Radio Galaxy Heating of Cooling Flow Clusters: Problems with Pure Hydrodynamic Models

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Abstract

Rich relaxed, clusters of galaxies cool, preferentially in the inner regions. Observationally however, there are strong limits to the amount of gas that could have cooled. Some form of heating (or some way to suppress cooling) is needed to reconcile these two observational facts. Energetic AGN are often viewed as a way to provide this heating. Most work indicates that they can provide enough energy to offset cooling. We have done a set of high resolution, three dimensional simulations that show that in the case of purely hydrodynamical AGN jets, although there is enough energy present, it is not spatially deposited in a way that can prevent catastrophic cooling of the cluster. We conclude that either some other physics (e.g., plasma transport processes or cosmic ray heating) is relevant for thermalizing the AGN energy output, or the role of AGN heating has been overestimated.

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.
- XMMS spectroscopy shows nothing below around $\frac{1}{3}T_{virial}$ $(1-2keV)$
- Massive galaxies have a maximum size and are not still forming.
  - So whatever offsets cooling probably stops the formation of massive galaxies.
- Since this occurs on many mass and temperature scales, mechanism 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.

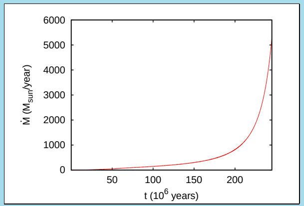
Thermal Bremsstrahlung Cooling

$$\Lambda = [C_1(k_BT)^\alpha + C_2(k_BT)^\beta + C_3]0.704\,(\frac{\rho}{m_p})^2 \times 10^{-22} \text{ ergs cm}^{-3}s^{-1}$$

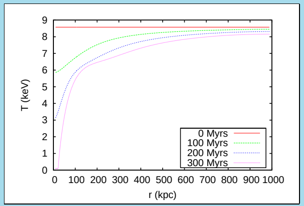
with $C_1 = 8.6\times10^{-3}$, $C_2 = 5.8\times10^{-2}$, $C_3 = 6.4\times10^{-2}$, $\alpha = -1.7$, and $\beta = 0.5$. This is the same cooling function used by Ruszkowski and Begelman (2002).

Pure Cooling

Thanks to n^2 cooling law, cooling runs away. It gets to a level we set as 'catastrophic' by around 250 Myrs.



Mass accretion for pure cooling.

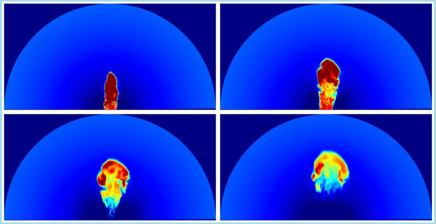


Temperature profile for pure cooling.

Types of Feedback

1. Single Jet
2. Immediate Feedback
3. Delayed Feedback
4. Extreme Feedback
5. Rotation

Single Jet



Entropy for single jet simulation.

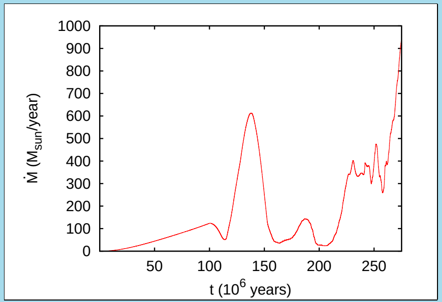
Single jet with kinetic luminosity of $L_{kin} = 9.3\times10^{45}$ erg s^{-1} for the Mach 10.5 jet (see also Reynolds et al. (2002)) delays catastrophic cooling by about 50 Myrs.

Feedback

Mass flow across inner boundary was calculated and used to set a jet velocity assuming some efficiency η 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.



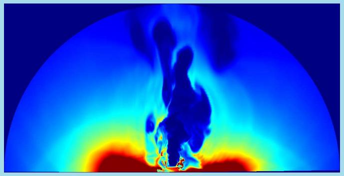
Mass accretion for delayed feedback.

Extreme Cases

Simulations were done with $\eta = 0.1$ and $\eta = 0.01$ for completeness. Both of these are far too high to be reasonable (0.1 is the theoretical maximum energy extraction). These were able to delay cooling for an extended period of time (finally falling below our cooling limit at 400 Myrs in the perfect case), but were not able to completely offset cooling, and only worked at he expense of highly unrealistic looking AGN cocoons.

Rotation

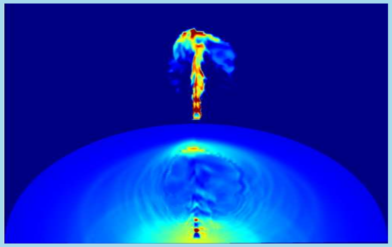
Several simulations were done with some background rotation of the ICM. In the one case where the rotation was fast enough to change the result, very little material crosses the inner boundary due to angular momentum. The cool, high angular momentum material forms a disk around the central galaxy.



Density in the inner regions of cluster with rotation.

Energy Deposition

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

We have done high resolution, three dimensional hydrodynamical simulations of jets in a cooling flow cluster. We find that when the full dynamics of the jet are included, hydrodynamic jets do not offset cooling on average, even though they are energetically capable of doing so.

ZEUS-MP

All simulations were done using a the ZEUS-MP 3D, parallel hydrocode (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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