INSTRUCTIONS FOR PRODUCING A CAMERA-READY MANUSCRIPT

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We present hydrodynamical simulations of galaxy clusters and groups, which include the effect of radiative cooling, star formation and non gravitational gas heating. Our simulations are aimed at investigating how the problem of gas overcooling within galaxy clusters can be prevented by a suitable extra heating of the ICM. As a general conclusion, we find that requiring that the fraction of cold gas locked into stars and the main X-ray ICM scaling relations all agree with observational constraints places non trivial constraints on the way non-gravitational heating should occur.

1 Introduction

A number of observational facts have now established that the thermodynamical properties of the intra-cluster medium (ICM) can not be determined gravitational heating only. For instance, the slope of the L_X–T relation[1,10], the entropy level of the gas in the central regions of poor clusters and groups[11], and the amplitude of the M–T relation[5] all show departures with respect to the prediction of the so-called self-similar model, which is based on gravitational processes only regulating the ICM thermal properties[6].

Two alternative routes have been proposed to solve this discrepancy. The first possibility assumes that the diffuse gas underwent non gravitational heating, possibly before the cluster collapse epoch, due to the action of some astrophysical source of energy feedback (e.g., SNe or AGN)[4]. The consequence of this heating is that of increasing its entropy and avoiding it from reaching high density during the DM halo collapse, thus suppressing its X ray emissivity[13]. The second possibility assumes radiative cooling to be responsible for the lack of ICM self similarity[9]. Cooling acts in such a way to remove from the hot X-ray emitting phase the gas having low enough entropy that its cooling time, t_{cool}, is shorted than the cluster typical lifetime[14]. In this case, the observed entropy excess is the consequence of the removal of low-entropy gas, while the suppressed L_X follows from the reduced amount of gas left in the diffuse phase. Both

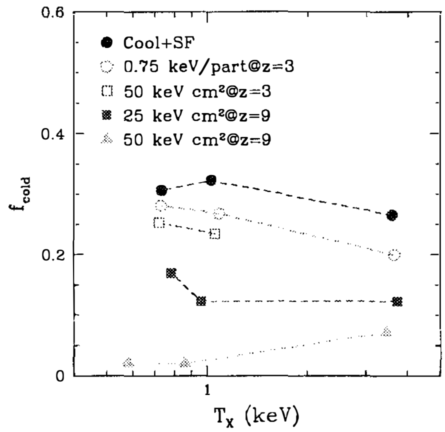

Figure 1: The fraction of cold gas in the simulated structures for different schemes of non–gravitational heating.

explanations have their pros and cons. While non–gravitational heating can hardly account for all the observations[3], cooling in itself gives rise to the well know overcooling problem, i.e., a too large fraction of ICM converted into a cold "stellar" phase[2].

In this contribution we present preliminary results from our undergoing project of running hydrodynamical simulations of clusters and groups, which include both cooling and different kinds of non–gravitational heating. Our simulations are aimed at understanding under which conditions extra–heating can prevent overcooling and, at the same time, provide a reliable description of the observed X–ray scaling properties of the ICM.

2 Simulations

We use GADGET, a parallel Tree+SPH code by Springel et al.[12], with fully adaptive time–stepping, to simulate at high resolution three halos extracted from a low resolution simulation of a flat ΛCDM model with $\Omega_m = 0.3$, $\sigma_8 = 0.8$, $h = 0.7$ and $f_{bar} = 0.13$, within a cosmological box of $70\,h^{-1}$ Mpc size. The version of the code, that we use for these simulations, includes radiative cooling and the effect of UV background, and an entropy conserving scheme for the energy integration. As for the adopted mass resolution, we have $m_{gas} \simeq 3.2 \times 10^8 M_\odot$ for the mass of the gas particles. The force resolution assumes $\epsilon = 5$ kpc for the Plummer–equivalent force softening scale, fixed in physical units out to $z = 2$, and then fixed in comoving units at higher redshifts. The simulations also include a star–formation scheme which progressively converts dense and cold gas particles into collisionless stars[7].

The implemented schemes for non–gravitational heating are the following: **(a)** Two entropy floors at $S_{fl} = 25$ and 50 keV cm^2 created at $z = 9$, i.e. before a substantial amount of gas starts undergoing cooling; **(b)** An entropy floor $S_{fl} = 50$ keV cm^2 at $z = 3$, i.e. at a redshift at which the SFR within clusters should stay around its maximum; **(c)** An additional thermal energy of 0.75 keV/particle for all the gas particles at overdensity $\delta_{gas} > 50$.

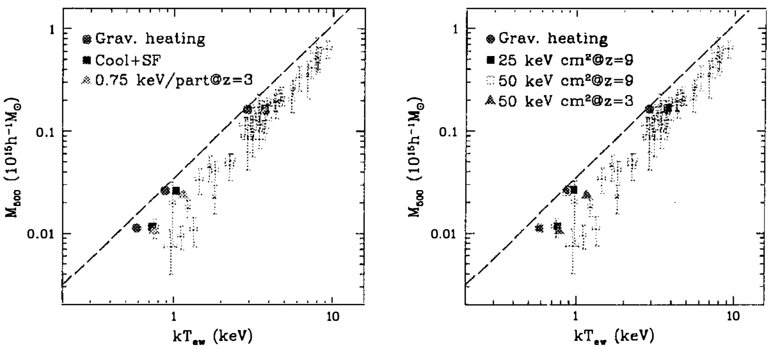

Figure 2: The relation between emission–weighted temperature and mass estimated at overdensity $\delta_c = \rho/\rho_{cr} = 500$. The dashed line represents the relation by Evrard et al. from their hydrodynamical cluster simulations, while data points are from Finoguenov et al.

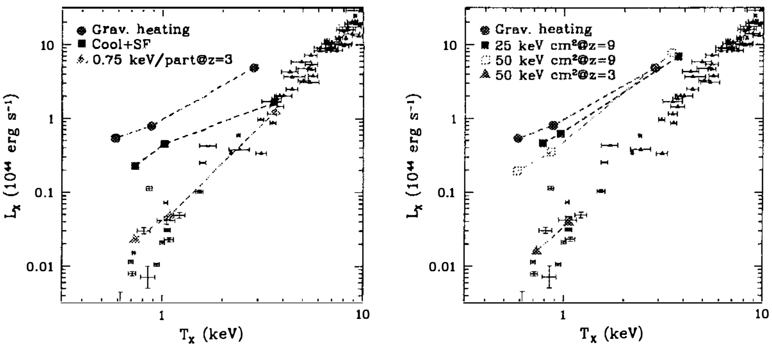

Figure 3: The relation between T_{ew} and X–ray luminosity, compared to observational data by Arnaud & Evrard, Markevitch and Ponman et al.

3 Results

Figure 1 shows the cold fraction within the virial radius for the three simulated systems, for the different heating schemes. It is apparent the excess of cold gas, $\simeq$ 25–30%, in the absence of any extra–heating. This fraction is somewhat reduced by heating at $z = 3$, while heating at $z = 9$ is even more efficient in preventing overcooling.

Figure 2 shows the mass–temperature relation, also compared to observational data[5]. The effect of cooling is that on increasing the emission–weighted temperature, as a consequence of the steeper gravitational potential created by the cooled gas. This effect in general is not compromised by the introduction of extra–heating. As a result, simulations including cooling and extra–heating show a better agreement with data than simulations including only gravitational gas heating.

In Figure 3 we show the results on the L_X–T relation and compare them to observational data. The effect of cooling only is that of suppressing the X–ray luminosity. While this reduction is sufficient to reach agreement with data for the most massive system, it is apparently not sufficient for the smaller groups. In general, we find a much better agreement with data when gas is heated at $z = 3$. This is just the consequence of the efficiency with which gas is removed from high–density regions. Heating at $z = 9$ has the effect of increasing the entropy and cooling time of the gas. However, subsequently this gas has the possibility of sinking within the central cluster region, while avoiding cooling as a consequence of its longer cooling time, thus remaining in the diffuse X–ray emitting phase. As a consequence, its X–ray luminosity remains high, if not increased. Quite surprisingly, combining the effect of cooling and extra–heating, which both act so as to suppress L_X, may have the effect of even increasing the X–ray emissivity.

Our results demonstrate that in general it is not easy to find a suitable recipe for extra–heating which is able at the same time to prevent overcooling and reproduce the observed X–ray scaling properties of galaxy systems. A significant reduction of gas cooling requires heating at a quite high redshift. In this case, however, one runs into the problem of not suppressing the X–ray luminosity. Therefore, the apparently simple question of how much extra heating is required to balance overcooling and reproduce X–ray scaling relations of clusters, does not have a simple answer. A realistic and successful ICM modelization should require gas heating and cooling to be self–consistently included: the source and amount of heating at a given epoch should be directly derived from the amount of gas undergoing cooling and therefore form stars and/or trigger AGN activity.

The results presented in this contribution should be regarded as preliminary. We are currently working on the implementation of ICM heating as derived from the SFR predicted, within the Lagrangian regions of the simulated structures, by semi–analytical models of galaxy formation[8]. Also, we intend to increase the resolution of the groups' simulations. At higher resolution we expect a somewhat higher fraction of cold gas at the group scale and a lower L_X as a consequence of the increased efficiency in removing gas from the diffuse phase.

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