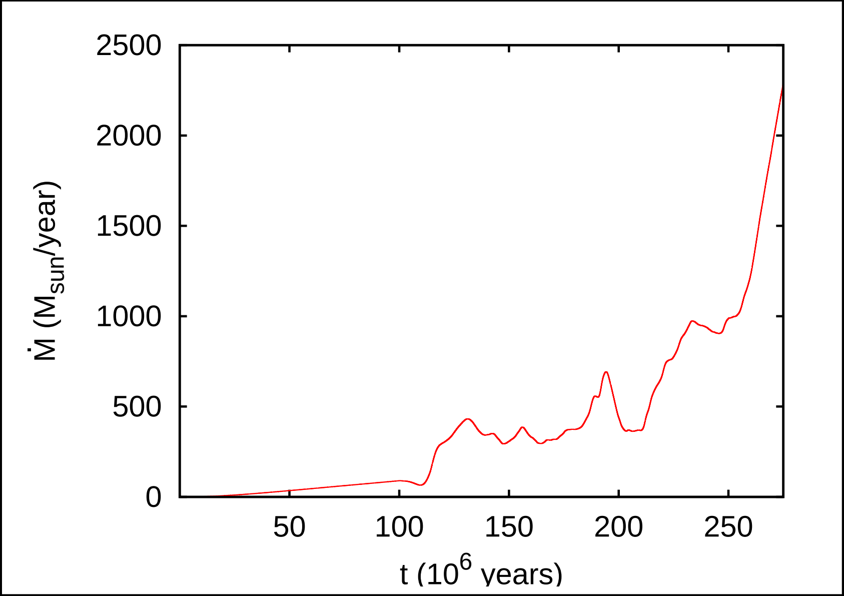
3. Precessing jets

- Vary the jet axis.
- This will break the symmetry that caused the channels in our previous work.
- Evidence for this in Perseus (Dunn et al. 2006).
- Large (45°) precession angle.

Precessing Jet – Density slice



Precessing Jet – Mass accretion on inner boundary



Still no stable solution.

- Basically get the same result for all $\dot{M}$ based feedback cases.
- Even without channel formation, cooling proceeds.
- Jet would need to cover entire range of angles in less than cooling time for central gas.
  - Seems unlikely.
- Hard to couple (powerful) jets to ICM core gas in ideal hydro.

Energy Localization

Calculate:

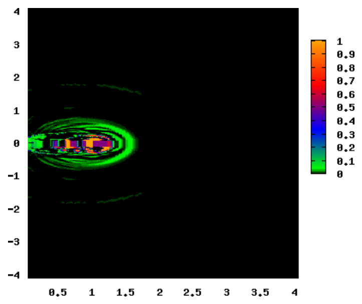
$$E_{tot} = \frac{1}{2}\rho v^2 + e_{int} - \rho\Phi$$

and difference

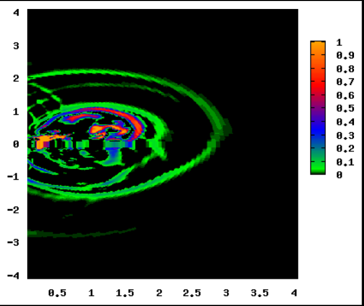
$$E_{tot\_\mathrm{t}} - E_{tot\_\mathrm{t}-1}$$

Sound Waves

Fixed



Precessing

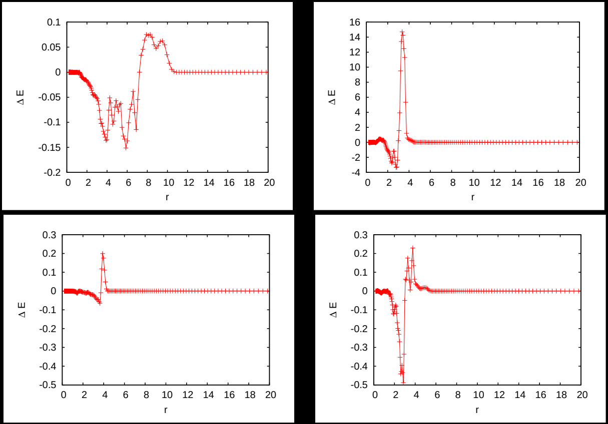


Energy in Angular Slices

Fixed | Precessing

inner ($\theta \leq 60^\circ$)

outer ($\theta > 60^\circ$)



Waves are an Energy Sink

- Need something to capture sound wave energy.
- In ideal hydro, too much of the AGN power is lost from the system in these waves since they cannot dissipate.
- We need other plasma processes in the gas to do this.

Missing ICM Physics

- Viscosity:
  - Intact bubbles in Perseus show some evidence for this.
  - Reynolds et al. 2005 did some simulations of this.
- Thermal Conduction
  - Conduction at some fraction of Spitzer value.
  - Bring heat from outer regions in.
  - Dissipate wave energy.
  - If conduction can help us tap the wave energy before it leaves the core, a stable balance should be possible (See Fabian et al. 2005).
- Magnetic Fields?
- Turbulence

Conclusions

- Jets have a major impact on the ICM, both thermal and in gross features.
- Bubble models not sufficient.
- We are unable to balance cooling by coupling jet power to cooling gas under ideal hydrodynamics.
- Jets excite lots of sound waves and weak shocks, but that energy is lost, with precessing jets driving more energy in waves.
- Possible solution in thermal conduction combined with sound waves.