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HYDRODYNAMICAL SIMULATIONS OF X-RAY CLUSTERS OF GALAXIES

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We present results from a series of cosmological SPH simulations which are designed to predict the statistical properties of X-ray clusters of galaxies as well as to study the formation of galaxies. We have several simulation runs with different assumptions on the thermal state of the intracluster gas, and all the simulations employ 2 million particles both for dark matter and gas. So, these simulations constitute the largest systematic catalogues of simulated clusters so far, and enable us to compare the analytical predictions on statistical properties of X-ray clusters in an unbiased manner. We find that the mass-temperature relation for simulated clusters is fairly insensitive to the thermal state of the intracluster gas, and agrees well with the analytic prediction. Therefore, the prediction for the X-ray temperature function of clusters on the basis of the Press-Schechter mass function is fairly reliable.

1 Introduction

Clusters of Galaxies are widely used as probes to extract the cosmological information from observed cluster abundance such as X-ray lumninosity function (XLF), X-ray temperature function (XTF) and number counts [1,2,3]. The essense of these probes is to compare the observed cluster abundance with the theoretical predictions based on the physically motivated Press–Schechter mass function for a given set of cosmological parameters and to find out the most optimal parameters by minimizing the difference between them. In this procedure, we have to use some relations among X-ray luminosity, temperature of intracluster medium (ICM), and cluster mass; temperature–mass (T–M) relation and luminosity–temperature (L–T) relation.

The T–M relation can be analytically predicted using some assumptions such as isothermality and hydrostatic equilibrium of ICM [2]. Several physical processes like radiative cooling, supernova feedback and non-sphericity of clusters, however, may invalidate this prediction. The L–T relation is also a matter of debate. It can be directory measured from observations, but has significant large scatter around the relation, especially for high redshift clusters due to large observational uncertainty [4,5,6]. Thus, these relations have to be fixed or confirmed by numerical simulations in a complementary manner to observational approaches.

In previous numerical simulations of clusters of galaxies, pure N-body simulations, which follow only gravitational dynamics of dark matter, can cover very large cosmological volume with sufficient numerical resolution by adopting very large number of particles and they were used to check the validity of Press–Schechter mass function. However, we need some simplified and/or heulistic assumptions on hydrodynamical processes in order to obtain the information about physical properties of the ICM. On the other hand, hydrodynamical simulations are quite demanding regardless of numerical algorithms and need much larger computational costs compared with pure N-body simulations. Thus, we were limited to simulations of a single cluster and could not have access to the statistical information of clusters [7].

In this paper, we show numerical simulations of clusters of galaxies which overcome these two drawbacks mentioned above, which mean hydrodynamical simulations with sufficient numerical resolution in the cosmological large volume. From these simulations, we construct the statistically unbiased catalogues of clusters of galaxies.

2 Description of Simulations

2.1 Simulation Code and Models

Our simulation code adopts Particle–Particle–Particle–Mesh (PPPM) algorithm for gravitational solver and smoothed particle hydrodynamics (SPH) for hydrodynamics, where we can include the effect of radiative cooling and UV-background heating in a consistent manner. In addition, we have implemented a phenomenological treatment of multiphase gas dynamics which we will discuss in the next subsection.

We consider a low-density spatially flat CDM universe with mean the mass density parameter $\Omega_0 = 0.3$, cosmological constatnt $\lambda_0 = 0.7$, the baryon density parameter $\Omega_{\rm b} = 0.015h^{-2}$, hubble constant $h = 0.7$ in units of 100 km/s/Mpc. And we adopt the rms density fluctuation on a scale of $8h^{-1}$ Mpc $\sigma_8 = 1.0$. This model is constrained by recent studies of cluster abundance [2,6] and *COBE* nomalization [8]. The size of simulation box is set to $75h^{-1}$ Mpc and $150h^{-1}$ Mpc so as to contain several rich clusters within a simulation box. We adopt about 2 million particles each for dark matter and gas in order to have sufficient numerical resolution.

2.2 Cold Gas Decoupling

It is well known that the effect of radiative cooling in SPH simulations results in unrealistically large X-ray luminosity. While Suginohara & Ostriker [9] ascribed this large luminosity to the missing physical processes like SN energy feedback and heat conduction, Pearce et al. [10] have found that the density of hot gas is overestimated in the vicinity of cold dens clump at the cluster center because of SPH smoothing effect. In order to avoid this numerical artifact, we decouple cold dense gas particles from hot gas particles. In practice, we exclude any contribution to hot ($T > 10^5$ [K]) gas density from cold gas particles which satisfy the following Jeans condition

$$h > \frac{c_s}{\sqrt{\pi G \rho_{\rm gas}}}, \tag{1}$$

where h is the smoothing length of gas particles, G the gravitational constant, c_s the sound speed and $\rho_{\rm gas}$ the gas density, while all the other SPH interactions are left unchanged.

Figure 1 shows the spherically averaged radial profiles of dark matter and hot gas density and enclosed X-ray luminosity for runs with and without cold gas decoupling. Without cold gas decoupling, we have very high density core of hot gas and unacceptably large X-ray luminosity which is consistent with the result in Suginohara & Ostriker [9]. On the other hand, this artificial features are highly suppressed for the cluster with cold gas decoupling,

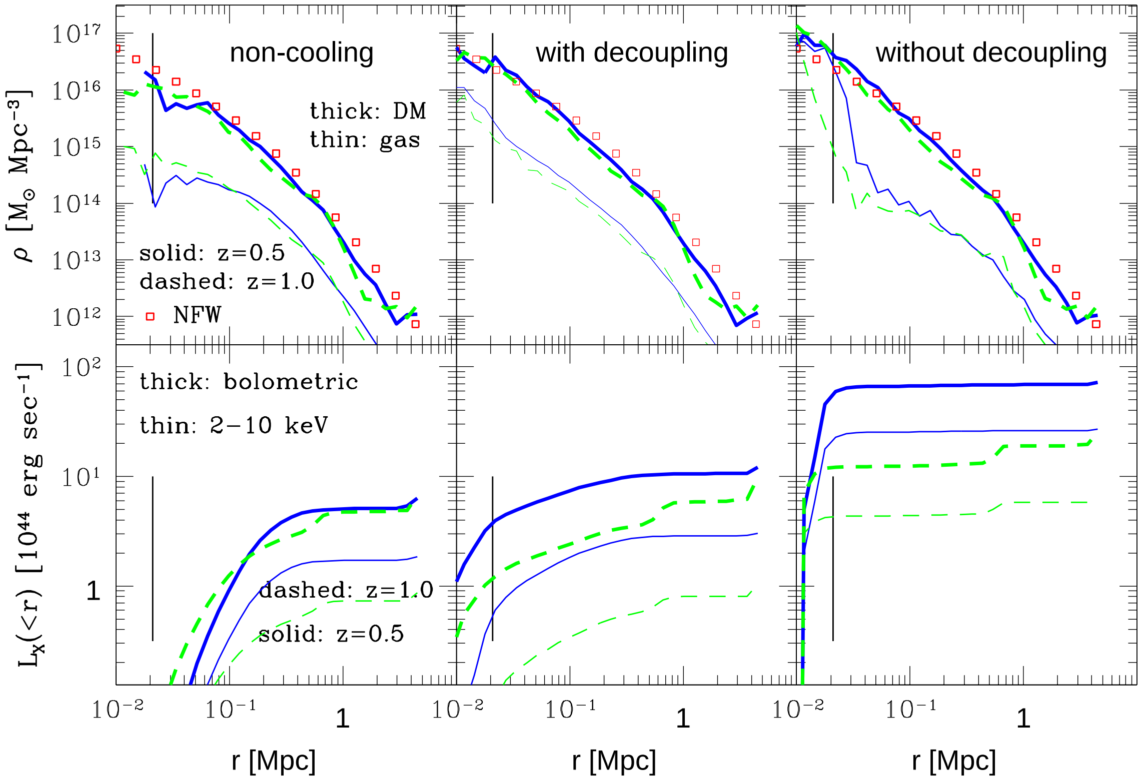

Figure 1: Radial profiles of dark matter and hot gas density and enclosed X-ray luminosity for a cluster at $z = 0.5$ (solid lines) and $z = 1.0$ (dashed lines). For reference, the universal density profile at $z = 0.5$ corresponding to the virial mass of the cluster is plotted in open squares.

3 Statistical Properties of X-ray Clusters

At each epoch, we identify gravitationally bound object using adaptive "friend-of-friend" algorithm [11] and select objects with more than 200 dark matter and gas particles as clusters of galaxies. The virial mass M of each cluster is defined as the total mass at the virial radius within which the average mass density is $\simeq 18\pi^2\Omega_0^{0.4}\rho_c(z)$ where $\rho_c(z)$ is the critical density of the universe at redshift z. The X-ray luminosity is computed on the basis of the bolometric and band limited thermal bremsstrahlung emissivity in Rybicki & Lightman [12] which ignores metal line emission. We also compute the mass weighted and emission weighted temperature of ICM, $T_X^{\rm m}$ and T_X, using 2–10 keV band emission.

According to Steinmetz & White [13], hydrodynamical simulations combined with N-body simulations can suffer from artificial heating for less massive objects. In order to avoid this artifact in the following analysis, we use clusters with $M > 10^{14}M_\odot$ and $M > 10^{13}M_\odot$ for the model with simulation box size $150h^{-1}$ Mpc and $75h^{-1}$ Mpc per side, respectively. These criteria for halo mass is equivalent with the one in Steinmetz & White [13].

3.1 T–M Relation

Assuming that the ICM is isothermal and hydrostatic equilibrium within the spherical dark matter potential, we have an analytical prediction for T–M relation as

$$k_{\rm B}T_X \sim 5.2\gamma \left(\frac{\Omega_0\Delta_c}{18\pi^2}\right)^{1/3}\left(\frac{M}{10^{15}h^{-1}M_\odot}\right)^{2/3}(1+z_{\rm f})\ {\rm keV}, \qquad (2)$$

where Δ_c is the mean overdensity of a virialized object at a formation redshift $z_{\rm f}$ and γ is a fudge factor of an order of unity [2]. Figure 2 depicts the simulated T–M relations for models

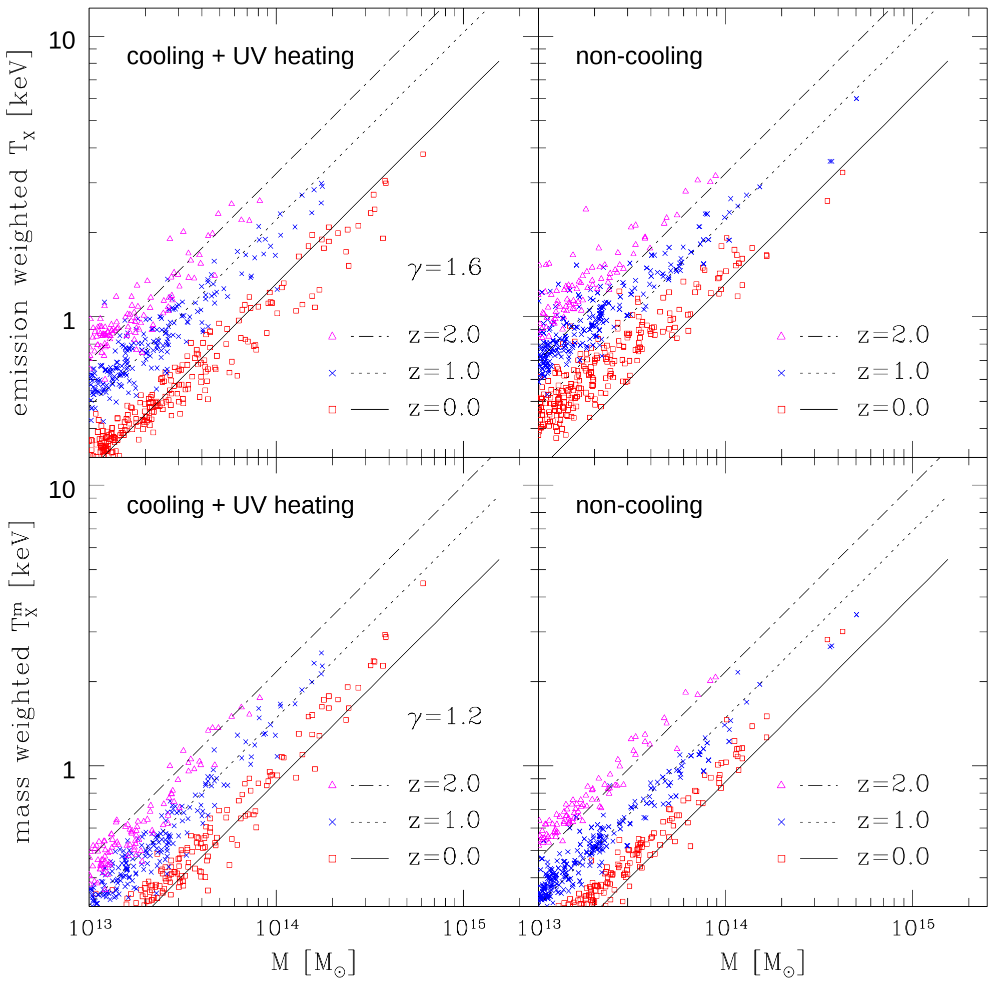

Figure 2: Temperature–mass relations for simulated clusters at redshift $z = 0.0$ $z = 1.0$ and $z = 2.0$ for runs with and without radiative cooling. The upper (lower) panels show the emission (mass) weighted temperature. Lines indicate the theoretical prediction for each redshift.

with and without radiative cooling. The upper and lower panels show emission-weighted and mass-weighted temperature, respectively. The simulated T–M relations are well fitted to the theoretical prediction (2) by setting $\gamma = 1.2$ for mass-weighted temperature and $\gamma = 1.6$ for emission-weighted one regardless of the models. From these results, we can see that the simulated T–M relations are robust and almost insensitive to the physical state of ICM like radiative cooling and well approximated by the theoretical prediction (2) even for high redshift clusters.

3.2 L–T relation

L–T relation of clusters of galaxies and its evolution is hard to predict because X-ray luminosity of clusters is sensitive to the gas density of ICM and hence to the physical state of ICM. The recent X-ray observations of clusters of galaxies implies

$$L_X \propto T_X^{\alpha} \, (1 + z_{\rm f})^{\eta}, \tag{3}$$

where $2.6 < \alpha < 3.4$ and $\eta \simeq 0$ [4,14], while a simple self-similar model [15] predicts $L_X \propto T_X^2 (1 + z_{\rm f})^{3/2}$. Figure 3 shows simulated L–T relations for a non-cooling run (left panel) and cooling runs (middle and right panels). We adopt the metalicity of the gas [Fe/H]$= -0.5$ for the right panel while primordial metal abundance is assumed for the middle panel. We can see that the

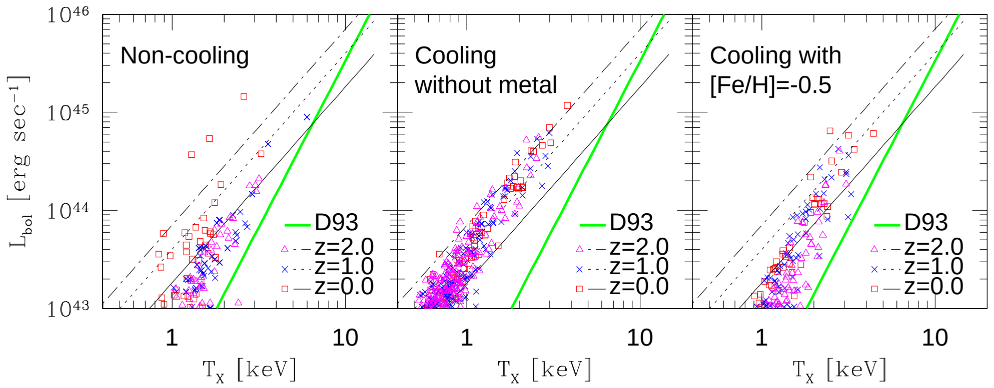

Figure 3: Luminosity–temperature relations for simulated clusters at redshift $z = 0.0$ $z = 1.0$ and $z = 2.0$ for runs with and without radiative cooling. Thin lines indicate the theoretical prediction for each redshift. Bold line is the observational result from David et al.

simulated relations are quite different from each other depending on the cooling rate of the ICM. Therefore, we need more realistic treatment of galaxy formation and its feedback in order to have a reliable estimation of X-ray luminosity of the ICM.

3.3 X-ray Temperature Function

Finally, we show the simulated XTFs for non-cooling and cooling runs in Figure 4 at $z = 0.0$ (lower panels) and $z = 1.0$ (upper panels) as a function of emission-weighted (left panels) and mass-weighted (right panels) temperature. The theoretical predictions of the XTF based on Press–Schechter mass function and analytical T–M relation (2) can fit our simulated XTFs by setting the fudge factor to $\gamma = 1.2$ for mass-weighted temperature and $\gamma = 1.6$ for emission-weighted temperature, regardless of the presence of radiative cooling. These results can justify the use of theoretical XTFs for probing cosmological parameters. We also show the observed XTF of local ($z < 0.1$) galaxy clusters by Markevitch [5] just for comparison.

4 Discussion

On the basis of cosmological SPH simulations of clusters of galaxies, we have extensively investigated the reliability of analytical prediction and statistical properties of clusters of galaxies. The main results are summrized as follows:

(i) In constrast to the huge uncertainties on the X-ray luminosity, the temperature of simulated clusters is fairly robust to the ICM thermal evolution and in fact is in good agreement with the analytic predictions.

(ii) The analytic predictions of XTFs translated from the Press–Schechter mass function are fairly accurate and consistent with the simulated results if we provide the appropriate values of the fudge factor γ.

In addition, by achieving the very wide dynamic range of the simulations, we have constructed statistically unbiased catalogues of clusters of galaxies, which contain the information about temperature of ICM, mass, and also the spatial distribution of clusters. With these catalogues, we can construct temperature limited mock samples of galaxy clusters which can be directory compared with the forthcoming cluster survey.

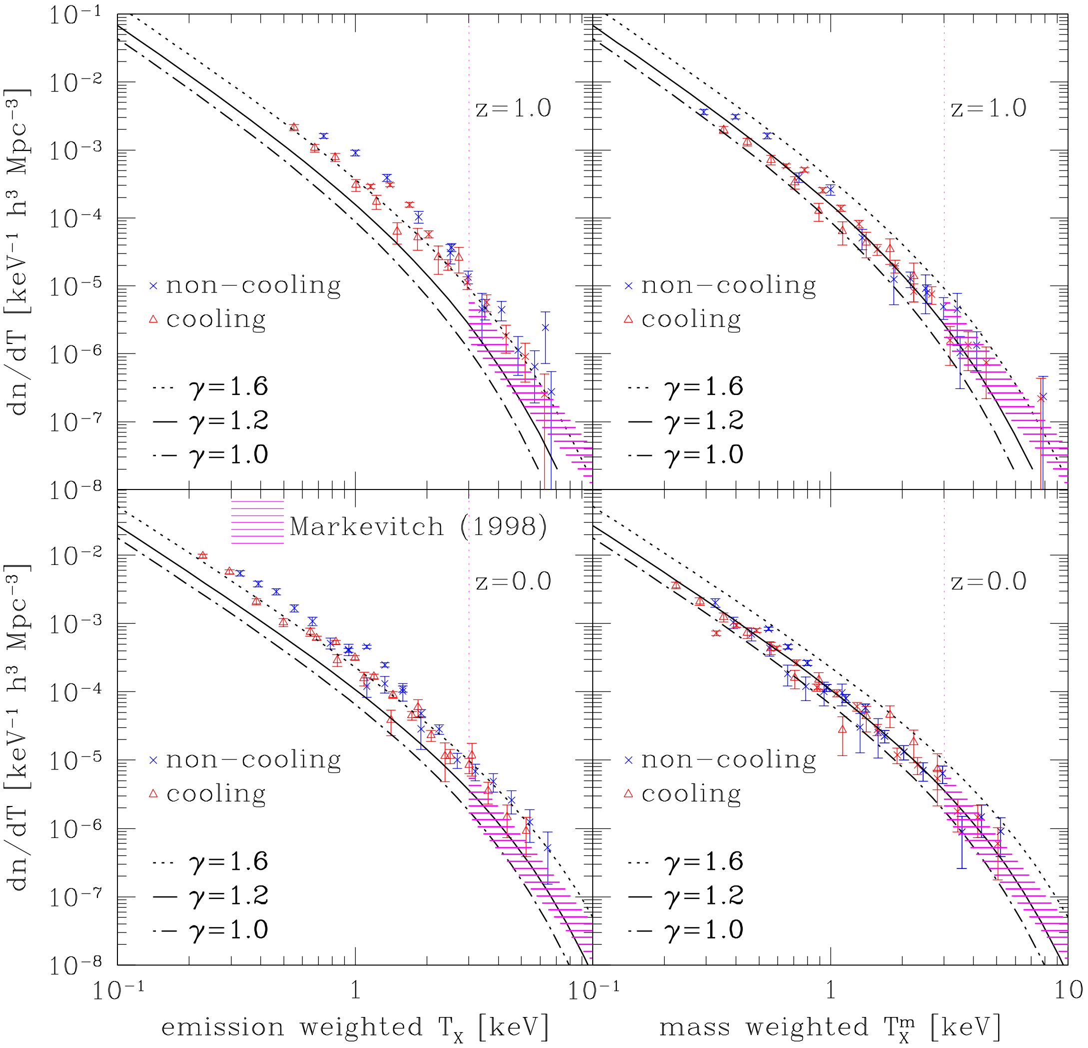

Figure 4: X-ray temperature function of simulated sample of galaxy clusters at $z = 0.0$ (lower panels) and $z = 1.0$ (upper panels). Left (right) panels show emission-weighted (mass-weighted) temperature. Lines are theoretical prediction based on Press–Schechter mass function and analytical T–M relation. The shaded region indicates the observed XTF of local ($z < 0.1$) galaxy clusters by Markevitch.

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