# AGN Heating of Cooling Flow Clusters: Problems with 3D Hydrodynamic Models

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## Abstract

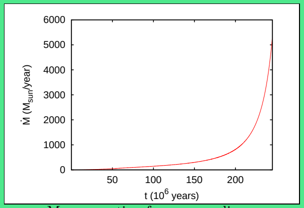
Numerous observations indicate that AGN (Active Galactic Nuclei) can have an impact on large scale structure and galaxy formation. We have performed a set of high resolution, three dimensional simulations of a jetted AGN embedded in a relaxed cooling cluster (Vernaleo and Reynolds 2006). These ideal hydrodynamic simulations show that, although there is enough energy present to offset cooling on average, the jet heating is not spatially deposited in a way that can prevent catastrophic cooling of the cluster.

## Background

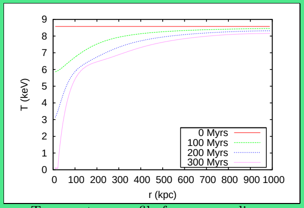
- Galaxy clusters have central cooling times less than the age of the cluster.
- There are observational limits to the amounts of cool gas that is present, and XMM-Newton spectroscopy shows nothing below around $\frac{1}{3}T_{virial}$ $(1-2keV)$.
- Galaxy luminosity function is truncated at the high end (Benson et al. 2003).
  - So whatever offsets cooling probably stops the formation of massive galaxies.
- This occurs on many mass and temperature scales: must have some self regulation.
- AGN are often given as a possible solution.
  - AGN inject energy on the same order as cooling luminosity ($\sim 10^{45}-10^{46}$ erg $s^{-1}$).
  - Fed by accretion, so self regulation may come naturally.

## Pure Cooling

Initial cluster is modelled after a rich, relaxed cluster with a $\beta$-law density profile: $r_{core} = 100\,\mathrm{kpc}$, $n_0 = 0.01\,\mathrm{cm}^{-3}$, and $c_s = 1000\,\mathrm{km\,s}^{-1}$. Cooling is thermal bremsstrahlung following Ruszkowski and Begelman (2002).



Mass accretion for pure cooling.



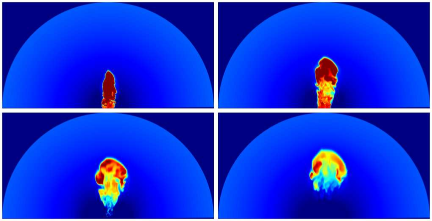
Temperature profile for pure cooling.

Due to $n^2$ dependence of ICM cooling, in the absence of any feedback, cooling runs away. It gets to a level we set as 'catastrophic' by around 250 Myrs.

## Types of Feedback

1. Single Jet
   - Single outburst lasting 50 Myrs.
2. Immediate Feedback
   - Jet power depends on $\dot{M}$ at each timestep.
3. Delayed Feedback
   - Jet power depends on $\dot{M}$, but with a delay introduced.
4. Extreme Feedback
   - Like delayed feedback, only with maximum possible efficiency ($\eta = 0.1$).

## Single Jet



Entropy for single jet simulation.

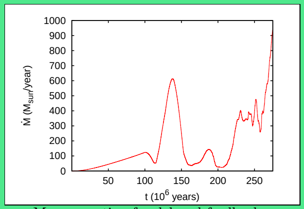
Single jet with kinetic luminosity of $L_{kin} = 9.3 \times 10^{45}$ erg $s^{-1}$ for the Mach 10.5 jet (see also Reynolds et al. (2002)) delays catastrophic cooling by about 50 Myrs.

## Feedback

Mass flow across inner boundary was calculated and used to set a jet velocity assuming some efficiency $\eta$ of the central blackhole.

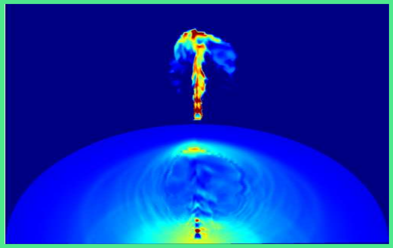
$$v_{jet} = (\frac{2\eta \dot{M} c^2}{A\rho})^{\frac{1}{3}}$$

Most realistic model seems to be low efficiency ($\eta = 10^{-4}$) and a delay of 100 Myrs (close to the dynamical time for the galaxy). Even this only delays the cooling catastrophe.



Mass accretion for delayed feedback.

The jets seem to cut channels in the ICM which allow them to avoid heating the inner region. This explains why simulations with bubbles placed in the center can do better at halting cooling, but are less realistic.



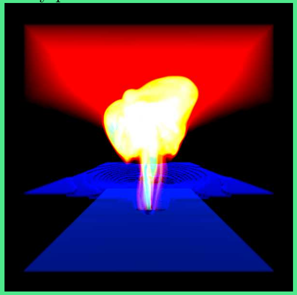
Channel formation in feedback simulation (Temperature (top) Pressure (bottom)).

## Conclusion

When the full dynamics of the jet are included, ideal hydrodynamics interactions do not seem able to offset cooling on average, even though they are energetically capable of doing so. We conclude that either some physical process beyond that captured by our ideal hydrodynamic simulations (e.g., plasma transport processes, cosmic ray heating, dramatic jet precession, or ICM turbulence) is relevant for thermalizing the AGN energy output, or the role of AGN heating of cluster gas has been overestimated.

## Current Extensions

We are currently adding thermal conduction, precessing jets, and magnetic fields to our models, motivated by parameters from the Perseus cluster.



Entropy map for preliminary version of precessing jet.

## ZEUS-MP

All simulations were done using a the ZEUS-MP 3D, parallel hydrocode (a version of the code in Stone and Norman (1992a,b)) for clusters. We have updated and modified the NCSA release. Our modifications and documentation are publicly available at: `http://www.astro.umd.edu/~vernaleo/zeusmp.html`

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