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# Properties of Galaxies in Rich Clusters

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**Abstract.** We present a model to investigate the formation and evolution of cluster galaxies using cosmological high-resolution $N$-body simulations. The $N$-body simulations are used to construct merging history trees of galactic dark halos. Gas cooling, star formation, supernova feedback and mergers of galaxies within dark halos are included by using simple prescriptions taken from semi-analytic models of galaxy formation. Using this method, we represent the morphology-density relation for simulated cluster galaxies and the color-magnitude relation of simulated cluster ellipticals under the major merger-driven bulge formation scenario. We find that this morphological evolution model gives a good explanation for the distribution and colors of the cluster ellipticals, while it cannot reproduce the distribution of S0 galaxies. These results suggest that the elliptical galaxies are mainly formed by the major mergers and the processes other than major mergers play important role in the S0 formation.

## 1. Introduction

Rich clusters of galaxies are large laboratories for studying galaxy evolution. It is well established that galaxy populations vary with the density of neighboring galaxies in clusters (Dressler 1980; so-called *morphology-density relation*; hereafter MDR). It is also well known that elliptical galaxies have the tight correlation between their colors and magnitudes (so-called *color-magnitude relation*; hereafter CMR). These observed relations give clues to galaxy formation theory.

The MDR indicates that dynamical processes that depend on environment of each galaxy mainly affect the final configuration of the stellar component and some mechanisms that may transform one morphological type into another have been proposed, for example, ram-pressure stripping of interstellar medium of spirals by a intracluster medium (Gunn & Gott 1972; Fujita & Ngashima 1999), galaxy harassment by cumulative tidal interactions in clusters (Moore et al. 1998), and galaxy mergers (Toomre 1977). $N$-body simulations have confirmed that merging disk galaxies produce galaxies resembling ellipticals as merger remnants (e.g. Barnes 1989), so that the galaxy merger is a favorite explanation for the predominance of early type galaxies in rich clusters (Kauffmann et al. 1993; Baugh et al. 1996).

The purpose of our study is to check this *major merger hypotheses* by investigating the MDR and CMR of the simulated cluster galaxies in the cosmological context. For this purpose, it is difficult in the present situation to use numerical simulations including both gravity and gas dynamics, because such simulations are expensive in CPU time and so only a limited range of parameter space can be explored with an insufficient spatial resolution.

Semi-analytic modeling of galaxy formation has been already proved to be a powerful technique (e.g. Kauffmann et al. 1993; Cole et al. 1994). However, we cannot identify the positions of galaxies by such approaches, because these models follow the collapse and merging histories of dark halos by using a probabilistic method on the mass distribution based upon an extension of the Press-Schechter formalism (Press & Schechter 1972; Lacey & Cole 1993).

One approach to identify the position and velocity of each galaxy is to track the merging histories of dark halos using $N$-body simulations and to combine them with the simple prescriptions of the semi-analytic models (Roukema et al. 1997; Kauffmann et al. 1999). Their schemes, however, do not deal with the substructures within dark halos. Since the dynamics within clusters may strongly affects the evolution of cluster galaxies (Okamoto & Habe 1999, 2000), we should use a new galaxy tracing method.

In this paper, we adopt the galaxy tracing method provided by Okamoto & Habe (1999, 2000), which enables us to trace the individual galactic dark halos within dense environments using high-resolution $N$-body simulations, that is, we can obtain the three-dimensional distribution of the galaxies within clusters. We also adopt a merger-driven scheme for the production of galactic bulges and the way of the morphological classification based on bulge-to-disk ratios as earlier studies (Kauffmann et al. 1993; Baugh et al. 1996).

## 2. Model

We examine the evolution of cluster galaxies in the standard cold dark matter (SCDM) universe ($\Omega_0 = 1,\ h \equiv H_0/100$ km s$^{-1}$Mpc$^{-1}$ $= 0.5,\ \sigma_8 = 0.67$) and the open CDM (OCDM) universe ($\Omega_0 = 0.3, h = 0.7,\ \sigma_8 = 1.0$). The baryon density is set to $\Omega_b = 0.1$ and 0.03 for SCDM and OCDM, respectively.

The merging histories of galactic dark halos are realized using the same method and simulation data as Okamoto & Habe (2000). While the merging histories are constructed with a 0.5 Gyr time-step in their paper, here we adopt a half of the time-step for high redshifts ($z > 2$) at which the galactic halos form and merge violently (Okamoto & Habe 2000). This improvement, however, hardly changes our results.

The outline of the procedures of galaxy formation is as follows. At first, the merging path of galactic halos are realized by the cosmological high-resolution $N$-body simulations. Next, in each merging path, evolution of the baryonic component, namely, gas cooling, star formation, and supernova feedback, are calculated based on Kauffmann et al. (1993) and Cole et al. (1994). We refer a system consisting of the stars and cooled gas as a *galaxy*. When two or more dark halos merge together, we estimate the merging time-scale based on the dynamical friction time-scale. When the merging of galaxies occurs, we change the morphology of the merger remnant by the type of the merger. Finally, we calculate the luminosity and color of each galaxy according to the ages and metallicites of stars in the galaxy using the population synthesis model by Kodama & Arimoto (1997). Chemical evolution is treated in almost the same way as Kauffmann & Charlot (1998) with the yield, $y = 2Z_{\odot}$. Through the above procedures, we obtain the morphology, luminosity, colors, and spatial distribution of the cluster galaxies.

Morphological evolution is treated as follows. When two or more halos merge together, we identify a galaxy contained in the largest progenitor as the central galaxy of the new common halo. Other galaxies are identified as satellites and then they merge with the central galaxy in the dynamical friction time-scale. When a satellite galaxy merges with a central galaxy and the mass ratio of the galaxy with smaller mass to that with larger mass, $R = (M_{\rm stars} + M_{\rm cold})_{\rm acc.sat.}/(M_{\rm stars} + M_{\rm cold})_{\rm cen.gal.}$, is larger than $f_{\rm bulge}$, all stars of the satellite and disk stars of the central galaxy are incorporated with the bulge of the central galaxy. Then, cold gases of both galaxies turn to stars in the bulge by *starburst*. Further cooling leads to the formation of a new disk component. We adopt $f_{\rm bulge} = 0.3$ and 0.2 for SCDM and OCDM, respectively, in order to reproduces the observed early type fraction roughly.

Morphology of each galaxy is determined by the $B$-band bulge-to-disk luminosity ratio ($B/D$). In this paper, galaxies with $B/D \geq 1.52$ are identified as ellipticals, $0.68 \leq B/D < 1.52$ as S0s, and $B/D < 0.68$ as spirals, according to the results of Simien & de Vaucouleurs (1986).

The feedback is key process which determines the feature of galaxies (e.g. Kauffmann & Charlot 1998). Therefore, we use three types of feedback models in this paper. Since the process by supernovae of massive stars has many uncertainties actually, we adopt a simple description (Cole et al. 1994),

$$\Delta M_{\rm reheat} = \left(\frac{V_{\rm c}}{V_{\rm hot}}\right)^{-\alpha_{\rm hot}} \dot{M}_{*}\Delta t, \tag{1}$$

where $V_{\rm hot}$ and $\alpha_{\rm hot}$ are free parameters and $\dot{M}_{*}$ is the star formation rate. We use following combination of the feedback parameters. We adopt $V_{\rm hot} = 280{\rm km\ s^{-1}}$ and $\alpha_{\rm hot} = 2$, $V_{\rm hot} = 140{\rm km\ s^{-1}}$ and $\alpha_{\rm hot} = 2$, and $V_{\rm hot} = 200{\rm km\ s^{-1}}$ and $\alpha_{\rm hot} = 5.5$ in the model A, B, and C, respectively. The model A is a strong feedback model and B is a normal feedback model. The model C inputs stronger feedback into smaller galaxies.

The details of above procedures are shown in Okamoto & Nagashima (2000).

## 3. Results

In Figure 1, we show the $B$-band luminosity functions of the model galaxies. The thick solid, dotted, and dashed lines indicate the luminosity functions given by the model A, B and C, respectively, and the thin dot-dashed line indicates the observed luminosity function of the Virgo cluster (Sandage et al. 1985). The model C reproduces the observed luminosity function well by flattening the faint-end slope of the luminosity function. This is caused by strong feedback

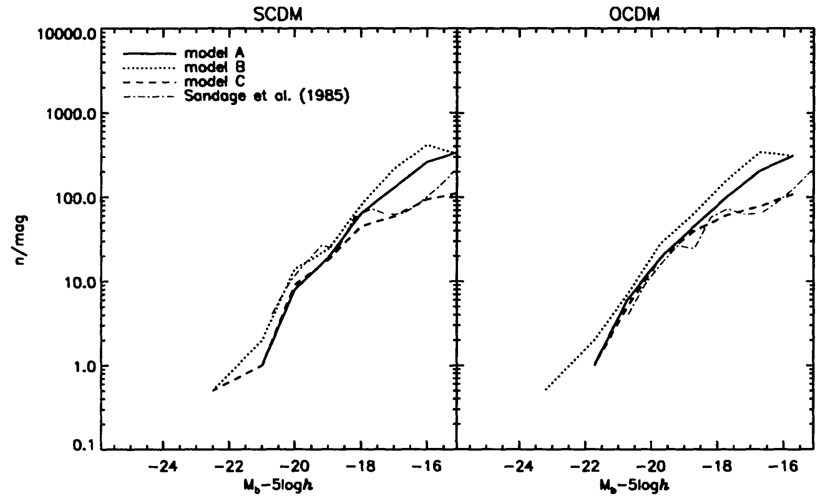


Figure 1. Luminosity functions of cluster galaxies. The left and right panels show those in SCDM and OCDM, respectively, and the thick solid, dotted, and dashed lines indicate those of the model A, B, and C, respectively. The thin dot-dashed line is the luminosity function of the Virgo cluster galaxies by Sandage et al. (1985).

to galaxies with low circular velocities compared to the model A and B due to $\alpha_{\rm hot} = 5.5$.

The MDRs for the simulated clusters are represented in the left panel of Figure 2 using the same luminosity cut-off and definition of the local projected density as Dressler (1980), i.e. the local projected density is defined by nearest 10 neighbors having the luminosity $M_V - 5\log h < -18.9$. The projected density is calculated in $x$–$y$, $y$–$z$, and $z$–$x$ projections for each model. The morphological fractions of our models and Dressler's (1980) are represented by thick and thin lines, respectively. We attach the $1\sigma$ error bars to the elliptical fractions according to the number of the galaxies in each density bin.

In all models, the E fractions increase toward the high-density regions, and this is consistent with the observed trend. The S0 fractions, however, are much smaller than the observed fraction and do not represent the observed trend of the moderate increase toward the high-density regions.

In the right panel of Figure 2, we plot the CMR of the simulated cluster ellipticals. The solid lines indicate the observed CMR of the ellipticals in the Coma cluster (Bower et al. 1992). The model A and C can reproduce the observed slope, because strong feedback prevents metal enrichment in small galaxies.

## 4. Discussion

In this paper, we represent a new method that combines high-resolution $N$-body simulations with a semi-analytic galaxy formation model for cluster galaxies. The high-resolution simulations enable us to identify and trace galactic

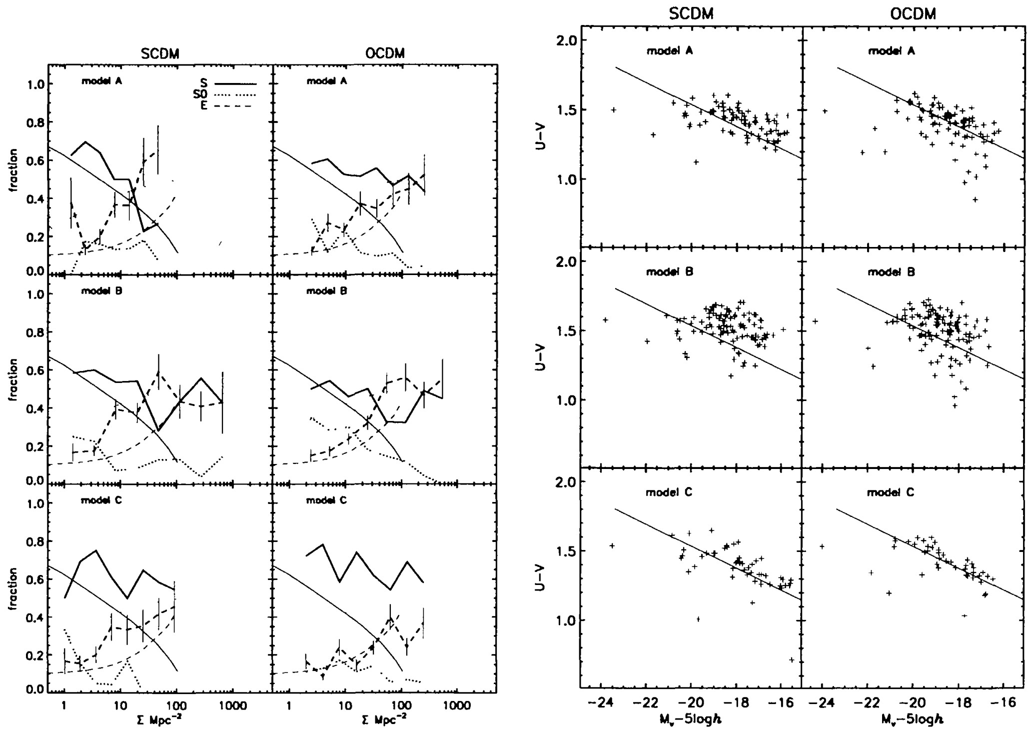


Figure 2. *Left panel*: Morphology-density relations for the simulated clusters. The thick lines are the MDRs for the simulated clusters and thin lines are the Dressler's (1980) MDR. S, E, and S0 fractions are represented by the solid, dotted and dashed lines, respectively. *Right panel*: Color-magnitude relations of the simulated cluster ellipticals. The solid lines indicate the observed CMR of the ellipticals in the Coma cluster (Bower et al. 1992).

halos within clusters directly. Therefore, we can obtain the three-dimensional distribution of the cluster galaxies and also we can incorporate the dynamical processes, for example merging and tidal stripping of the galactic halos in the clusters, into our modeling of galaxy formation in principle. For the first study of the cluster galaxies using this method, we have shown the MDRs and CMRs for the simulated clusters with two cosmological models based on the major merger-driven bulge formation scenario.

The model which reproduces the observed luminosity function well (model C) is successful in explaining both the observed elliptical fraction as a function of the local density and the observed CMR of the cluster ellipticals. However, any model cannot reproduce the observed trend in the distribution of the cluster S0s. In all models, the S0 fractions are too small, especially in the high-density regions.

The reason is probably considered as follows. In the model adopted here, a S0 galaxy in mainly formed by the disk formation after the last major merger. The efficiency of merging is, however, high before cluster formation, and then it rapidly decreases due to the large internal velocity dispersions of the clusters and the reduction of the size of tidally truncated halos as the mass of clusters grows.

The accretion onto the galactic halos is also prevented by the strong tidal field after beginning of the cluster formation (Okamoto & Habe 1999). Hence, the cluster ellipticals formed by the mergers at high redshifts hardly change their morphologies into S0s by minor mergers or gas accretion, which form additional stellar disks.

We conclude that the morphological evolution model by major mergers gives a good explanation for the distribution and colors of the cluster ellipticals, while it cannot produce the S0 galaxies sufficiently. To reproduce the observed S0 fraction, other physical processes that directly change the morphology from spiral galaxies into S0 galaxies should be considered, for example the minor mergers (Walker et al. 1996), the ram-pressure stripping (Gunn & Gott 1972; Fujita & Nagashima 1999) and the galaxy harassment (Moore et al. 1998).

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