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PREHEATING THE INTRACLUSTER MEDIUM IN HIGH-RESOLUTION SIMULATIONS: THE EFFECT ON THE GAS ENTROPY

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ABSTRACT

We present first results from high-resolution tree + smoothed particle hydrodynamics simulations of galaxy clusters and groups that are aimed at studying the effect of nongravitational heating on the entropy of the intracluster medium (ICM). We simulate three systems having emission-weighted temperatures $T_{ew} \simeq 0.6$, 1, and 3 keV with spatial resolutions better than 1% of the virial radius. We consider the effect of different prescriptions for nongravitational ICM heating, such as supernova energy feedback, as predicted by semianalytical models of galaxy formation, and two different minimum entropy floors, $S_{fl} = 50$ 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 that depends on the total injected energy and on the cluster mass. We use the observational results on the excess entropy in central regions of galaxy systems to constrain the amount of extra heating required. We find that by setting the entropy floor $S_{fl} = 50$ keV cm^2, which corresponds to an extra heating energy of about 1 keV per particle, we are able to reproduce the observed excess of ICM entropy.

Subject headings: cosmology: theory — galaxies: clusters: general — hydrodynamics — intergalactic medium — methods: numerical — X-rays: galaxies

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 because of bremsstrahlung emission (e.g., Borgani & Guzzo 2001). With the recent advent of the *Chandra* and *XMM-Newton* satellites, the levels of detail at which the physics of the intracluster medium (ICM) can be observationally described are undergoing an order-of-magnitude improvement in both spatial and energy resolution. From a theoretical point of view, Kaiser (1986) first attempted to model the thermodynamical properties of the ICM by assuming that they were entirely determined by gravitational processes, like adiabatic compression and shock heating. Since gravity alone does not introduce characteristic scales, this model predicted the gas within clusters of different mass to behave in a self-similar way. Under the assumption of hydrostatic equilibrium and bremsstrahlung emissivity, the self-similar model predicts the scaling $L_X \propto T^2$ between X-ray luminosity and gas temperature, while the scaling that is approximately proportional to T^3 is observed (e.g., Arnaud & Evrard 1999). Furthermore, by defining the ICM entropy as $S = T/n_e^{2/3}$ (where n_e is the electron number density; Ponman, Cannon, & Navarro 1999, hereafter PCN), self-similarity implies $S \propto T$. This is at variance with the observational evidence that entropy at 1/10 of the cluster virial radius tends to a constant value, $S \sim 100$ keV cm^2 for $T \lesssim 2$ keV, with self-similar scaling recovered for $T \gtrsim 6$ keV systems (PCN; Lloyd-Davies, Ponman, & Cannon 2000). The current interpretation for such discrepancies requires the self-similarity to be broken by nongravitational gas heating (e.g., Kaiser 1991; Evrard & Henry 1991; Cavaliere, Menci, & Tozzi 1998; Balogh, Babul, & Patton 1999; Tozzi & Norman 2001, hereafter TN01; Brighenti & Mathews 2001), which increases the entropy of the gas, places it on a higher adiabat, and therefore prevents it from reaching high central densities during gravitational collapse. Despite the general consensus on the need for nongravitational heating (cf. also Bryan 2000, Pearce et al. 2000, and Muanwong et al. 2001) and for determining the astrophysical source responsible for it, this is still a widely debated issue. The two most credible hypotheses are based on energy feedback from supernovae (SNe; e.g., Loewenstein 2000; Bower et al. 2001; Menci & Cavaliere 2000) and from active galactic nucleus (AGN) activity (e.g., Valageas & Silk 1999; Wu, Fabian, & Nulsen 2000). In this context, numerical hydrodynamical simulations give an exact treatment of the dynamical complexities, like the merging of substructures and nonspherical 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 detail the effect of nongravitational heating and the amount of energy required to reproduce observations (e.g., Navarro, Frenk, & White 1995; Bialek, Evrard, & Mohr 2001). In particular, Bialek et al. (2001) 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 high-resolution cluster simulations using different schemes for injecting nongravitational energy feedback into the ICM. We will concentrate here on the effect of extra heating on the ICM entropy, and we will compare the results with the observational constraints by PCN. We reserve for a separate paper (F. Governato, S. Borgani, J.

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Wadsley, N. Menci, P. Tozzi, G. Lake, T. Quinn, & J. Stadel 2001, in preparation and hereafter Paper II) a thorough description of the simulations and a detailed analysis of the resulting ICM properties.

2. THE SIMULATIONS

We use GASOLINE, a parallel, multistepping tree + smoothed particle hydrodynamics (SPH) code with periodic boundary conditions (J. Wadsley, T. Quinn, & J. Stadel 2001, in preparation) to resimulate at high resolution three halos taken from a cosmological box (100 Mpc on each side) of a ΛCDM universe, with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 1$, $h = H_0/(100$ km s^{-1} Mpc$^{-1}) = 0.7$, and $f_{\rm bar} = 0.13$. In the following discussion, we give 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 the Virgo Cluster, Fornax group, and Hickson group. Thanks to the good mass resolution, with 32 particles we are able to resolve structures having a total mass as small as about 5.5×10^{10} and $1.6 \times 10^{10}\ M_\odot$ within the Virgo Cluster and within the two smaller groups, respectively.

The first scheme for nongravitational heating is based on setting a minimum entropy value at some precollapse redshift (e.g., Navarro et al. 1995; TN01; Bialek et al. 2001). For gas with local electron number density n_e and temperature T, expressed in units of keV, at redshift z, we define the entropy as

$$S = \frac{T}{n_e^{2/3}} = \left[\frac{f_{\rm bar}}{m_p}\frac{1+X}{2}\bar{\rho}(z)(1+\delta_g)\right]^{-2/3} T \text{ keV cm}^2, \quad (1)$$

where $\bar{\rho}(z) = \bar{\rho}_0(1+z)^3$ is the average cosmic matter density at redshift z, δ_g is the gas overdensity, m_p is the proton mass, and X is hydrogen mass fraction ($X = 0.76$ is assumed in the following discussion). Accordingly, the entropy of the ith gas particle in the simulation is defined as $s_i = T_i/n_i^{2/3}$, where T_i and n_i are the temperature and the electron number density, respectively, associated with that particle. At $z = 3$, we select all the gas particles with overdensity $\delta_g > 5$, so that they correspond to structures that have already undergone the turnaround. After assuming a minimum floor entropy, $S_{\rm fl}$, each gas particle having $s_i < S_{\rm fl}$ is assigned an extra thermal energy, so as to bring its entropy to the floor value, according to equation (1). We choose two values for this entropy floor, $S_{\rm fl} = 50$ and 100 keV cm^2. We computed the mean density of the heated gas at $z = 3$ to be $\langle\delta_g\rangle \simeq 185, 280$, 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 SNe 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 into the ICM in these preheating 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 $S_{\rm fl} = 50$ keV cm^2 amounts to giving an average extra heating energy of $E_h = (3/2)\ T_h \simeq 1.4$ keV per particle for the Fornax and Hickson groups and $E_h \simeq 0.9$ keV per particle for the Virgo Cluster. Such values are twice as large for $S_{\rm fl} = 100$ keV cm^2. We also verified that the fraction of gas particles within the virial radius that has been heated at $z = 3$ is of about 75% for both values of $S_{\rm fl}$, almost independent of the mass of the simulated system.

As for the preheating by SN feedback (e.g., Kauffmann, White, & Guiderdoni 1993; Somerville & Primack 1999; Cole et al. 2000), we resort to semianalytical modeling 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. 1999) 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 SNe. During the cluster evolution, this energy is shared among all the gas particles having $\delta_g \geq 50$ (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 the final results do not change by changing by a factor of 10 the above value of the limiting δ_g. Under the assumption that all the energy released by SNe is thermalized into the ICM, this scheme dumps a total amount of about 0.35 keV per particle extra energy per particle.

TABLE 1
CHARACTERISTICS OF THE SIMULATED SYSTEMS

Run	$M_{\rm vir}$ [a] ($\times 10^{13}\ M_\odot$)	$R_{\rm vir}$ [b] (Mpc)	$T_{\rm ew}$ [c] (keV)	$m_{\rm gas}$ [d] ($\times 10^8\ M_\odot$)	ϵ [e] (h^{-1} kpc)
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

[a] Total virial mass.
[b] Virial radius.
[c] Emission-weighted virial temperature for the runs including only gravitational heating.
[d] Mass of gas particles.
[e] Plummer-equivalent softening for gravitational force.

3. RESULTS AND DISCUSSION

The entropy maps of Figure 1 show qualitatively the effect of nongravitational 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 gas particles that have been accreted early, and therefore they are only weakly shocked. A higher entropy level instead characterizes 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 in 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 that separates the inner gas, which sets in hydrostatic equilibrium, from the external cooler and adiabatically compressed medium, which is the interface occurring around the virial radius. Quite remarkably, small halos merging into the cluster's main body are able to keep their low-entropy structure for a few crossing timescales before their gas is stripped. As a consequence, sharp structures arise well inside the virial region, with entropy discontinuities and the tail of gas stripped from the merging subhalos by the effect of the ram pressure. This picture changes as the gas receives nongravitational heating. As the gas is placed on a higher adiabat, it is no longer able to accrete inside the small-mass halos, and

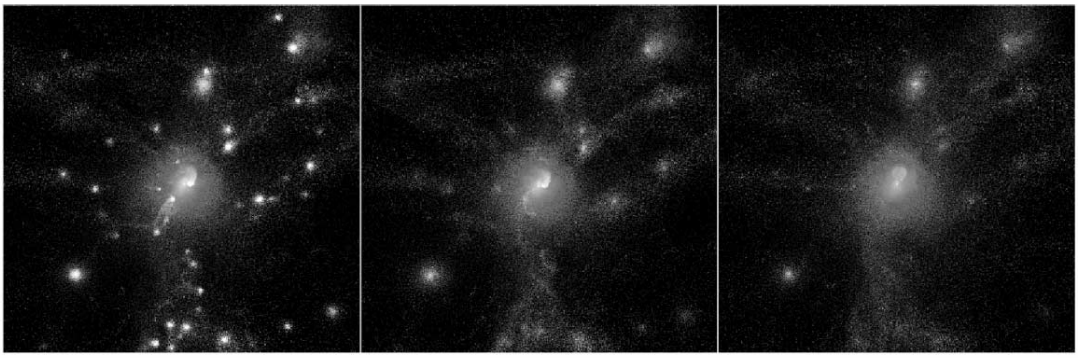

FIG. 1.—Entropy maps for the Virgo Cluster at $z = 0$, within a box of 12.5 Mpc. *Left panel*: Gravitational heating only; *middle panel*: SN feedback with unity efficiency; *right panel*: entropy floor $S_{fl} = 50$ keV cm^2 imposed at $z = 3$. Brighter regions indicate gas with lower entropy.

therefore the accretion shocks are switched off. However, while the small-scale features are progressively washed, a halo of high-entropy, recently shocked gas still surrounds the cluster's main body. Although somewhat smoothed, some discontinuities in the gas entropy are still visible, even in the cluster's central regions. It is quite tempting to associate such features with those recently observed by the *Chandra* satellite (e.g., Markevitch et al. 2000; Fabian et al. 2001; 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 intracluster 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_{ew}, as a function of the radius, in units of the virial radius R_{vir}, we emphasize the self-similar behavior of the ICM in the presence of gravitational heating only (the plotted quantity would be proportional to $\rho_{gas}^{-2/3}$ 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 Figure 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 illustrate 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 subhalos, appearing in Figure 1, which bring low-entropy gas inside the main body of the clusters. Although such merging structures violate the assumption of the spherical accretion of the TN01 model, they do not alter the global behavior of the cluster entropy. The presence of nongravitational heating has the twofold effect of making the entropy profiles shallower while breaking the self-similarity to a degree that 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 $S_{fl} = 50$ 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 $\sim 0.2 R_{vir}$. In general, although extra heating largely modifies gas entropy in the cluster central regions, it has only a marginal effect at $\sim R_{vir}$. This is consistent with the expectation that gravitational shocks provide the dominant mechanism for establishing the global heating of the gas.

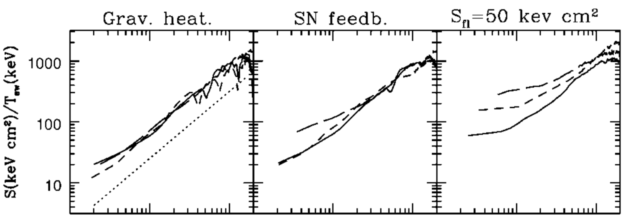

FIG. 2.—Profiles of specific entropy in units of T_{ew}. The three panels, from left to right, correspond to the same heating schemes as in Fig. 1. The solid, short-dashed, and long-dashed curves are for the Virgo Cluster, the Fornax group, and the Hickson group, respectively. Each profile is shown down to the radius encompassing 100 gas particles, which is taken as the smallest scale adequately treated by the SPH scheme. The dotted line in the left panel shows the analytical prediction by TN01 for the profile of entropy induced by gravitational heating.

We compare in Figure 3 the observational data by PCN on the gas entropy for clusters and groups at $0.1R_{vir}$ with the results obtained from our simulations. As discussed by PCN, such data indicate that some preheating 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 $S \propto T_{ew}$. 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 the central entropy by a larger amount for smaller systems. Heating with about $\frac{1}{3}$ keV per particle, with a redshift modulation as

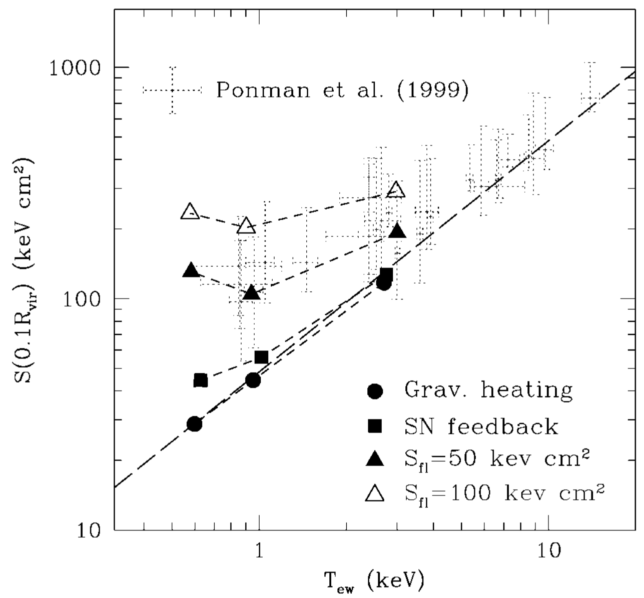

FIG. 3.—Relation between specific gas entropy at $0.1R_{vir}$ and the emission-weighted virial temperature, T_{ew}. The filled circles are for the runs with gravitational heating, the filled squares are for SN energy feedback, and the filled and open triangles are for an entropy threshold settled at $z = 3$ at the two different values reported in the labels. The dotted crosses are the data by PCN, rescaled to $h = 0.7$. The long-dashed line shows the relation $S(0.1R_{vir}) = 50(T/\mathrm{keV})(f_{bar}/0.06\ h^{-2})^{-2/3}$ keV cm², which fits the observational results for $T \gtrsim 6$ keV clusters (PCN).

predicted by our SN model, has quite a 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_{ew} almost unchanged. Even for the Hickson group, the value of $S(0.1R_{vir})$ for such heating schemes turns out to be about twice as large as S_{fl}. This shows how after the gas is preheated, gravitational effects still act to increase its entropy down to $0.1R_{vir}$. We also find that varying the heating redshift from $z_h = 1$ to $z_h = 5$ in the Fornax simulation does not affect the central entropy, thus indicating that this quantity depends mainly 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 nongravitational 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. 2001; Paper II). What are the implications of this result on the astrophysical sources responsible for the heating of the intergalactic medium? Although our results suggest that the majority of the required energy budget cannot be supplied by Type II SNe, the final answer to the above question requires a better understanding and a more accurate treatment of several physical processes. Radiative cooling, which is not 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 on the outskirts of clusters starts flowing inside, thus increasing the central entropy level. Since the cooling timescale is always much shorter than the dynamical timescale in central cluster regions, a fraction of gas as large as ~50% can leave the diffuse hot phase (e.g., Balogh et al. 2001; Paper II). This result is at variance with observations that instead indicate only a small fraction of cluster baryons residing in the cold phase (~10%; Balogh et al. 2001), thus calling for the presence of a feedback mechanism, which was 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 *XMM-Newton* satellites (e.g., Böhringer et al. 2000) will shed light on the interplay between ICM physics and the history of star formation in clusters.

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