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Structure of Clusters of Galaxies and open CDM and Λ CDM

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ABSTRACT

We investigate possibility of utilizing substructures in clusters of galaxies as a probe of the non-zero cosmological constant, Λ. Using high-resolution cosmological N-body/SPH simulations of flat ($\Omega_0 = 0.3,\ \lambda_0 = 0.7, \Lambda$CDM) and open ($\Omega_0 = 0.3, \lambda_0 = 0$, OCDM) cold dark matter dominated universes, we obtain indicators that are closely related with the substructures from each cosmological model. As the indicators, we calculate center shifts, and multipole moment power ratios for the simulated clusters at $z = 0$ and 0.5. These indicators are calculated for both X-ray surface brightness and column density of the matter. In ΛCDM all these indicators tend to be larger than those in OCDM at $z = 0$. This result is consistent with the analytical prediction, that is, clusters in ΛCDM are formed later than in OCDM and then clusters in OCDM are more relaxed at $z = 0$. We make Kolmogorov-Smirnov test on each indicator. We then find that the results for the multipole moment power ratios and the center shifts for the X-ray surface brightness are under the significant level (5%) and we distinguish these two models more clearly at $z = 0$ than $z = 0.5$.

Subject headings: galaxies:clusters:general – cosmology:theory – methods:numerical

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1. INTRODUCTION

The quest for cosmological parameters, such as the Hubble constant H_0, the density parameter Ω_0, and the cosmological constant Λ, is one of the most important problem in the observational cosmology. From observational evidences, the density parameter Ω_0 is estimated to be around 0.3 (e.g. Bahcall et al. 1999). The inflation cosmology requires $\Omega_0 + \lambda_0 = 1$ that is supported by the recent observation of the cosmic microwave background (de Bernardis et al. 2000). Distant Type Ia supernovae (SNe Ia) are used to be cosmological candles to explore effect of the cosmological constant and evidence of the acceleration expansion (Perlmutter et al. 1999; Riess et al. 1998). However, several systematic uncertainties in the observational data of SNe Ia are pointed out (Totani & Kobayashi 1999; Gibson et al. 2000). Further studies are needed to confirm the presence of the cosmological constant. We study the effect of the cosmological constant on structures of galaxy clusters and what statistical indicator, which quantifies irregularity of the structure, is suitable to study it.

Richstone, Loeb, & Turner (1992) proposed that structures of clusters are closely related to a cosmological model, since the recently formed fraction of the clusters is strongly depends on a cosmological model. They showed that, in a denser universe, this fraction becomes larger. Several authors studied what indicator is suitable to show the effect of cosmological parameters in numerical simulations. Studied indicators are the axial ratio (Mohr et al. 1995; Jing et al. 1995; Thomas et al. 1998), $M_{\rm int}$ and $M_{\rm ext}$ (Thomas et al. 1998), the center shift (Jing et al. 1995; Thomas et al. 1998), the centroid variation (Mohr et al. 1995; Crone, Evrard, & Richstone 1996), the multipole moment power ratio (Buote & Tsai 1995, 1996; Tsai & Buote 1996; Buote & Xu 1997; Valdarnini, Ghissardi, & Bonometto 1999), and Δ-statistic (Dutta 1995; Crone, Evrard, & Richstone 1996). These simulations have been performed in various cosmological models. In some of these studies they compared the results in cosmological models of different density parameters, including in the case of existence of cosmological constant (e.g. Crone, Evrard, & Richstone 1996; Buote & Xu 1997).

In this paper, we investigate the difference between ΛCDM and OCDM using the numerical simulations of clusters of galaxies in these models by Yoshikawa, Jing, & Suto (2000). We identify the clusters and calculate various statistical indicators. The Kolmogorov-Smirnov test (hereafter KS-test) is performed to measure how these indicators are effective to distinguish these two cosmological models.

The organization of this paper is as follows. In §2, we describe the data used in this paper, cluster identification, and definitions of indicators we used. We derive the values of the indicators for simulated clusters and show results of the KS-test on them in §3. In §4, we discuss our results and present our conclusion.

2. METHOD

2.1. Simulation Data

Our simulations are based on particle-particle-particle-mesh (P^3M)-Smoothed Particle Hydrodynamics (SPH) algorithm (Yoshikawa, Jing, & Suto 2000). These simulations have sufficient resolution to research the substructure of the clusters and enough number of the clusters to perform statistical tests. We use two cosmological models, OCDM and ΛCDM. Cosmological parameters, which are same for two models, except for the cosmological constant (λ_0), are as follows: the Hubble constant in units of $100 km\, s^{-1}\, Mpc^{-1}$, $h = 0.7$, the density parameter, $\Omega_0 = 0.3$, the baryon density parameter, $\Omega_b = 0.015h^{-2}$, the rms density fluctuation amplitude on a scale $8h^{-1}Mpc$, $\sigma_8 = 1.0$, and the power-law index of the primordial density fluctuation, $n = 1.0$. The cosmological constant, λ_0 is 0 (for OCDM) or 0.7 (for ΛCDM).

The simulation employs $N_{DM} = 128^3$ dark matter particles and the same number of gas particles. Mass of dark matter and SPH particles are $1.7 \times 10^{11} M_\odot$ and $2.0 \times 10^{10} M_\odot$, respectively. COSMICS package (Bertschinger 1995) is used to generate initial conditions at $z = 25$. Comoving size of simulation box, $L_{\rm box} = 150h^{-1}Mpc$, and the box is on the periodic boundary condition.

We use the data at $z = 0.5$ and 0 to calculate statistical indicators. The reason of this is that the formation rate of galaxy clusters in ΛCDM exceeds that in OCDM in $z < 0.8$.

2.2. Cluster Identification

The way of identification of galaxy clusters is friends-friends method (Jing & Fang 1994; Thomas et al. 1998).

Table 1 shows numbers of clusters found in each model. The numbers of the clusters increase from $z = 0.5$ to $z = 0$. Table **??** is the ratio of mass included clusters to total mass in the simulation box. These ratios in both models are similar to each other at $z = 0$, but the ratio in ΛCDM is smaller than that in OCDM at $z = 0.5$. This is consistent with the fact that ΛCDM clusters form later than OCDM clusters.

2.3. Projection to Two Dimension

Two of the indicators we use in this paper, the center shifts and the power ratios, are calculated for the X-ray surface brightness, and the column density of dark matter and gas in simulated clusters.

2.4. Statistical Indicator

We calculate statistical indicators for each cluster of galaxies to quantify its substructure and perform the KS-test. As statistical indicators, we use the axial ratio, the $M_{\rm int}$, the multipole moment power ratio, and the center shift. Definitions of them are described below.

2.4.1. Center Shift

We calculate the center shift for each cluster in a slightly different way to Jing et al. (1995). We first pick up a peak value, $c_{\rm peak}$, of projected σ or Σ_X of the cluster. Then the lowest contour level, $c_{\rm lowest}$, is defined by the mean value at $0.5r_{200}$. And then the i-th contour level is determined as $c_i \equiv c_{\rm peak}(c_{\rm lowest}/c_{\rm peak})^{i/n}$, where n is the total number of contours. For the larger

Model	z=0	z=0.5
ΛCDM	66	28
OCDM	74	38

Table 1: The number of the clusters for each model and redshift.

n, the intervals of contour levels become smaller.

The center shift, C, is defined as

$$C = \sum_{i=1}^{n} w_i \left\{ (x_i - \bar{x})^2 + (y_i - \bar{y})^2 \right\}, \quad (1)$$

where (x_i, y_i) is the center of ith contour, and $\bar{x} = \sum_i w_i x_i$, and $\bar{y} = \sum_i w_i y_i$. The weight of each contour, w_i, is proportional to the surface integral of σ or Σ_X in a region between this contour and the adjacent outer contour. The center shift shows emission-weighted dispersion of the centers of contours. If a cluster has a substructure, outer contour's center is expected to shift from $(\bar{x}, \bar{y})$ and the center shift becomes large.

2.4.2. Power Ratio

The power ratios quantify the shape of projected cluster's potentials and are derived from its multipole expansion(e.g. Buote & Tsai 1995; Buote 1998; Valdarnini, Ghissardi, & Bonometto 1999).

Two-dimensional potential, $\Psi(R, \phi)$, and column density, $\sigma(R, \phi)$, are related by Poisson equation,

$$\nabla^2 \Psi(R, \phi) = \sigma(R, \phi), \quad (2)$$

where R and ϕ are a projected polar coordinate about the cluster center, and we here ignore constant factor. Multipole expansion of $\Psi(R, \phi)$ which relies on the interior material of R_{ap} (e.g. Buote & Tsai 1995) is

$$\Psi(R_{ap}, \phi') = -a_0 \ln \left(\frac{1}{R_{ap}} \right) - \sum_{m=1}^{\infty} \frac{1}{m R_{ap}^m} \times (a_m \cos m\phi' + b_m \sin m\phi'), \quad (3)$$

where a_m and b_m are defined as follows.

$$a_m = \int_{R \le R_{ap}} \sigma(R, \phi) R^m \cos m\phi \, d^2x \quad (4)$$

and

$$b_m = \int_{R \le R_{ap}} \sigma(R, \phi) R^m \sin m\phi \, d^2x. \quad (5)$$

The m-th moment power, $P_m(R_{ap})$, is defined by integration of squared m-th term of $\Psi(R, \phi)$ over the boundary of a circular aperture of radius R_{ap}.

$$P_m(R_{ap}) = \frac{1}{2m^2 R_{ap}^{2m}} (a_m^2 + b_m^2) \quad (6)$$

for $m > 0$ and

$$P_0 = a_0^2 \quad (7)$$

for $m = 0$.

The moment power depends on not only the irregularity of the potential shape, but also the magnitude of σ. Thus we use the moment power ratio, P_m/P_0, as an indicator of cluster's substructure. We define the unit of R, radius of polar coordinate, as r_{200}, so that the power ratio to be independent of the size of the cluster. Since the origin of polar coordinate is the center, the dipole moment, P_1, is vanished. Since the higher order ($m > 4$, in this paper) terms are affected by minor irregularity of cluster shape, we use power ratio for only $m = 2, 3$, and 4.

We also use the same definition of the power ratio for Σ_X in stead of σ in equations (4) and (5).

3. RESULT

According to the analytical results by Richstone, Loeb, & Turner (1992), the formation epoch of the galaxy clusters in ΛCDM delays to later epoch than in OCDM. This delay clearly appears in low-z ($z \lesssim 0.8$–0.7). Then we calculate indicators described in §2 at $z = 0$ and $z = 0.5$ and perform the KS-test for each set of indicators calculated for two cosmological models, ΛCDM and OCDM. The KS-test can be used as a statistical test to estimate the ability of a indicator to be used to distinguish between the two models. The result of the KS-test is the probability of null-hypothesis that two distributions of the indicator are generated from the same population (Press et al. 1988). The significant level of the KS-test adopted in this paper is 5%. If the result of the KS-test for a indicator is under this level, we can distinguish two cosmological models by using this indicator.

3.1. Center Shift

The number of the contours, $n_{\rm cont}$, is varied from 4 to 8 to investigate effect of the number of the contours. For large n, i.e. a small interval of contour level, C is large. In the case of a small interval, the center shift is easy to reflect small substructure nearby the center of the cluster.

The center shifts for σ, C_σ, are significantly larger than those for Σ_X, C_{Σ_X}. The shapes of the Σ_X contours reflect the distribution of the gas and gas in the cluster relaxes more quickly than the collisionless dark matter (Frenk et al. 1999). This is the reason why the shapes of Σ_X contour become rounder than those of σ and the center shifts for Σ_X become smaller more quickly than those for σ.

The center shifts in ΛCDM are larger than those in OCDM at the same red-

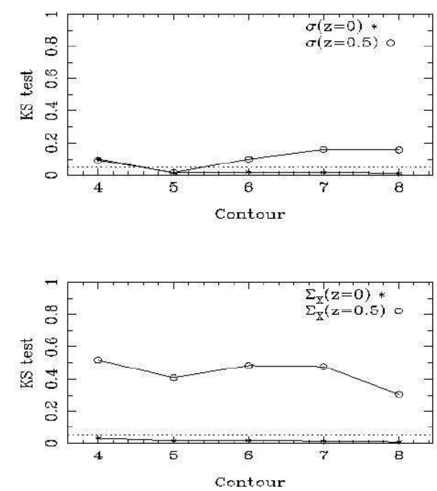

Fig. 1.— The result of the KS-test for center shifts as a function of the number of contours. Asterisks indicate the results at $z = 0$, and circles indicate the results at $z = 0.5$. Dotted line describes the significant level(5%)

shift. This results reflects that the formation epoch of the clusters in ΛCDM is in later than in OCDM.

Fig.1 is the result of the KS-test for the center shifts. The upper panel describes the results for the center shifts for the column density and the lower one describes the results for the X-ray surface brightness. Dotted line indicates the significant level(5%). Asterisks indicate the results at $z = 0$, and circles indicate the results at $z = 0.5$. Using the center shifts for Σ_X at $z = 0$, we can distinguish two cosmological models in this range of number of contours. The effect of contour level interval is not so significant for the KS-test.

3.2. Power Ratio

We calculate the power ratios for various R_{ap}, that is, 0.4, 0.5, 0.6, 0.8, and 1.0 times r_{200}, in order to show how R_{ap} affects the result of the KS-test. We show the mean values and the standard deviations of logarithm of the power ratio in Table **??** and **??**, for the column density and the X-ray surface brightness, respectively.

For small R_{ap}, the power ratios are large. The most likely explanation of this property is that the power ratios for small R_{ap} are easy to reflect the small size substructure nearby the center of the cluster.

From $z = 0.5$ to $z = 0$ the power ratios become smaller in both models. This is due to the fact that fraction of relaxed clusters increases with time. Similar to the other indicators, the power ratios in ΛCDM are larger than those in OCDM at the same redshift. This is explained by the fact that galaxy cluster formation proceeds in later epoch in ΛCDM than in OCDM.

Table **??** shows the results of the KS-test for the power ratio for the column density, and Table **??** shows those for the X-ray surface brightness. The results with asterisk in these tables mean that they are under the level of significance (5%). Figure 2 show the results of the KS-tests summarized in Table **??** and **??**. At $z = 0$, we can distinguish two cosmological models by the power ratios for Σ_X for all R_{ap}. Using the power ratios for σ for most R_{ap}, except for P_3/P_0, we can also distinguish two cosmological models.

4. DISCUSSION AND CONCLUSION

We have examined the substructure of the simulated galaxy clusters in two different cosmological models, ΛCDM and OCDM, at $z = 0$ and $z = 0.5$. For each cluster we have calculated the axial ratio, $M_{\rm int}$, the center shift, and the multipole moment power ratio as statistical indicators which quantify substructure of clusters. At $z = 0$ all of mean values of these indicators in ΛCDM show larger values than those in OCDM. These large values of the indicators, which mean large irregularity of clusters, implies a recent formation of the cluster. This can be explained by the fact that the typical formation epoch of galaxy clusters in ΛCDM is later than in OCDM and a cluster which is formed in later epoch is expected to have more irregular structure now (Richstone, Loeb, & Turner 1992). Our results are consistent with this analytical prediction and other previous numerical studies (Mohr et al. 1995; Crone, Evrard, & Richstone 1996; Buote & Xu 1997).

The power ratio and the center shift

are calculated for X-ray surface brightness (Σ_X) and column density (σ) distributions of clusters. Both of the indicators for σ show larger value than those for Σ_X. This implies that the dark matter distribution of a cluster, which dominates the structure of σ, is harder to relax than the gas distribution which is closely related with the structure of Σ_X (Frenk et al. 1999).

We use the KS-test to estimate the ability of the indicators to distinguish between two cosmological models. We can not distinguish two models by the axial ratio and $M_{\rm int}$. Using the center shift and the power ratio for Σ_X at $z = 0$, we can distinguish two cosmological models. We can also distinguish two cosmological models by the center shifts, P_2/P_0, and P_4/P_0 for σ at $z = 0$. At $z = 0.5$ we can distinguish two cosmological models by the power ratio for Σ_X, but can not by the center shift for Σ_X and both the power ratio and the center shift for σ.

Although Other study (Mohr et al. 1995) employs gas particle, the number of sample cluster is small (8 clusters for each model). We use the data of so large size simulation ($L_{box} = 150h^{-1}Mpc$) that we can obtain a number of clusters enough to perform statistical test (70–80 clusters at z=0). The KS-test is significant when the number of samples $\gtrsim 20$ (Press et al. 1988).

We conclude that the power ratios and the center shifts for Σ_X can be used to distinguish between ΛCDM and OCDM more clearly at $z = 0$ rather than $z = 0.5$.

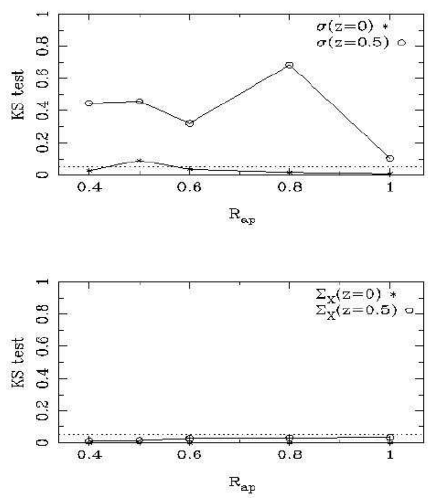

Fig. 2.— The results of the KS-test for P_2/P_0. Asterisks indicate the results at $z = 0$, and circles indicate the results at $z = 0.5$. Dotted line indicates the significant level(5%)

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