STUDY OF GALAXY CLUSTER PROPERTIES FROM HIGH-RESOLUTION SPH SIMULATIONS

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Abstract

We present some of the results of an ongoing collaboration to study the dynamical properties of galaxy clusters by means of high resolution adiabatic SPH cosmological simulations. Results from our numerical clusters have been tested against analytical models often used in X-ray observations: $\beta$ model (isothermal and polytropic) and those based on universal dark matter profiles. We find a universal temperature profile, in agreement with AMR gasdynamical simulations of galaxy clusters. Temperature decreases by a factor 2-3 from the center to virial radius. Therefore, isothermal models (e.g. $\beta$ model) give a very poor fit to simulated data. Moreover, gas entropy profiles deviate from a power law near the center, which is also in very good agreement with independent AMR simulations. Thus, if future X-ray observations confirm that gas in clusters has an extended isothermal core, then non-adiabatic physics would be required in order to explain it.

1. Introduction

Clusters of galaxies are the largest gravitationally bound structures in the universe. Therefore, they have often been considered as a canonical data set for cosmological tests. During the last two decades, a great effort has been devoted to investigate the mass distribution in CDM haloes by means of numerical N-body simulations. It is now firmly established that dark matter density profiles can be fitted by an universal two-parameter function, valid from galactic to cluster scales. For the gas component, the situation is less clear. The ICM is in the form of a hot diffuse X-ray emitting plasma, where the cooling time (except in the innermost regions) is typically longer than the age of the universe. Adiabatic gasdynamical simulations have therefore been used to study the formation and evolution of galaxy groups and clusters in different cosmologies. The Santa Barbara Cluster Comparison Project (Frenk et al., 1999, SBCCP) showed a clear difference between SPH and Eulerian Adaptive
Mesh Refinement (AMR) codes. While (the only one available at that time) Bryan and Norman’s AMR code predicted an isentropic gas profile at the center, all the SPH codes used in SBCCP predicted an isothermal gas distribution almost to the virial radius of the Coma-like simulated cluster. As pointed out by several people (e.g. Lewis et al., 2000; Serna et al., 2003), the standard SPH method could suffer from entropy conservation problems. This is particularly accentuated in low mass resolution SPH simulations (see Borgani et al., 2002). A new implementation of SPH has been recently proposed (Springel and Hernquist, 2002) in which entropy conservation is much better fulfilled.

In order to assess the reliability of our numerical results, we did an extensive convergence study in terms of resolution (mass and spatial), as well as numerical technique. For this last purpose, we resimulated one of our clusters with 3 different numerical codes: Tree-SPH GADGET, both with the standard (Springel et al., 2001) and the entropy conserving SPH implementation (Springel and Hernquist, 2002), as well as the Eulerian AMR code ART (Kravtsov et al., 2002). Radial profiles of gas and dark matter are compared in Figure 1. The agreement between AMR and the entropy version of GADGET is remarkable. The standard SPH GADGET still shows the same trend reported in Frenk et al. (1999), although our mass resolution is 64 times better (512^3 effective particles).

2. Numerical experiments

We have carried out a series of high-resolution gasdynamical simulations of cluster formation in a flat LCDM universe ($\Omega_m = 0.3; \Omega_\Lambda = 0.7; h = 0.7; \sigma_8 = 0.9; \Omega_b = 0.02 h^{-2}$). Simulations were run with the entropy conserving SPH version of the parallel Tree code GADGET. We have selected 15 clusters extracted from a low-resolution (128^3) volume of 80$h^{-1}$ Mpc. Each object has been re-simulated by means of the multiple mass technique (e.g. Klypin et al., 2001). We use 3 levels of mass refinement, reaching an effective resolution of 512^3 CDM particles ($\sim 3 \times 10^8 h^{-1} M_\odot$). Gas has been added in the highest resolved area only. The gravitational smoothing was set to $\epsilon = 2 - 5 h^{-1}$ kpc, depending on number of particles within the virial radius (Power et al., 2003). The minimum smoothing length for SPH was fixed to the same value as $\epsilon$. The X-ray temperature of these objects ranges from 1 to 3 keV. For a more extended description of the numerical experiments, the reader is referred to Ascasibar (2003).

3. Results

A detailed discussion of the results from our numerical experiments can be found elsewhere (Ascasibar, 2003; Ascasibar et al., 2003). Here, we will focus on the radial structure of gas and dark matter in clusters.
Figure 1. **Left:** Comparison of density, temperature and entropy profiles for a cluster simulated with 3 different numerical hydro codes: Standard SPH GADGET (dashed lines); Entropy-conserving GADGET (solid lines) and eulerian AMR ART code (crosses). **Right:** Testing Hydrostatic equilibrium (upper panel) and polytropic equation of state (lower panel) in our numerical clusters, classified according to their dynamical state.

We have considered four self-consistent analytical models, based on the hypotheses that the hot ICM gas is in hydrostatic equilibrium with the dark matter halo and that it follows a polytropic equation of state. Two of our models assume NFW (Navarro et al., 1997) and MQGSL (Moore et al., 1999) formulae to describe the CDM density profile, whereas the other two assume a $\beta$-model for the gas distribution. One is an isothermal version with $\beta = 2/3$ (BM) and the other is a polytropic model with $\gamma = 1.18$ and $\beta = 1$ (PBM). We have first tested the hypothesis of hydrostatic equilibrium (HE) and polytropic equation of state (e.o.s) for the gas in our clusters. In Figure 1 (right) we show the results of this test. H.E. is nicely fulfilled by those clusters that are in a relaxed or minor merger state. The e.o.s for the gas in these clusters can be reasonably approximated by a constant polytropic index of $\gamma \sim 1.2$. Then, we compared the simulated radial distributions of gas and dark matter with each analytical model. By fitting the numerical X-ray surface brightness, the models based on universal CDM profiles are able to estimate the ICM properties within $30 \sim 40\%$ errors. $\beta$-models yield similar estimates for $r \geq 0.1R_{200}$, but the shape of the inferred profiles at smaller radii are severely misleading.

In Figure 2 (left) we plot the spherically averaged temperature profile of our halos, together with the best fit for each analytical model. As can be seen, the $\beta$-model gives the poorest fit because gas in simulations is far from being isothermal.

The projected emission-weighted temperature profile is also shown in Figure 2 (right), compared with recent AMR cluster simulations (Loken et al., 2002) and with X-ray observations. Both sets of simulations predict the same
universal gas temperature profile for clusters, with no indication of an isothermal core. This is one of the few cases in which SPH and AMR simulations agree so well on one issue. If the existence of a large isothermal core is indeed confirmed by upcoming X-ray observations, it would be an indication that non-adiabatic processes must be considered in numerical simulations of galaxy cluster formation.

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