3D Numerical Simulations of AGN Outflows in Clusters and Groups

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Abstract. We compute 3D gasdynamical models of jet outflows from the central AGN, that carry mass as well as energy to the hot gas in galaxy clusters and groups. These flows have many attractive attributes for solving the cooling flow problem: why the hot gas temperature and density profiles resemble cooling flows but show no spectral evidence of cooling to low temperatures. Subrelativistic jets, described by a few parameters, are assumed to be activated when gas flows toward or cools near a central SMBH. As the jets proceed out from the center, they entrain more and more ambient gas. Using approximate models for a rich cluster (A1795), a poor cluster (2A 0336+096) and a group (NGC 5044), we show that mass-carrying jets with intermediate mechanical efficiencies ($\sim 10^{-3}$) can reduce for many Gyr the global cooling rate to or below the low values implied by X-spectra, while maintaining T and ρ profiles similar to those observed, at least in clusters. Groups are much more sensitive to AGN heating and present extreme time variability in both profiles. Finally, the intermittency of the feedback generates multiple generations of X-ray cavities similar to those observed in Perseus cluster and elsewhere. Thus we also study the formation of buoyant bubbles and weak shocks in the ICM, along with the injection of metals by SNIa and stellar winds.

Keywords: cooling flow, galaxy clusters, groups, AGN, jet outflows, ICM, X-rays, 3D simulations
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INTRODUCTION

XMM and Chandra spectra of hot gas in galaxy groups and clusters fail to detect line emission from gas having low temperatures ($T < T_{vir}/2$), implying the cooling rate is at least 5-10 times less than previously assumed ([1]) . The currently most popular explanation for the absence of detectable cooling is that the hot gas is being heated by the central AGN ([2]). Thus, in order to solve the cooling flow (CF) problem we compute a large number of evolutionary models of gas flows, heated mainly by AGN outflows, in which gas near the core of cD elliptical galaxies is accelerated in bipolar subrelativistic "jets", when triggered by a SMBH feedback mechanism. Both mass and energy are transported out from the center. An inspiration for this work are HI ([3]), UV ([4]) and X-ray ([5]) observations of AGNs, showing blue-shifted absorption or emission lines along the line of sight. The outflow velocity is typically several 100-1000 km s^{-1}. At least half of all AGNs exhibit outflows so it is plausible that they exist in all objects and with substantial covering factors.

The most realistic feedback seems to be linked to the amount of cooled gas which accretes in the center, so that the total power injected is $P_{jet} = \varepsilon \, \dot{M}_{cool} \, c^2$. The mechanical efficiency, ε, is the free parameter: it varies in the range $10^{-1} \div 10^{-5}$ and represents all the unknown physics behind AGN outflows (BH accretion, gas entrainment, etc.).

NUMERICAL SIMULATIONS

We used a modified version of YGUAZÚ-A, a 3D AMR (adaptive mesh refinement) code, which solves the hydrodynamic equations through the "flux vector splitting" of Van Leer (1982), and is described in [6]. The simulations start with the hot gas in hydrostatic equilibrium in the potential well generated by a NFW dark halo plus the deVaucoleaurs profile of a cD galaxy. The temperature profile is set to agree with observations and the density profile is calculated from hydrostatic equilibrium equation. The finest grids have resolution of 1-2 kpc, and every model is evolved for 3 Gyr. Radiative cooling is included assuming a metallicity of 0.3 $Z_\odot$ (clusters) or 1 $Z_\odot$ (group). Cooled gas is removed by adding a mass sink term to the continuity equation: $-q(T)r/t_{cool}$ (as described by [7]); this term is used to remove the unphysical clutter of zones containing cold gas without affecting the hotter flow. The outflow, activated when gas cools near the SMBH, is generated by imposing momentum and kinetic energy to the gas located in a small central cylindrical region (few kpc). We also consider SNIa and stellar winds in the central elliptical galaxy to estimate metal enrichment.

The objects chosen for the simulations are rich cluster A1795 ($M_{vir} \sim 10^{15}$ $M_\odot$), poor cluster 2A 0335+096 ($\sim 2 \times 10^{14}$ $M_\odot$) and galaxy group NGC 5044 ($\sim 4 \times 10^{13}$ $M_\odot$).

Radial Profiles and Cooling Rates

***Rich and Poor Cluster*.**
In Fig.1 we show that, without heating (solid lines), a classical CF is soon established in all two systems; the cooling rate approaches ~ 300 $M_\odot$ yr^{-1} after ~ 1 Gyr, which greatly exceeds the observed upper limit. The ρ and T profiles move away from the observed ones. The classical model is clearly unacceptable. On the other hand, models with heating illustrate the fundamental characteristic of AGN heated cooling flows. When the heating is very strong ($\varepsilon = 10^{-1}$, long dash), it can significantly reduce the cooling rate under 1% of pure CF, but the temperature in the central regions gets too high and has the wrong gradient (negative). Conversely, when the heating is weak ($\varepsilon = 10^{-5}$, dot - long dash) , the T profile is less disturbed, but the cooling rate is not reduced by much ($\sim 90\%$). However, when we set an intermediate mechanical efficiency ($\varepsilon = 10^{-3}$, dot - short dash), we are able to find acceptable models, which means not perfect data overlap, but a good trend in density and temperature. Indeed, in these good models with a mean jet velocity of ~ 5000 km s^{-1}, ρ is not too peaked and T not too shallow, compared to pure CF. Finally, another interesting feature are the weak shocks at distant radius (the so-called "ripples", seen by [8]).

***Group*.**
A first analysis reveals that the simulated pure CF has a T profile very similar to that observed in NGC 5044. That means the AGN heating does not have to be so dominant, like in clusters. So, when we inject AGN outflows, the heating seems to be always too little or too much. When $\varepsilon = 10^{-5}$ the flow differs little from the standard CF, except for fluctuations that accompany the heating episodes. The cooling rate is not

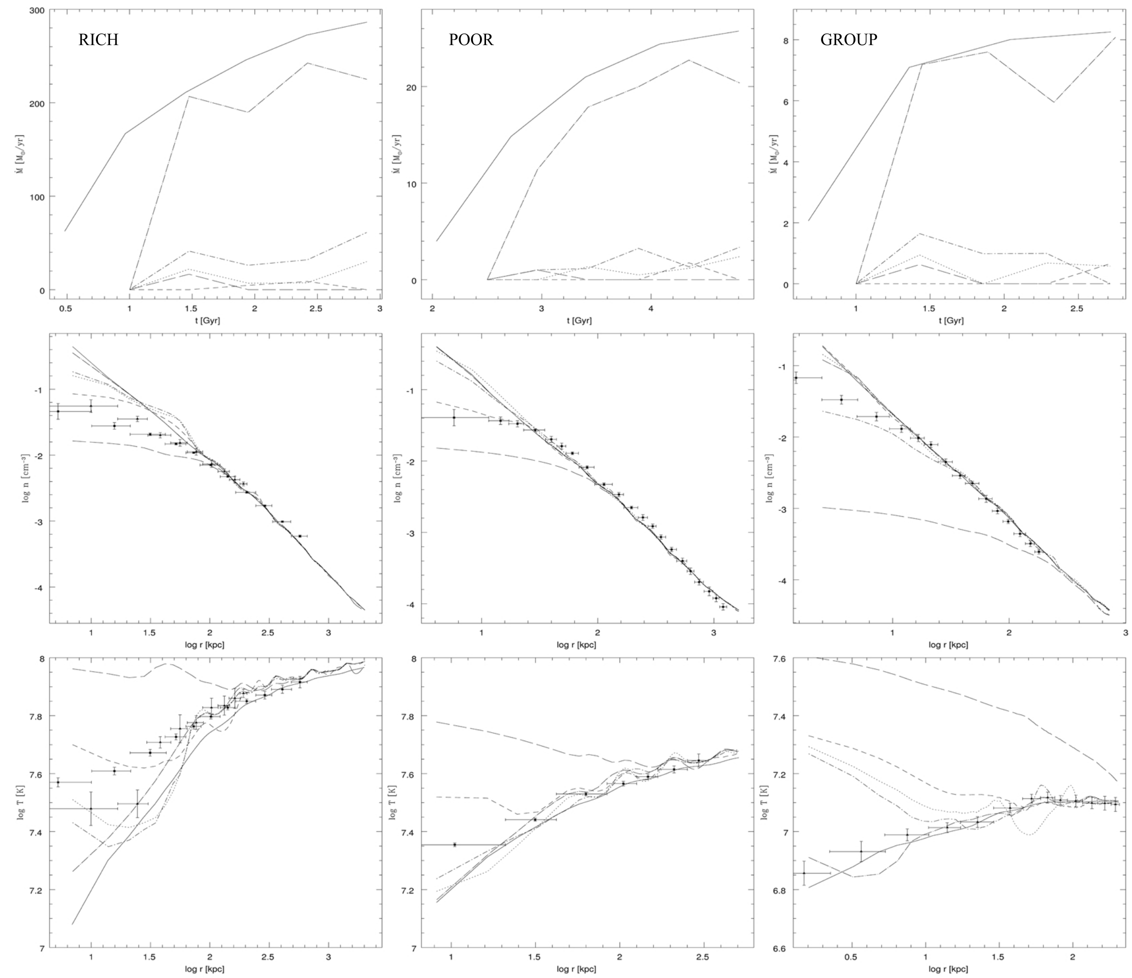

FIGURE 1. First row: cooling rates as a function of time. Second and third rows: radial profiles of n_e and T (emission-weighted) after 3 Gyr. Solid curves represent pure CF (no heating), while others have the following feedback: dot (fixed $\mathrm{v}_j = 5 \times 10^3$ km s^{-1}), short dash (fixed $\mathrm{v}_j = 10^4$ km s^{-1}), long dash (self-regulated, $\varepsilon = 10^{-1}$), dot - short dash (self-reg., $\varepsilon = 10^{-3}$), dot - long dash (self-reg., $\varepsilon = 10^{-5}$). Points represent observations of A1795, 2A 0335+096 and NGC 5044, from first to third column.

appreciably reduced until $\varepsilon = 10^{-3}$, but in this case ρ and T profiles strongly disagree with observations. Even with a higher resolution, ~ 0.5 kpc, and thus a thinner jet, the problem still persists. We also noticed that, in groups, profiles are extremely variable in time, in particular with high efficiencies, following the AGN feedback activation cycle.

Outflow Analysis and 2D Maps

A detailed analysis of our simulation will be presented elsewhere (Gaspari et al, in preparation). We give here only a sketch of the main results.

The main outflows properties of best models are (from group to rich clusters): velocity $\sim 10^{3-4}$ km s^{-1}, with average power 10^{44-45} erg s^{-1}. The single jet-event does not have

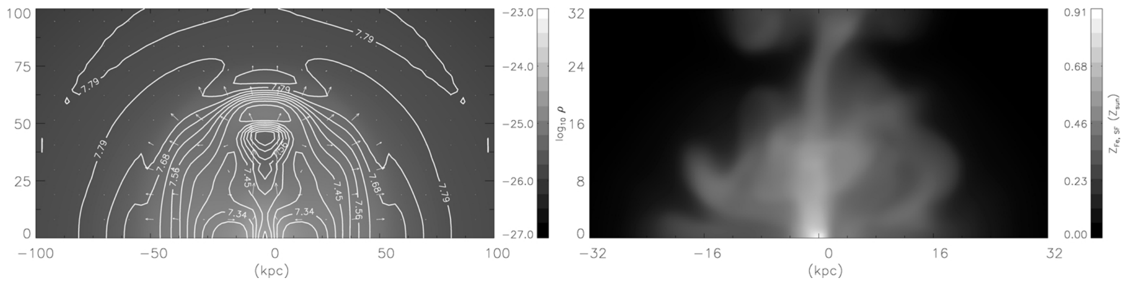

FIGURE 2. Left: slice through rich cluster center of density, with T and $\vec{v}$ superimposed ($\varepsilon = 10^{-3}$; t= 2.5 Gyr). Right: Fe-map of the group, emission-weighted along line of sight at 3 Gyr ($\varepsilon = 5 \times 10^{-4}$).

to be so frequent (every 250 Myr, about 10 Myr long), with E_{tot} injected a few percent of total "available" BH accretion energy (0.1 M_{BH} $c^2 \sim 10^{62}$ erg, with $M_{BH} \sim 10^9$ $M_\odot$). Outflows with self-regulated feedback naturally produce several generations of bubbles and weak shocks, similar to those observed in X-ray (Perseus, M87; [8]), even if it is not present a real relativistic jet that properly inflates the cavity (Fig.2, left). Bubbles slowly float upwards buoyantly. Cavity properties, in best models, are: $5 - 12$ kpc diameter (from group to rich cluster), with $10^7 - 10^8$ yr lifetime.

In simulations with SNIa and winds, iron maps become asymmetrical after a few Gyr, showing long filaments. Maximum values are nearly solar after 3 Gyr (Fig.2, right).

CONCLUSIONS

Three are the most important features to emphasize. First, the analysis of the computed gas radial profiles in clusters, rich and poor, shows that outflows with intermediate efficiencies ($\varepsilon = 10^{-3}$) can reproduce the observed $\rho(r)$ and $T(r)$ with the low cooling rate implied by X-Ray spectra (5 - 10% of classical CF). Second, models of galaxy groups have a serious problem: when the heating (AGN plus SNe) is able to stop or reduce the cooling rate, the T profile strongly disagrees with the observed one (wrong central gradient, T too high). Higher computational resolution (thinner jet) helps the density profile, but the problem still persists. Extreme time variability of profiles could be explained with the AGN active - quiescent cycle. Third, intermittency of the feedback naturally generates multiple X-Ray cavities and weak shocks, similar to those observed in Perseus and in many other galaxy clusters and groups.

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