PRE-HEATING THE ICM IN HIGH RESOLUTION SIMULATIONS: THE EFFECT ON THE GAS ENTROPY

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To appear in The Astrophysical Journal Letters

ABSTRACT

We present first results from high-resolution Tree+SPH simulations of galaxy clusters and groups, aimed at studying the effect of non–gravitational heating on the entropy of the intra–cluster medium (ICM). We simulate three systems, having emission–weighted temperature $T_{\text{em}} \sim 0.6, 1$ and $3$ keV, with spatial resolution better than 1% of the virial radius. We consider the effect of different prescriptions for non–gravitational ICM heating, such as supernova (SN) energy feedback, as predicted by semi–analytical models of galaxy formation, and two different minimum entropy floors, $S_0 = 50$ and 100 keV cm$^2$, imposed at $z = 3$. Simulations with only gravitational heating nicely reproduce predictions from self–similar ICM models, while extra heating is shown to break the self–similarity, by a degree which depends on total injected energy and on cluster mass. We use observational results on the excess entropy in central regions of galaxy systems, to constrain the amount of extra–heating required. We find that setting the entropy floor $S_0 = 50$ keV cm$^2$, which corresponds to an extra heating energy of about 1 keV per particle, is able to reproduce the observed excess of ICM entropy.

Subject headings: Cosmology: Theory – Galaxies: Intergalactic Medium – Methods: Numerical – X–Rays: Galaxies: Clusters

1. INTRODUCTION

The high temperature reached by diffuse baryons within the potential wells of galaxy clusters makes them directly observable in the X–rays, mostly due to bremsstrahlung emission (e.g., Borgani & Guzzo 2001) With the recent advent of the Chandra–AXAF and Newton–XMM satellites, the level of details at which the the physics of the intra–cluster medium (ICM) can be observationally described is undergoing an order–of–magnitude improvement, both in spatial and in energy resolution. From the theoretical viewpoint, the first attempt to model the thermodynamical properties of the ICM assumed them to be entirely determined by gravitational processes, like adiabatic equilibrium and bremsstrahlung X–rays, mostly due to bremsstrahlung emission ($e^+e^-$ annihilation and pair production), which are the main sources of X–ray emission in galaxy clusters and groups. However, significant deviations from the adiabatic equilibrium ($p \propto m_\gamma T$, where $p$ and $m_\gamma$ are the pressure and the mass of the electron, respectively) are observed in many clusters, which require the existence of non–adiabatic processes, like shock heating (e.g., Borgani et al. 2001). This extra heating is attributed to non–gravitational heating sources, such as supernovae (SN) or AGN activity (e.g., Babul & Patton 1999; Tozzi & Norman 2001; TN01 hereafter), or to AGN activity (e.g., Valageas & Silk 1999; Wu, Fabian & Nulsen 2000). In this context, numerical hydrodynamical simulations represent an invaluable tool to correctly follow dynamical complexities, like merging of substructures and non–spherical shocks, whose relevance for ICM properties is emphasized by recent X–ray cluster observations at high spatial resolution (e.g., Markevitch et al. 2000). Different groups have run such simulations with the aim of understanding in details the effect of non–gravitational heating and the amount of energy required to reproduce observations (e.g., Navarro, Frenk & White 1995; Bialek, Evrard & Mohr 2000). In particular, Bialek et al. have run simulations at intermediate resolution for a fairly large ensemble of clusters. After assuming different initial values for the gas entropy, they checked the effect of pristine extra heating on several ICM scaling relations.

In this Letter we present results from our ongoing project of running high–resolution cluster simulations, using different schemes for injecting non–gravitational energy feedback into the ICM. We will concentrate here on the effect of extra–heating on the ICM entropy and will compare the results to the observational constraints by PCN. We reserve for a separate paper (Governato et al. 2001, Paper II hereafter) a thorough description of the simulations and a detailed analysis of the resulting ICM properties.

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2. THE SIMULATIONS

We use GASOLINE, a parallel, multistepping tree+SPH code with periodic boundary conditions (Wadsley, Quinn & Stadel 2001), to re-simulate at high resolution three halos taken from a cosmological box (100 Mpc aside) of a ΛCDM Universe, with Ω_m = 0.3, Ω_λ = 0.7, σ_8 = 1, h = H_0/(100 km s^{-1} Mpc^{-1}) = 0.7 and f_{bat} = 0.13. In the following we give a short descriptions of the simulations, while we refer to Paper II for further details and for the discussion about the effect of radiative cooling, which we neglect here. The main characteristics of the three halos are listed in Table 1. Owing to their virial mass and temperature, in the following we will refer to the three simulated structures as Virgo cluster, Fornax group and Hickson group. Thanks to the good mass resolution, we are able to resolve with 32 particles structures having total mass as small as about 5.5 × 10^{13} M_☉ and 1.6 × 10^{10} M_☉ within the Virgo cluster and within the two smaller groups, respectively.

TABLE 1

| Run   | M_{vir} | R_{vir} | T_{vir} | m_{gas} | ε  |
|-------|---------|---------|---------|---------|----|
| Virgo | 30.4    | 1.75    | 2.07    | 2.21    | 7.5 |
| Fornax| 5.91    | 1.01    | 0.95    | 0.65    | 5.0 |
| Hickson| 2.49    | 0.76    | 0.60    | 0.65    | 5.0 |

Column 2: total virial mass (10^{13} M_☉); Column 3: virial radius (Mpc); Column 4: Emission-weighted virial temperature (keV) for the runs including only gravitational heating; Column 5: mass of gas particles (10^9 M_☉); Column 6: Plummer-equivalent softening for gravitational force (h^{-1} kpc).

The first scheme for non-gravitational heating is based on setting a minimum entropy value at some pre-collapse redshift (e.g. Navarro et al. 1995; TN01; Bialek et al. 2000). For gas with local electron number density n_e and temperature T, expressed in keV, at redshift z, we define the entropy as

\[ S = \frac{T}{n_e^2 \bar{\rho}^2} = \left[ \frac{f_{bat}}{m_p} \right] \bar{\rho}(1 + \delta_g)^3 T \text{ keV cm}^{-2}, \tag{1} \]

where \( \bar{\rho}(z) = \bar{\rho}_0(1 + z)^3 \) is the average cosmic matter density at redshift z, \( \delta_g \) the gas overdensity, \( m_p \) the proton mass and \( X \) hydrogen mass fraction (X = 0.76 is assumed in the following). Accordingly, the entropy of the i-th gas particle in the simulation is defined as \( S_i = T_i n_e^{2/3} \), where \( T_i \) and \( n_i \) are the temperature and the electron number density associated to that particle. At \( z = 3 \), we select all the gas particles with overdensity \( \delta_g > 5 \), so that they correspond to structures which have already undergone turnaround. After assuming a minimum floor entropy, \( S_{fl} \), each gas particle having \( S_i < S_{fl} \) is assigned an extra thermal energy, so as to bring its entropy to the floor value, according to eq. (1). We choose two values for this entropy floor, \( S_{fl} = 50 \) and 100 keV cm^{-2}. We computed the mean density of the heated gas at \( z = 3 \) to be \( \langle \delta_g \rangle \approx 185, 280 \) and 215 for the Virgo, Fornax and Hickson runs, respectively. We assume \( z_h = 3 \) for the reference heating redshift, since it is close to the epoch at which sources of heating, like SN or AGNs, are expected to reach their maximum activity. We check the effect of changing \( z_h \) by also running simulations of the Fornax group for \( z_h = 1, 2 \) and 5. We estimate the amount of energy injected in the ICM in these pre-heating schemes by selecting at \( z = 0 \) all the gas particles within the virial radius and tracing them back to \( z = 3 \). We find that taking \( S_{fl} = 50 \) keV cm^{-2} amounts to give an average extra heating energy of \( E_h = \frac{4}{3} T_h \) \approx 1.4 \text{ keV/} \text{part} \) for the Fornax and Hickson groups and \( E_h \approx 0.9 \text{ keV/} \text{part} \) for the Virgo cluster. Such values are twice as large for \( S_{fl} = 100 \) keV cm^{-2}. We also verified that the fraction of gas particles within the virial radius, that have been heated at \( z = 3 \), is of about 75%, almost independent of the mass of the simulated system, for both values of \( S_{fl} \).

As for the pre-heating by SN feedback (e.g., Kauffmann, White & Guiderdoni 1993; Somerville & Primack 1999; Cole et al. 2000), we resort to semi-analytical modelling of galaxy formation to compute the star-formation rate within halos having the same mass as the simulated ones (see Poli et al. 1999, for a detailed description of the method). We assume a feedback parameter (\( \alpha_h = 2 \) in the model by Poli et al.) so as to reproduce both the local B-band luminosity function and the Tully–Fisher relation (see also Cole et al. 2000). The resulting star-formation rates are used to derive the history of energy release from type II SN. During the cluster evolution, this energy is shared among all the gas particles having \( \delta_g \geq 10 \) (see Paper II). This density threshold, which roughly corresponds to the density contrast at the virial radius, has been chosen to guarantee that gas heating takes place inside virialized regions. We
verified that final results do not change by changing by a factor ten the above value of the limiting $\delta_T$. Under the assumption that all the energy released by SN is thermalized into the ICM, this scheme dumps a total amount of about 0.35 keV/part extra energy per particle.

3. RESULTS AND DISCUSSION

The entropy maps of Figure 1 show a qualitative description of the effect of non–gravitational heating on the ICM entropy. In the absence of extra–heating (left panel) the high resolution achieved in our simulation of a Virgo–like cluster reveals a wealth of substructures in the entropy pattern. Small–size halos, which are the first to have collapsed, are characterized by low entropy as a consequence of the fact that they contain early accreted, and therefore only weakly shocked, gas particles. A higher entropy level characterizes, instead, the large–scale filaments, which are surrounded by shells of recently accreted and strongly shocked gas. The main structure of the cluster also shows a low–entropy core, surrounded by regions of progressively higher entropy associated with recently accreted gas: as a consequence of the continuous increase of the total virialized cluster mass, the later the baryons are accreted, the larger their infall velocity and, therefore, the stronger the experienced shock. This process gives rise to an expanding shock separating the inner gas, which sets in hydrostatic equilibrium, with the external cooler and adiabatically compressed medium, the interface occurring around the virial radius. Quite remarkably, small halos merging into the cluster main body are able to keep their low–entropy structure for a few crossing time scales, before their gas is stripped. As a consequence, sharp structures arise well inside the virial region, with entropy discontinuities and tail of gas stripped from the merging subhalos by the effect of the ram pressure. This picture changes as the gas receives non–gravitational heating. As the gas is placed on a higher adiabat, it is no longer able to accrete inside the small–mass halos and, therefore, accretion shocks are switched off. However, while the small–scale features are progressively washed out as the amount of energy injection increases, a halo of high–entropy, recently shocked gas still surrounds the cluster main body. Although somewhat smoothed, some discontinuities in the gas entropy are still visible even in the cluster central regions. It is quite tempting to associate such features to those recently observed by the Chandra satellite (e.g., Markevitch et al. 2000; Fabian et al. 2000; Mazzotta et al. 2001). Although a close comparison between such details of the ICM structure in simulations and in observational data requires a more careful analysis, there is little doubt that the increasing quality of X–ray data will soon permit the reconstruction of the thermodynamic history of the intra–cluster gas.

A more quantitative look at the ICM entropy is provided by Figure 2, where we show the entropy profiles for the different schemes of ICM extra–heating. By plotting the entropy, in units of emission–weighted temperature $T_{\text{ew}}$, as a function of the radius, in units of the virial radius $R_{\text{vir}}$, we emphasize the self–similar behavior of the ICM in the presence of gravitational heating only (the plotted quantity would be proportional to $\rho_\text{gas}^{-2/3}$ if the gas were isothermal). Indeed, the profiles for the three structures do coincide to a good accuracy in the absence of any extra heating. In this case, the shock model developed by TN01 under the assumption of spherical accretion, predicts the entropy profile $S \propto R^{1.1}$. This scaling is shown by the dotted line in the left panel of Fig. 2, and nicely agrees with the scaling found in the simulations with gravitational heating only. This agreement and the absence of any significant flattening of the entropy profiles at small radii are witnessing that our simulations are correctly capturing gravitational shocks and do not produce numerical artifacts over the considered range of scales. The wiggles in the entropy profiles mark the positions of the small–scale merging sub–halos, appearing in Fig. 1, which bring low–entropy gas inside the main body of the clusters. Although such merging structures violate the assumption of spherical accretion of the TN01 model, they do not alter the global behavior of the cluster entropy. The presence of non–gravitational heating has the twofold effect of making the entropy profiles shallower, while breaking the self–similarity to a degree which depends on the amount of injected extra energy. As expected, the effect of heating is more pronounced for the halo with the smallest virial temperature, for which the extra–energy per particle corresponds to a larger fraction of the total virial temperature. As for the case with $S_0 = 50$ keV cm$^2$, the floor value is almost recovered in the innermost resolved region only for the Virgo simulation, while it is significantly larger for the two smaller groups. Since the effect of the heating is that of decreasing the gas density, a significant fraction of the shocked gas can now flow down to the cluster central regions.
thus further increasing the entropy level. As for the heating by SN feedback, its effect is only marginal on the Virgo cluster and on the Fornax group, while it significantly changes the entropy profile of the smaller Hickson group below $\sim 0.2R_{\text{vir}}$. In general, although extra heating largely modifies gas entropy in the cluster central regions, it has only a marginal effect at $\sim R_{\text{vir}}$. This is consistent with the expectation that gravitational shocks provide the dominant mechanism for establishing the global heating of the gas.

We compare in Figure 3 the observational data by PCN on the gas entropy for clusters and groups at $0.1R_{\text{vir}}$ with the results obtained from our simulations. As discussed by PCN, such data indicates that some pre–heating should have established an excess entropy in central cluster regions, which causes the flattening of the $S–T$ relation for low–temperature systems, while being negligible for the more massive systems, whose gas has been mainly heated by gravitational processes. Again, in the presence of gravitational heating only, our simulations nicely reproduce the expectations from self–similar scaling $S \propto T_{\text{ew}}$. The agreement with the prediction of self–similar scaling confirms once more that the resolution of our simulations is more than adequate to correctly capture global ICM thermodynamical properties. As expected, adding extra heating breaks the self–similarity and increases central entropy by a larger amount for smaller systems. Heating with about one-third of keV per particle, with redshift modulation as predicted by our SN model, has a quite small effect and is not adequate to reproduce observational results. Both heating recipes, based on setting an entropy floor at $z = 3$, have a much larger effect on the entropy, while still leaving $T_{\text{ew}}$ almost unchanged. Even for the Hickson group, the value of $S(0.1R_{\text{vir}})$ for the such heating schemes turns out to be about twice as large as $S_{\text{fb}}$. This shows how after the gas is pre–heated, gravitational effects still act to increase its entropy down to $0.1R_{\text{vir}}$. We also find that varying the heating redshift from $z_{\text{fb}} = 1$ to $z_{\text{fb}} = 5$ in the Fornax simulation does not affect the central entropy, thus indicating that this quantity mainly depends on the entropy floor level and not on the epoch at which it is established.

As a general conclusion, our results show that observational data on the excess gas entropy in central regions of small clusters and groups require a non–gravitational energy injection of about 1 keV per particle. This result is in qualitative agreement with that derived by comparing simulation results with observational data on the slope of the luminosity–temperature relation of clusters and groups (Bialek et al. 2000; Paper II). Which are the implications of this result on the astrophysical sources responsible for the heating of the inter–galactic medium? Although our results suggest that the majority of the required energy budget can not be supplied by type II SN, the final answer to the above question requires a better understanding and a more accurate treatment of several physical processes. Radiative cooling, which is non included in the simulations presented here, has been advocated as a possible solution to the problem of ICM excess entropy (e.g., Bryan 2000). Gas undergoing cooling in central cluster regions is converted into collisionless stars, and, as such, does not provide pressure support. Therefore, strongly shocked gas in the cluster outskirts starts flowing inside, thus increasing the central entropy level. Since the cooling time scale is always much shorter than the dynamical time scale in central cluster regions, a fraction of gas as large as $\sim 50\%$ can leave the diffuse hot phase (e.g., Balogh et al. 2001; Paper II). This result is at variance with observations which, instead, indicate only a small fraction, $\sim 10\%$, of cluster baryons to reside in the cold phase (Balogh et al. 2001), thus calling for the presence of a feedback mechanism, which were able to prevent this “cooling crisis”. Furthermore, a detailed understanding of the process of the diffusion of the energy feedback into the ICM and of the relative role played by different heating sources are far from being reached. In this respect, the improvement of observational data on the abundance and spatial distribution of heavy elements from Chandra and Newton–XMM satellites (e.g., Böhringer et al. 2000) will shed light on the interplay between ICM physics and the history of star formation in clusters.

The simulations have been realized at CINECA (Bologna) and ARSC (Fairbanks) supercomputing centers. We thank A. Cavaliere for reading the manuscript.

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Fig. 3.— The relation between specific gas entropy at $0.1R_{\text{vir}}$ and the emission–weighted virial temperature, $T_{\text{ew}}$. Circles are for the runs with gravitational heating, squares for SN energy feedback, while filled and open triangles for an entropy threshold settled at $z = 3$ at the two different values reported in the labels. Dotted crosses are the data by PCN, rescaled to $h = 0.7$. The long–dashed line shows the relation $S(0.1R_{\text{vir}}) = S_{\text{fb}} + S_{\text{et}}$ for about $1 \text{ keV cm}^{-2}$, which fits the observational results for $T_{\text{ew}} \gtrsim 6 \text{ keV clusters}$ (Ponman et al. 1999).
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