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Clusters of galaxies: new results from the CLEF hydrodynamics simulation

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Abstract

Preliminary results are presented from the CLEF hydrodynamics simulation, a large ($N = 2 \times 428^3$ particles within a 200 h^{-1} Mpc comoving box) simulation of the ΛCDM cosmology that includes both radiative cooling and a simple model for galactic feedback. Specifically, we focus on the X-ray properties of the simulated clusters at $z = 0$ and demonstrate a reasonable level of agreement between simulated and observed cluster scaling relations.

Keywords: Cosmology; Clusters of galaxies; X-ray, Numerical simulations; Hydrodynamics; Galaxy formation

1. Introduction

As the largest and latest virialised structures to form, galaxy clusters are especially useful cosmological probes (e.g. see Viana et al., 2003, and references therein). Next generation cluster cosmology surveys, such as the XCS (Romer et al., 2001), will detect sufficiently large numbers of clusters that uncertainties in values of cosmological parameters will be mainly systematic, requiring for example an accurate calibration between cluster X-ray temperature and mass. Such measurements demand an improved understanding of cluster physics, therefore realistic numerical simulations of the cluster population are essential.

In this paper, we present a preliminary analysis of the $z = 0$ cluster population within the CLEF hydrodynamics simulation, a large state-of-the-art cosmological simulation that, besides gravity and gas dynamics, includes a model for the effects of galaxy formation. As we will show, the simulation does a reasonably good job at reproducing X-ray scaling relations at $z = 0$.

2. The CLEF hydrodynamics simulation

The CLEF (CLuster Evolution and Formation) hydrodynamics simulation (see Fig. 1) is a large simulation of structure formation within the ΛCDM cosmology, with the following cosmological parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b\ h^2 = 0.0238$, $h = 0.7$ and $\sigma_8 = 0.9$. These values are in good agreement with recent *WMAP* analyses (Spergel et al., 2003).

Initial conditions were generated using a modified version of the COSMIC software package provided with the HYDRA code (Couchman et al., 1995). The appropriate

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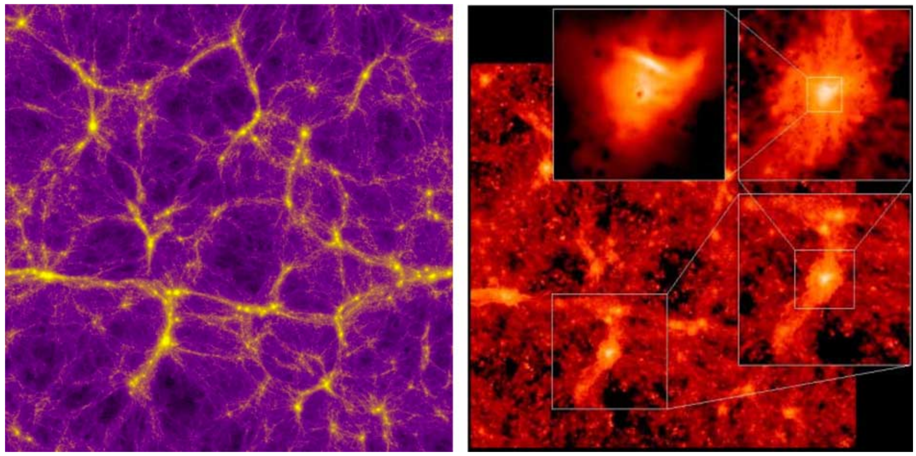

Fig. 1. Left: optical depth image of the gas in a $200 \times 200 \times 10\ \mathrm{h}^{-1}$ Mpc slice at $z = 0$. Right: series of zooms showing images of the mass-weighted temperature of the gas, from the full box width to an individual cluster.

transfer function, generated using CMBFAST (Seljak and Zaldarriaga, 1996), was read in and a displacement field generated for a $200\ \mathrm{h}^{-1}$ Mpc comoving box at $z = 49$. Two regular cubic grids of 428^3 particles, separated by half the interparticle distance in each of the x, y and z directions, were then perturbed by these displacements to create the initial particle positions. Thus, the gas and dark matter particle masses were set to $m_{\rm gas} = 1.4 \times 10^9\ \mathrm{h}^{-1}\ M_\odot$ and $m_{\rm dark} = 7.1 \times 10^9\ \mathrm{h}^{-1}\ M_\odot$, respectively.

This initial configuration was then evolved to $z = 0$ using version 2 of the GADGET code (Springel et al., 2001), a hybrid Particle-Mesh/Tree gravity solver with a version of Smoothed Particle Hydrodynamics (SPH) that explicitly conserves entropy where appropriate. In addition, the gas could cool radiatively, assuming a fixed metallicity of $Z = 0.3\,Z_\odot$. Cooled gas, with $n_{\rm H} > 10^{-3}\ \mathrm{cm}^{-3}$ and $T < 1.2 \times 10^4$ K, could either form stars if $r > f_{\rm heat}$ or be reheated by stars if $r < f_{\rm heat}$, where r is a random number drawn for each particle from the unit interval and $f_{\rm heat} = 0.1$ is the reheated mass fraction parameter. Each reheated gas particle was given a fixed amount of entropy, $S_{\rm heat} = 1000\ \mathrm{keV\ cm}^2$, where $S \equiv kT/n^{2/3}$, which further heats the ICM as the particle does work on its surroundings. Further details may be found in Kay et al. (2004).

3. X-ray scaling relations at $z = 0$

In this paper, we concentrate on comparing a selection of simulated and observed X-ray cluster scaling relations at $z = 0$. Clusters were identified by first identifying local maxima in the density field and growing spheres around these maxima until the average density within each sphere was a fixed factor, Δ, above the critical density, $\rho_{\rm cr} = 3H_0^2/8\pi G$. Values of Δ used will be given in each subsection. For the virial density ($\Delta \sim 104$) there are >400 clusters with $kT_{\rm vir} > 1$ keV (>60 above 3 keV).

3.1. Temperature–mass relation

We begin by showing in Fig. 2 the relation between hot gas mass-weighted temperature ($T_{\rm gas} \equiv \sum_i m_i T_i / \sum_i m_i$, where the sum is over all gas particles with $T_i > 10^5$ K) and total mass for a density contrast $\Delta = 2500$. All clusters with $M_{2500} > 3 \times 10^{14}\ \mathrm{h}^{-1}\ M_\odot$ are considered. The dashed line is a best-fit relation to the clusters for a fixed slope of 2/3, as expected if the clusters form a self-similar population. This relation is

$$\log(kT_{\rm gas}/\mathrm{keV}) = (0.614 \pm 0.003) + (2/3) \times \log(M_{2500}/M_{14}), \qquad (1)$$

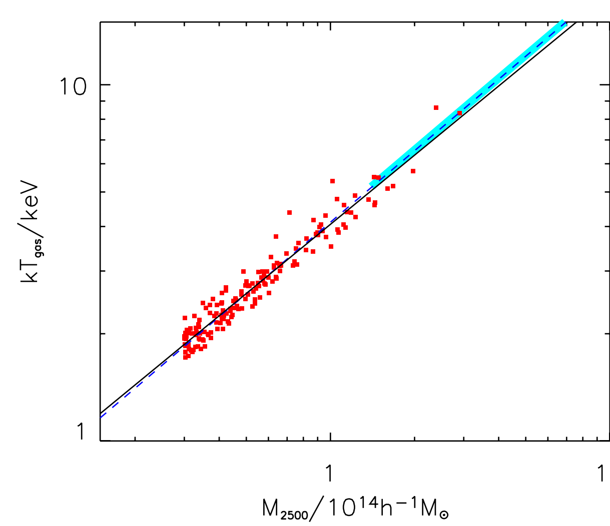

Fig. 2. Gas mass-weighted temperature versus mass, evaluated at $\Delta = 2500$. The dashed line is the best-fit relation with the self-similar slope 2/3. The solid line is the best-fit relation, allowing both the normalisation and slope to vary. The solid band is the best-fit relation to clusters studied by Allen et al. (2001).