Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Studying clusters of galaxies with hydrodynamical simulations

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Abstract. I review recent results of cosmological hydrodynamic simulations for clusters of galaxies. Such simulations have developed into an increasingly powerful tool to make theoretical predictions for clusters, and to confront them with observations. I focus, in particular, on the continuing challenge to reproduce the observed cluster X-ray scaling relations in CDM simulations. Self-consistent simulations that include radiative cooling, star formation and supernova feedback generally overpredict the X-ray luminosity on group scales and exhibit overly strong cooling flows. Solving these problems may require the consideration of more physics in cluster simulations, for example thermal conduction or heating by a central AGN.

1. Introduction

Beginning with the pioneering study by Evrard (1990), hydrodynamical simulations have developed into an indispensable tool for studying the formation of clusters of galaxies, and to explore the physics of the intra-cluster medium (ICM). Direct simulation is the only available technique to capture the dynamics of clusters in full generality, and hence to make detailed theoretical predictions for cluster properties expected in CDM cosmologies. Unsurprisingly, the list of topics investigated with hydrodynamic simulations has therefore become very long. It includes basic cluster properties like the run of gas density and temperature with radius, the X-ray emission of clusters, or their radiative cooling properties. Recently, this list has been augmented with studies of the thermal and kinetic Sunyaev-Zeldovich effects, AGN heating processes by jets and radio bubbles, cold fronts in the ICM, dissipative heating of the ICM by sound waves, metal enrichment, thermal conduction, magnetic field amplification during cluster formation, and gravitational lensing using simulated cluster mass models.

A fundamental topic of particular interest in numerical simulations of structure formation are the basic scaling relations of clusters, which have been addressed as a primary goal in numerous simulation studies. As I will discuss in more detail in Section 2, the theory here still faces substantial challenges in accurately matching the observed scaling relations.

Another serious challenge for cluster simulations lies in the observed absence of strong cooling flows in most clusters of galaxies, despite their copious X-ray emission. Apparently, a not yet conclusively identified heating source offsets the cooling losses. It appears likely that this problem is intertwined with that of the scaling relations, i.e. a successful solution may be able to resolve both at once. In Section 3, I will discuss some recent lines of work to study thermal conduction as a potential heating source for the centers of clusters, followed by a brief summary and a discussion of future directions in Section 4.

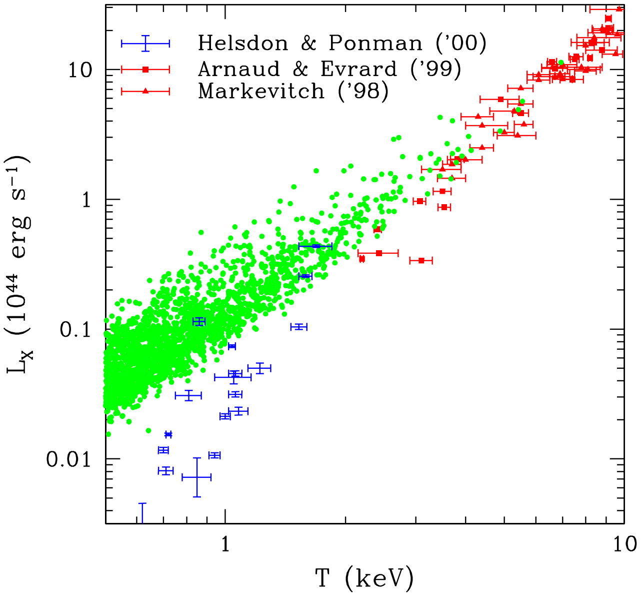

Figure 1. Relation between X-ray luminosity and cluster temperature measured for clusters formed in a large cosmological hydrodynamical simulation. For comparison, symbols with error bars give different observational data sets.

2. Cluster scaling relations

Assuming that clusters of galaxies are approximately self-similar, one expects scale-free scaling relations between basic cluster properties, for example $L_X \propto T^2(1+z)^{3/2}$ for the relation between X-ray luminosity and temperature, or $M \propto T^{3/2}/(1+z)^{3/2}$ for the mass-temperature relation. Already Navarro, Frenk & White (1995) were able to show that these relations are also recovered in CDM simulations where the gas is treated in a non-radiative, 'adiabatic' approximation. This result has been confirmed in numerous subsequent studies with higher resolution, although some small systematic deviations from the ideal self-similar scaling relations exist even here, depending on how cluster properties are measured in detail (see the poster by Sijacki & Tormen).

However, observed cluster-scaling relations differ strongly from self-similar models. In particular, the X-ray luminosity-temperature relation has a considerably steeper slope than the self-similar value of 2, meaning that poor clusters emit comparatively little compared to rich systems, much less than would be expected based on a self-similar scaling. Of course, it is to be expected that the scales imprinted by the physics of radiative cooling invalidate the assumption of self-similarity of clusters, so it is not really unexpected that the self-similar scalings do not hold for real clusters. However, perhaps somewhat more surprising is the fact that two seemingly opposite explanations have been put forward to explain the deficit of luminosity on the group scale.

One idea is to allude to the effect of radiative cooling alone (Bryan 2000; Voit, Bryan, Balogh & Bower 2002). Indeed, if one compares the ICM cooling times with the Hubble time and assumes that all the gas that can cool according to this criterion has dropped out of the ICM, one finds a substantial steepening of the scaling relations, simply because poorer clusters cool more efficiently, i.e. a comparatively larger amount of gas is removed

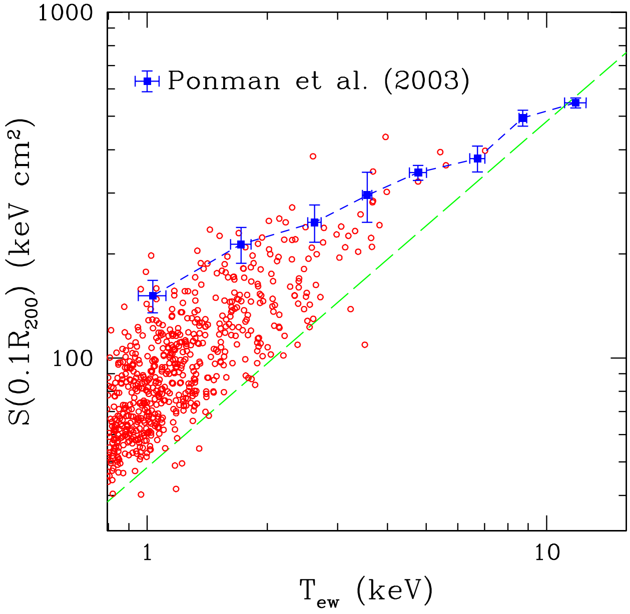

Figure 2. Entropy of clusters as a function of cluster temperature.

from the diffuse gaseous phase. The gas in the center that cools out will then be replaced by inflowing gas of higher entropy, an effect that can then also account for the observed 'entropy excess' on the group scale. This scenario has also been explored in simulations (e.g. Davé, Katz & Weinberg 2002).

The central problem with the 'cooling-only' model is that the amount of gas that is postulated to have cooled out appears to be uncomfortably large, reaching up to $\sim 40\%$ of all the baryons in the cluster. This is at least a factor 3-4 larger than the mass of baryons locked up in long-lived stars (e.g. Balogh, Pearce, Bower & Kay 2001), and much larger than the mass one can hide in supermassive black holes, cold gas, or dark stellar remnants.

The alternative explanation therefore suggests that the high entropy of the intracluster gas in poor clusters is caused by non-gravitational heating of gas, either before it collapsed into the cluster in an epoch of 'preheating', or in situ, for example by AGN or star-formation activity. This lowers the gas densities and X-ray luminosities without necessarily removing the gas from the ICM. These heating processes occur concurrently with cooling, such that the observed cluster scaling relations arise due to a non-linear coupling of heating and cooling, in ways that are actively studied with detailed hydrodynamical simulations (e.g. Muanwong et al. 2002, Tornatore et al. 2003, Kay et al. 2003) that use ad-hoc prescriptions for the heating. A self-consistent, fully successful model has still to be found, however.

Nevertheless, steady progress in hydrodynamical simulations has been made. In Figure 1, results from a recent study by Borgani et al. (2004) are shown, based on a very large cosmological SPH simulation with a particle number of 2×480^3, gas mass resolution of $6.9 \times 10^8\, h^{-1}\mathrm{M}_\odot$, and gravitational softening length of $7.5\, h^{-1}$kpc. The simulation followed radiative cooling, star formation and feedback by supernova and weak galactic winds, using the sub-resolution multiphase model for the interstellar medium proposed

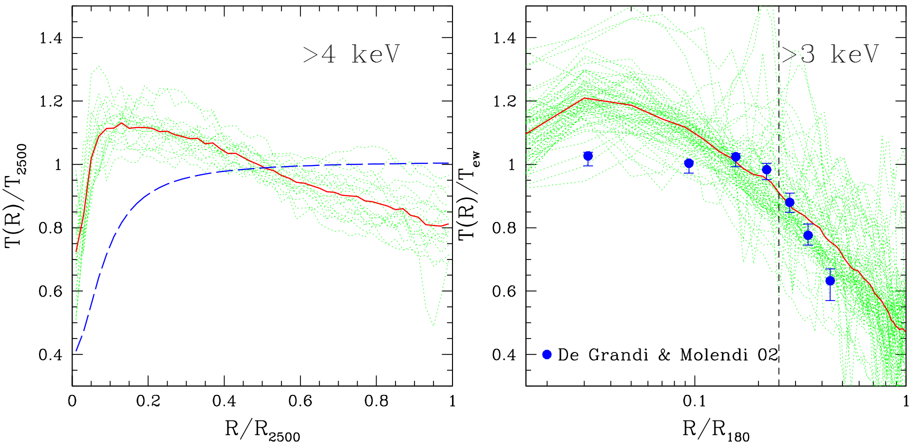

Figure 3. Projected temperature profiles of simulated clusters. The left panel compares with the best-fitting universal temperature profile of Allen, Schmidt & Fabian (2001), while the right panel compares with data from De Grandi & Molendi (2002).

by Springel & Hernquist (2003a,b). The simulation is in fact one of the largest computations carried out thus far with this amount of physics. The large simulation box size of 192 h^{-1}Mpc allowed the identification of a sizable cluster sample, including a few rich systems. Figure 1 shows the X-ray temperature relation measured for the clusters in this simulation, and compares it with observational data points. While there is good agreement for the most massive clusters, poorer systems on the group scale are clearly too luminous, or in other words, the simulated $L_X - T$ relation is not steep enough.

Figure 2 shows the relation between entropy and cluster temperature for the same simulation, compared both to the self-similar expectation, and to observed data, which exhibits a progressively larger 'entropy excess' towards lower mass systems. While the simulation results show clear signs of non-gravitational entropy injection due to feedback on the group scale, the effect is too weak to reconcile them with the observations. We should note however that the simulation shows a gratifying consistency with the observed abundance of clusters as a function of temperature. Also, the mass-temperature relation is in reasonable agreement with observations, highlighting that the bulk properties of clusters are quite well reproduced.

A problematic point concerns the radial temperature profiles of simulated clusters, which tend to be in significant conflict with the observed shape, as illustrated in Figure 3. Instead of showing a largely flat run of temperature with radius, and a shallow decline towards the center, the temperature rises in the inner parts of the simulated clusters and turns into a sharp drop only at the very center where the gas begins to cool rapidly. This is a manifestation of the strong cooling flows that are present in the simulated clusters, which are not observed in this form in reality. This problem appears to be quite universal in simulations with radiative cooling and has been found in similar form by a number of authors (e.g. Lewis et al. 2000; Pearce et al. 2000; Valdarnini 2002).

3. Thermal conduction

The observed absence of strong cooling flows in clusters, despite their copious X-ray emission, is a considerable challenge for hydrodynamical simulations. A number of possible physical heating sources have been proposed that may offset central cooling losses in the cluster. Suggestions include heating by buoyant bubbles inflated by central AGN activity, viscous dissipation of sound waves in the ICM, or supernova explosions in the

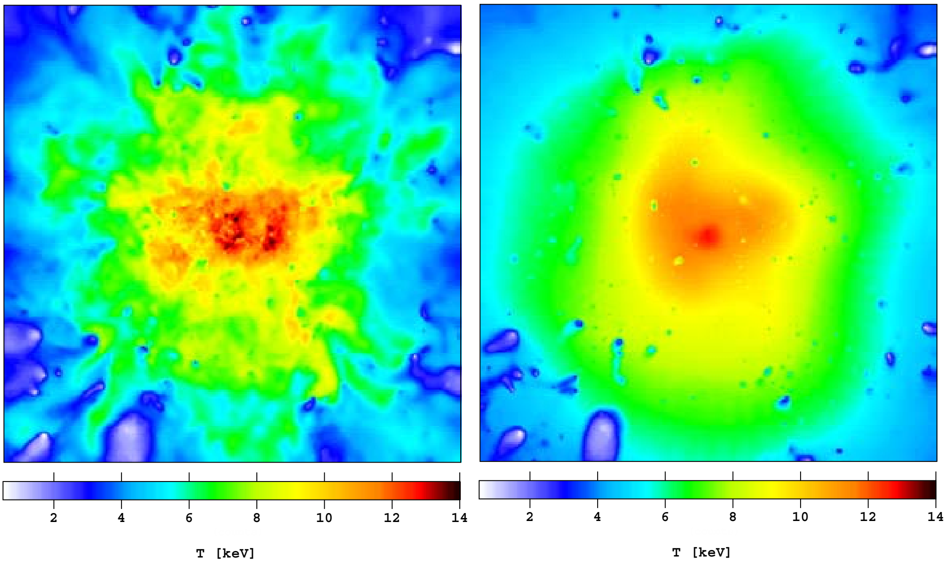

Figure 4. Thermal conduction in a massive cluster of galaxies. The panel on the left shows a temperature map in a simulation with cooling and star formation only, while the panel on the right includes thermal conduction as well.

ICM itself. Recently, Narayan & Medvedev (2001) proposed that thermal conduction may be a viable candidate for such a heating source. Due to the observed declining temperature towards the inner parts of clusters, the resulting temperature gradient should give rise to a heat current into the central parts of the cluster, provided the conductivity of the ICM is large enough. Note that the conductivity of an ionized plasma can be reduced substantially by magnetic fields, so that a major uncertainty in this conjecture lies in the unknown value of the remaining effective conductivity of the ICM.

Zakamska & Narayan (2003) have shown that for conductivities in the range 0.1-0.3 of the Spitzer value, the temperature profiles of a number of observed clusters can be explained well using a hydrostatic model where local radiative losses are assumed to be compensated by conductive heating. These required conductivities may be plausible even in the presence of magnetic fields, provided the field is sufficiently turbulent such that electrons can effectively ‘diffuse’ from field line to field line (Narayan & Medvedev 2001). A weakly tangled magnetic field may however reduce the conductivity by a factor > 100 compared with the unmagnetized Spitzer rate.

Depending on the magnetic field topology, there may hence be room for conduction in clusters. Note that due to the strong temperature dependence of the conductivity, $\kappa \propto T^{5/2}$, it can however be expected that it will affect the richest clusters most strongly, while becoming rapidly less important for lower mass systems.

Leaving the uncertainties about the real effective thermal conductivity of the ICM aside, it is then interesting to ask whether temperature profiles that support conductive heating of the inner parts of clusters could naturally arise in self-consistent cosmological simulations of cluster formation. Due to the non-linear interplay of cooling and conduction, with their different temperature dependences, this question is difficult to answer without hydrodynamical simulations from cosmological initial conditions.

Jubelgas, Springel & Dolag (2004) have introduced a new formulation of conduction in the SPH formalism, and implemented it in the cosmological simulation code GADGET-2.

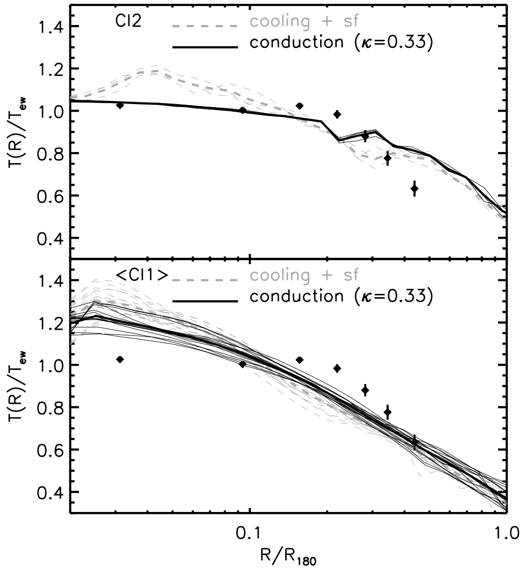

Figure 5. Radial temperature profiles in simulated clusters, for a very massive cluster (top) and several poor systems (bottom). In each case, simulations with conduction (solid lines) are compared with simulations that just included radiative cooling and star formation (grey dashed lines).

Dolag et al. (2004) used the method to study the formation of poor and rich clusters, assuming an effective isotropic conductivity equal to 1/3 of the Spitzer value $\kappa_{\rm Sp}$.

Figure 4 shows temperature maps of a massive cluster which was simulated twice (Dolag et al. 2004), once with cooling and star formation only, and a second time by also including conduction with an effective isotropic conductivity of $\kappa = 1/3\,\kappa_{\rm Sp}$. It is seen that the temperature structure is drastically modified by conduction. Small-scale temperature fluctuations are largely wiped out, except for the cold gas still bound to the centers of cluster galaxies. Also, the outer cluster regions are heated relatively to the simulation without conduction. We note that the heat loss to the outer IGM is however bounded by saturation effects, which are included in the simulation and become important for very low gas densities.

4. Discussion

Cosmological hydrodynamical simulations have proved instrumental to advance the theoretical understanding of cluster formation. While the bulk thermodynamic properties of clusters can be reproduced reasonably well with the present generation of high-resolution simulations, reproducing the detailed thermodynamic state of the ICM gas is still an elusive goal. Early hopes that inclusion of radiative cooling and some form of (comparatively weak) feedback associated with star formation would resolve the problems have not been fulfilled.

Based on the first dynamical calculations with thermal conduction, it also appears increasingly unlikely that conduction may solve the cooling flow riddle. It may still play a role in rich systems, although the strong temperature dependence of conduction may cause new problems in the scaling relations.

Future simulations of cluster formation may therefore need to include additional physics, with the most promising candidate arguably being AGN feedback. Using idealized simulations of buoyant bubbles, Churazov et al. (2001) and Quilis, Bower & Balogh (2001) have shown that heated bubbles may rise in the cluster and uplift cool gas. Combing this with radiative cooling, Dalla Vecchia et al. (2004) explored a model with periodic bubble heating, showing that the cooling losses in the central cluster region can be completely compensated for by periodic AGN activity. The required energy and duty cycle appear plausible, showing that the AGN certainly has enough power to provide the necessary heating. One key problem is how much of the energy released by the accreting black hole is coupled into the ambient gas. A number of detailed simulations of the interaction of the AGN-driven jet with the diffuse gas have already been carried out (e.g. Brüggen & Kaiser 2002; Reynolds, Heinz & Begelman 2002), and will continue to shed more light on this issue in the future. What is missing at the moment are cosmological simulations that follow cluster formation *and* AGN activity from high-redshift to the present. Such self-consistent simulations will be needed to show whether AGN feedback will bring us yet a step closer to simulation models that will eventually capture the most important physics of real clusters of galaxies.

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