

SIMULATIONS OF AGN FEEDBACK IN GALAXY CLUSTERS AND GROUPS: IMPACT ON GAS FRACTIONS AND THE $L_X - T$ SCALING RELATION

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ABSTRACT

Recently, rapid observational and theoretical progress has established that black holes (BHs) play a decisive role in the formation and evolution of individual galaxies as well as galaxy groups and clusters. In particular, there is compelling evidence that BHs vigorously interact with their surroundings in the central regions of galaxy clusters, indicating that any realistic model of cluster formation needs to account for these processes. This is also suggested by the failure of previous generations of hydrodynamical simulations without BH physics to simultaneously account for the paucity of strong cooling flows in clusters, the slope and amplitude of the observed cluster scaling relations, and the high-luminosity cut-off of central cluster galaxies. Here we use high-resolution cosmological simulations of a large cluster and group sample to study how BHs affect their host systems. We focus on two specific properties, the halo gas fraction and the X-ray luminosity-temperature scaling relation, both of which are notoriously difficult to reproduce in self-consistent hydrodynamical simulations. We show that BH feedback can solve both of these issues, bringing them in excellent agreement with observations, without alluding to the ‘cooling only’ solution that produces unphysically bright central galaxies. By comparing a large sample of simulated AGN-heated clusters with observations, our new simulation technique should make it possible to reliably calibrate observational biases in cluster surveys, thereby enabling various high-precision cosmological studies of the dark matter and dark energy content of the universe.

Subject headings: methods: numerical, galaxies: clusters: general, cosmology: theory, black hole physics

1. INTRODUCTION

Numerous observational and theoretical studies of galaxy clusters and groups show that the astrophysical processes relevant for determining their properties are still poorly understood. Hydrodynamical simulations of cluster formation which only include radiative cooling processes (e.g. Lewis et al. 2000; Muanwong et al. 2001; Yoshida et al. 2002) suffer from excessive overcooling within the densest cluster regions, where gas cooling times are short. This translates into a very large fraction of cold gas and consequently a large amount of stars that would form out of it, reaching at least 40–50% of the baryonic cluster content. While the associated removal of low-entropy gas from cluster centers breaks the self-similarity of the cluster scaling relations in a way that resembles observations (Bryan 2000; Davé et al. 2002; Nagai et al. 2007), this ‘cooling-only’ scenario is generally discounted because observed clusters do not show such strong cooling flows and enormously bright central galaxies. Instead, it is widely believed that some non-gravitational energy input must strongly affect the physics of the intracluster medium (ICM).

There has been considerable effort (see Borgani et al. 2004, and references therein) to include feedback mechanisms associated with star formation in hydrodynamical simulations in order to reduce excessive overcooling in cluster cores. However, so far simulation models have failed to simultaneously reproduce the masses and colors of central galaxies, the observed temperature and metallicity profiles, as well as the observed X-ray luminosity-temperature ($L_X - T$) relation. In particular, the X-ray luminosities have been found to be substantially larger than the observed values (Borgani et al. 2004) on the group scale. Furthermore the observed baryon fractions

in clusters and groups are typically smaller than in simulations, which for ‘standard’ physics invariably predict a value close to the universal cosmic baryon fraction (e.g. Frenk et al. 1999; O’Shea et al. 2005; Kravtsov et al. 2005).

Several attempts have been made to tackle these problems with so-called ‘preheating’ schemes (e.g. Bialek et al. 2001; Borgani et al. 2005), that are meant to mimic more energetic astrophysical processes than the relatively inefficient supernovae feedback. However, the preheating scenarios are physically not well motivated and rely on an ad-hoc choice of the amount and epoch of energy injection into the ICM.

On the other hand, it is becoming increasingly clear that active galactic nuclei (AGN) play an important role for understanding the properties of clusters and groups (see McNamara & Nulsen 2007, for a recent review). Also analytic work (e.g. Valageas & Silk 1999; Bower et al. 2001; Cavaliere et al. 2002) suggests that including self-consistent feedback from AGN in simulations might resolve the discrepancies by providing a heating mechanism that offsets cooling, lowers star formation rates and removes gas from the centers of poor clusters and groups, thereby reducing their X-ray luminosities to values compatible with the observed $L_X - T$ relation.

In this work we investigate whether AGN feedback can indeed solve these problems by performing hydrodynamical simulations of galaxy clusters and groups that employ a state-of-the-art model (Sijacki et al. 2007) for BH growth and associated feedback processes.

2. METHODOLOGY

We have selected a large sample of cluster- and group-sized halos from the Millennium simulation (Springel et al. 2005b) and resimulated them at higher resolution, including a gaseous component and accounting for hydrodynamics, ra-

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diative cooling, heating by a UV background, star formation and supernovae feedback. For each halo, two kinds of resimulations were performed. One containing the physics just described and an additional one including a model for BH growth and associated feedback processes as in Springel et al. (2005a) and Sijacki et al. (2007). This allows us to compare the very same clusters simulated with and without AGN heating in order to clearly pin down the imprints of AGN activity on galaxy cluster and group properties, and to which extent this resolves discrepancies with X-ray observations.

2.1. The simulations

In total we have selected 21 Millennium run dark matter (DM) halos at $z = 0$, and resimulated them at much higher mass and force resolution. The selection was only based on mass and otherwise random, aiming to approximately uniformly cover a large mass range from $8 \times 10^{12} M_{\odot}$ to $1.5 \times 10^{15} M_{\odot}$. New initial conditions were created by populating the Lagrangian region of each halo in the original initial conditions with more particles and adding additional small-scale power, as appropriate. At the same time, the resolution has been progressively reduced in regions that are sufficiently distant from the forming halo. Gas has been introduced into the high-resolution region by splitting each parent particle into a gas and a DM particle.

We have adopted the same flat Λ CDM cosmology as in the parent Millennium simulation, namely $\Omega_m = 0.25$, $\Omega_{\Lambda} = 0.75$, $h = 0.73$, $n_s = 1$ and $\sigma_8 = 0.9$. $\Omega_b = 0.04136$ has been chosen so as to reproduce the cosmic baryon fraction inferred from current cosmological constraints (Komatsu et al. 2008).

In our high-resolution resimulations of halos with virial masses below $2 \times 10^{14} h^{-1} M_{\odot}$, the DM particle mass is $m_{\text{DM}} = 3.1 \times 10^7 h^{-1} M_{\odot}$, the gas particle mass is $m_{\text{gas}} = 6.2 \times 10^6 h^{-1} M_{\odot}$ and the gravitational softening is $\epsilon = 15 h^{-1} \text{kpc}$ co-moving (Plummer-equivalent) for redshift $z > 5$, which is then replaced with a physical softening of $2.5 h^{-1} \text{kpc}$ for $z < 5$. For four of these halos we have additionally performed very high resolution simulations with mass resolution improved by a factor $(3/4)^3$. The change in halo properties resulting from this resolution increase is negligibly small, especially compared to the impact of the AGN heating, indicating that results are approximately converged and our comparison is not affected by resolution issues. For the four most massive clusters we used a somewhat lower resolution with a DM particle mass of $m_{\text{DM}} = 1.1 \times 10^8 h^{-1} M_{\odot}$ and a gas particle mass of $m_{\text{gas}} = 2.1 \times 10^7 h^{-1} M_{\odot}$. This makes these simulations computationally affordable, while assuring reasonable convergence.

The simulations were run with the GADGET-3 code (based on Springel 2005), which employs an entropy-conserving formulation of smoothed particle hydrodynamics (SPH). Radiative cooling and heating was calculated for an optically thin plasma of hydrogen and helium, and for a time-varying but spatially uniform UV background. We did not include metal-cooling as we wanted to study the impact of AGN feedback independently from the problems involved in following the metal-enrichment of the ICM. One should keep in mind, however, that metal-cooling might have some effect on halo properties on the group scale. Star formation and supernovae feedback were modeled with a subresolution multi-phase model for the interstellar medium as in Springel & Hernquist (2003).

2.2. The black hole growth and feedback model

Here we summarize the main features of our model for incorporating BH growth and feedback in simulations; full de-

tails are given in Springel et al. (2005a), Sijacki & Springel (2006), and Sijacki et al. (2007). In short, we assume that low-mass seed BHs are produced sufficiently frequently that any halo above a certain threshold mass contains one such BH at its center. In the simulations, an on-the-fly friends-of-friends group finder puts seed BHs with a mass of $10^5 h^{-1} M_{\odot}$ into halos when they exceed a mass of $5 \times 10^{10} h^{-1} M_{\odot}$ and do not contain any BH yet. The BHs are represented by collisionless sink particles and are allowed to grow by mergers with other BHs and by accretion of gas at the Bondi-Hoyle-Lyttleton rate, but with the Eddington limit additionally imposed. Two BHs are merged when they fall within their local SPH smoothing lengths and have small relative velocities.

Motivated by growing theoretical and observational evidence that AGN feedback is composed of two modes (e.g. Churazov et al. 2005, and references therein), we use two distinct feedback models depending on the BH accretion rate (BHAR) itself (see Sijacki et al. 2007). For large accretion rates above 0.01 of the Eddington rate, the bulk of AGN heating is assumed to be in the form of radiatively efficient quasar activity with only a small fraction of the luminosity being thermally coupled to the ICM. We adopt this thermal heating efficiency to be 0.5% of the rest mass-energy of the accreted gas, which reproduces the observed relation between BH mass and bulge stellar velocity dispersion (Di Matteo et al. 2005). For BHARs below 0.01 of the Eddington rate, we assume that feedback is in a so-called ‘‘radio-mode’’, where AGN jets inflate hot, buoyantly rising bubbles in the surrounding ICM. The duty cycle of bubble injection, energy content of the bubbles as well as their initial size are determined from the BHAR. We assume the mechanical feedback efficiency provided by the bubbles to be 2% of the accreted rest mass-energy, which is in good agreement with observations of X-ray luminous elliptical galaxies (Allen et al. 2006).

It was shown in Sijacki et al. (2007) that this model leads to a self-regulated BH growth and brings BH and stellar mass densities into broad agreement with observational constraints.

2.3. X-ray properties

We obtain realistic X-ray luminosities and spectroscopic temperatures for each simulated halo by sorting the gas particles inside r_{500} , the radius that encloses a mean density 500 times the critical density today, into temperature bins and summing up the emission measure for each bin. Using the XSPEC package (Arnaud 1996), we then simulate a spectrum of the X-ray emission in that region as a sum of MEKAL emission models (Liedahl et al. 1995), one for each temperature bin, assuming a constant metallicity of 0.3 times the solar value and using *Chandra*’s response function. In order not to be limited by photon noise we adopted a large exposure time of 10^6 s. The combined spectrum of the emission inside r_{500} is then fit by a single temperature MEKAL model with temperature, metallicity and normalization of the spectrum as free parameters. The resulting emission model then yields an estimate of the bolometric luminosity L_{500} , while the spectroscopic temperature T_{500} is taken directly from the fitted model. Note, however, that we use the gas particles inside the three-dimensional radius r_{500} to calculate L_{500} , while we use the gas particles inside the projected radius r_{500} to obtain T_{500} . Also note that we exclude very cold high-density gas particles with $T < 3 \times 10^4 \text{K}$ and densities above 500 times the mean baryon density as well as multiphase particles to avoid spurious contributions from the multiphase model for the star-forming gas.

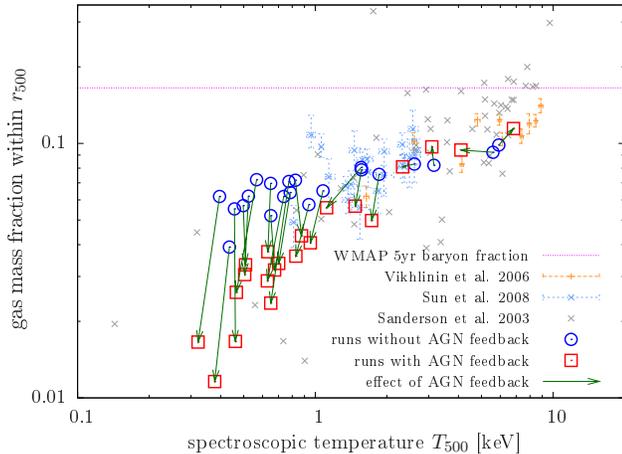


FIG. 1.— Halo gas mass fractions within r_{500} of clusters and groups simulated without AGN feedback (circles) and with the feedback model included (squares). The arrows illustrate the effect of the AGN heating for each halo.

3. RESULTS

We focus in this work on how AGN feedback affects the $L_X - T$ relation and the gas mass fractions in clusters. Additional cluster properties and simulations where the feedback energy in the “radio mode” is not injected thermally but in the form of cosmic rays (Sijacki et al. 2008) will be discussed in a forthcoming companion paper.

3.1. Halo gas fractions

In Figure 1, we show the ratio of gas mass to total mass inside the radius r_{500} as a function of halo X-ray temperature. For each simulated halo, arrows connect the results obtained without and with AGN heating. For comparison, we show constraints on halo gas fractions obtained from X-ray observations (Vikhlinin et al. 2006; Sun et al. 2008). Also shown are gas fractions we computed from the gas density and temperature profile parameters given in Sanderson et al. (2003).

The most obvious effect of the AGN feedback is the significantly reduced gas fraction at the low temperature end of our sample, i.e. in poor clusters and groups. There the AGN heating drives a substantial fraction of the gas to radii outside of r_{500} . This lowers halo gas fractions in spite of the reduced fraction of gas that is converted into stars in the runs with AGN. The potential wells of massive clusters are, on the other hand, too deep for AGN heating to efficiently remove gas from them. Thus the effect of the suppressed star formation becomes more important or even dominant towards more massive systems. While the gas fraction in the very inner regions of massive clusters is somewhat reduced by the AGN, we find it unchanged or slightly increased within r_{500} .

3.2. The $L_X - T$ relation

Given that AGN heating removes gas from the centers of poor clusters and groups, it is no surprise that it also suppresses their X-ray luminosities and affects the $L_X - T$ relation. In Figure 2, we plot the X-ray luminosities L_{500} against the spectroscopic temperatures T_{500} , for all halos of our sample. The arrows indicate the change due to the AGN feedback for each halo. Data from a number of observational X-ray studies is shown for comparison (Horner 2001; Helsdon & Ponman 2000; Osmond & Ponman 2004; Arnaud & Evrard 1999; Markevitch 1998).

Without the AGN feedback, we obtain substantially larger X-ray luminosities for poor clusters than observed, while for

massive clusters there is reasonable agreement. This finding is in line with previous numerical studies (see e.g. Borgani et al. 2004), and is a manifestation of the long-standing problem to explain the scaling relations of galaxy clusters in hydrodynamical simulations. However, when we employ the model for BH growth and feedback the discrepancies between simulated and observed $L_X - T$ relation are resolved. In particular, the $L_X - T$ relation on the group scale is steepened significantly, as AGN heating removes a larger fraction of gas from smaller halos and thereby reduces their X-ray luminosity. For massive clusters, the effect of the feedback is less important. Overall, the $L_X - T$ relation obtained from the simulations with AGN feedback is consistent with observations at all mass scales, from massive clusters to small groups.

Note that while the $L_X - T$ relation of massive clusters is in a reasonable agreement with observations even without the AGN feedback, this is only because an unrealistically large amount of cold gas, which is eventually converted into stars, is produced so that the stellar fractions within the virial radius reach of order of 35–45%, in clear conflict with observations. On the other hand, AGN-heated massive clusters not only lie closer to the observed $L_X - T$ relation but also have much lower stellar fractions which are reduced by at least one third. Especially their central galaxy is prevented from becoming too bright, due to the suppression of strong cooling flows. Also, the mass fraction of stars bound to cluster galaxies agrees very well with observations in our simulations with AGN. There is also a significant component of intra-cluster stars of up to 50% which lies at the upper end of the observational estimates (see e.g. Lin & Mohr 2004, for an overview).

4. SUMMARY AND CONCLUSIONS

We have performed very high-resolution numerical simulations of a mass-selected sample of galaxy clusters and groups. In order to investigate whether AGN feedback makes simulations and X-ray observations of cluster and groups compatible, we have carried out two kinds of simulations for each halo, namely (1) hydrodynamical simulations with a treatment of radiative cooling, star formation, supernovae feedback, and heating by a UV background, and (2) simulations that additionally employ a model for black hole growth and associated feedback processes. Our main findings are:

- AGN feedback significantly lowers the gas mass fractions in poor clusters and groups, even though fewer baryons are turned into stars at the same time. This is because the AGN heating drives gas from halo centers to their outskirts. In massive clusters, on the other hand, it mainly lowers the central gas density and substantially reduces the amount of stars formed. Overall, both the gas and stellar fractions of the whole sample of our simulated groups and clusters are in a much better agreement with observations when AGN are included than in simulations without AGN.
- AGN feedback significantly reduces the X-ray luminosities of poor clusters and groups, while the X-ray temperature within r_{500} stays roughly the same or is even slightly reduced. This results in a steepening of the $L_X - T$ relation on the group scale.
- The $L_X - T$ relation obtained from simulations with AGN feedback is in excellent agreement with observations at all mass scales.

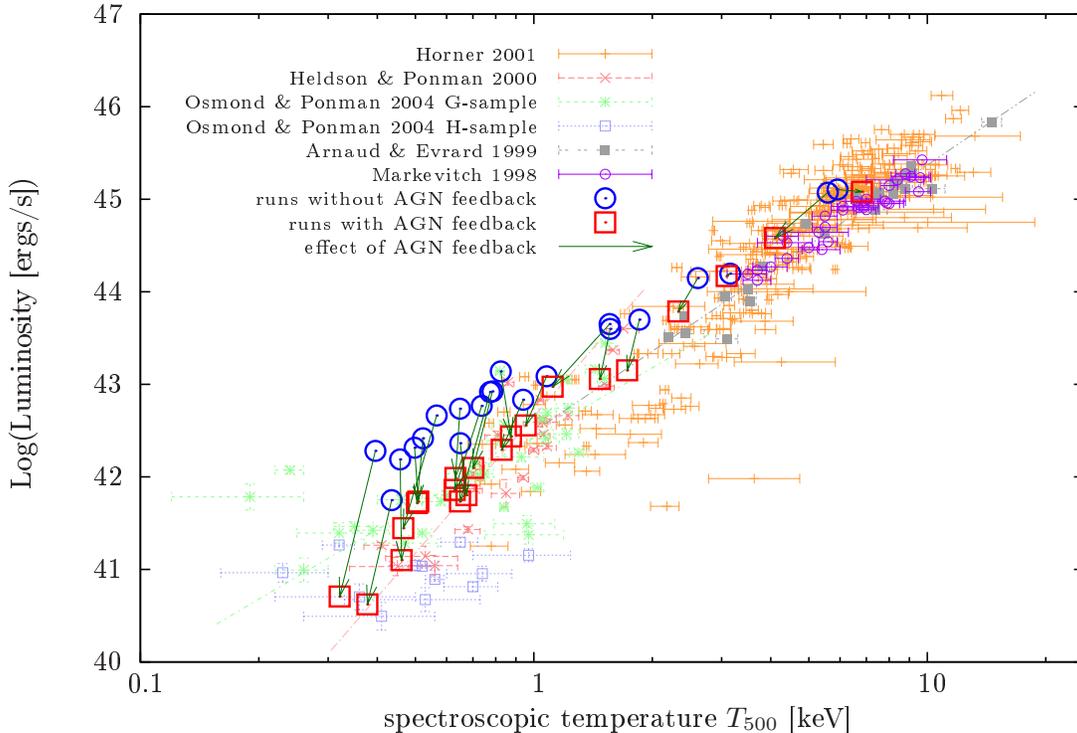


FIG. 2.— X-ray luminosity as a function of spectroscopic temperature for clusters and groups simulated without AGN feedback (circles) and with the feedback model included (squares). For each halo, the arrow illustrates the effect of the AGN heating. Data from several observational X-ray studies is shown for comparison. For a subset also the best-fit power-law $L_X - T$ relation is plotted. Including AGN feedback into the simulations drastically improves the agreement with observations and resolves the discrepancy that otherwise exists on the group scale.

We find it extremely encouraging that this simple model for BH growth and feedback is capable of bringing the analyzed properties of galaxy clusters and groups into much better agreement with observations. This not only resolves a long-standing problem in their hydrodynamical modeling, but also opens up new exciting possibilities for using numerical simulations to investigate the properties of clusters and groups, and their co-evolution with central supermassive BHs. Also, it considerably brightens the prospects to use simulations of cluster formation to accurately calibrate and correct

systematic effects in future X-ray and Sunyaev-Zel'dovich cluster surveys. This is essential for the exploitation of the full potential of clusters as cosmological probes to accurately constrain the expansion history of the Universe.

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