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

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1 Introduction

Relaxed galaxy clusters have central cooling times less than the age of the cluster. However, there are observational limits to the amounts of cool gas present, and XMM-Newton spectroscopy shows nothing below $\sim \frac{1}{3}T_{\text{virial}} (1-2keV)$. This discrepancy is the heart of the classical cooling flow problem.

Viewed from another angle, the galaxy luminosity function is truncated at the high end [1]. So whatever offsets cooling probably also stops the formation of massive galaxies. This must occur on many mass and temperature scales: therefore some self regulation seems to be required. AGN (Active Galactic Nuclei) are often given as a possible solution. AGN inject energy on the same order as cooling luminosity ($\sim 10^{45}-10^{46}$ erg s$^{-1}$). They are fed by accretion, so self regulation may come naturally.

Numerous observations indicate that AGN can have an impact on large scale structure. We have performed a set of high resolution, three dimensional simulations of a jetted AGN embedded in a relaxed cooling cluster [5]. To the best of our knowledge, these are the first simulation to include both full jet dynamics and a feedback model. 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.

2 Models

For comparison, we start with a pure cooling cluster. All other clusters start with the same, with some additional effects added. The initial cluster is modelled after a rich, relaxed cluster with a $\beta$-law density profile: $r_{\text{core}} = 100$ kpc, $n_0 = 0.01$ cm$^{-3}$, and $c_s = 1000$ km s$^{-1}$. The cooling is modelled as thermal bremsstrahlung emission, following [3]. Due to $n^2$ dependence of the ICM cooling, in the absence of any feedback, cooling runs away, showing a featureless increase with time. It gets to a level we set as ‘catastrophic’ by around 250 Myrs.

We added several types of feedback to our models. The first type is a single jet outburst lasting 50 Myrs. To model actual feedback, the velocity of
the jet (and hence the kinetic luminosity of the source) was varied based on \( \dot{M} \) across the inner edge of the simulation. This was done with various time delays (up to 100 Myrs) and efficiencies (\( \eta = 0.00001 - 0.1 \)).

For the single burst jet, with a kinetic luminosity of \( L_{\text{kin}} = 9.3 \times 10^{45} \text{ erg s}^{-1} \) and a Mach 10.5 jet (see also [2]), catastrophic cooling was delayed by about 50 Myrs. The results of this simulation (which show the bubble the jet inflates) can be seen in Figure 1.

**Fig. 1.** Entropy for single jet simulation.

For feedback, mass flow across inner boundary was calculated and used to set a jet velocity assuming some efficiency \( \eta \) of the central blackhole using the formula \( v_{\text{jet}} = (\frac{2M_c}{\dot{M}})^{\frac{1}{2}} \).

The most realistic model seems to be the low efficiency (\( \eta = 10^{-4} \)) model with a delay of 100 Myrs (close to the dynamical time for the galaxy). Even this only delays the cooling catastrophe (see Figure 2 for mass accretion rates).

**Fig. 2.** Mass accretion for delayed feedback.

The jet seems to cut a channel (see Figure 3) in the ICM which allows it to avoid heating the inner regions. This explains why simulations with bubbles placed in the center can do better at halting cooling than jets, but are less realistic.

**Fig. 3.** Channel formation (Temperature (top) Pressure (bottom)).
3 Conclusions

We have preformed the first simulations that we are aware of to include both the full dynamics of a jet and an feedback model. 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.

4 ZEUS-MP

All simulations were done using the ZEUS-MP 3D parallel hydrocode (a version of the code in [4]). We have updated and modified the NCSA release (v1.0). Our modifications (v1.5) and documentation are publicly available at: http://www.astro.umd.edu/~vernaleo/zeusmp.html There is also a version 2 of ZEUS-MP which we are not affiliated with.

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References

1. A. J. Benson, R. G. Bower, C. S. Frenk, C. G. Lacey, C. M. Baugh, and S. Cole. What Shapes the Luminosity Function of Galaxies? *ApJ*, 599:38–49, December 2003.
2. C. S. Reynolds, S. Heinz, and M. C. Begelman. The hydrodynamics of dead radio galaxies. *MNRAS*, 332:271–282, May 2002.
3. M. Ruszkowski and M. C. Begelman. Heating, Conduction, and Minimum Temperatures in Cooling Flows. *ApJ*, 581:223–228, December 2002.
4. J. M. Stone and M. L. Norman. ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. I - The hydrodynamic algorithms and tests. *ApJS*, 80:753–790, June 1992.
5. J. C. Vernaleo and C. S. Reynolds. AGN Feedback and Cooling Flows: Problems with Simple Hydrodynamic Models. *ApJ*, 645:83–94, July 2006.