A SUBHALO-GALAXY CORRESPONDENCE MODEL OF GALAXY BIASING

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Received 2008 January 21; accepted 2008 April 7

ABSTRACT

We propose a model for allocating galaxies in cosmological N-body simulations. We identify each subhalo with a galaxy and assign luminosity and morphological type, assuming that the galaxy luminosity is a monotonic function of the host subhalo mass. Morphology is assigned using two simple relations between the subhalo mass and galaxy luminosity for different galaxy types. The first uses a constant luminosity ratio between early-type (E/SO) and late-type (S/IR) galaxies at a fixed subhalo mass. The other assumes that galaxies of different morphological types but equal luminosity have a constant ratio of subhalo mass. We made a series of comparisons of the properties of these mock galaxies with those of SDSS galaxies. The resulting mock galaxy sample is found to successfully reproduce the observed local number density distribution except in high-density regions. We study the luminosity function as a function of local density, and find that the observed luminosity functions in different local density environments are overall well reproduced by the mock galaxies. A discrepancy is found at the bright end of the luminosity function of early types in the underdense regions and at the faint end of both morphological types in very high density regions. A significant fraction of the observed early-type galaxies in voids seem to have undergone relatively recent star formation and become brighter. The lack of faint mock galaxies in dense regions may be due to the strong tidal force of the central halo, which destroys less massive satellite subhalos around the simulation. The mass-to-light ratio is found to depend on the local density in a way similar to that observed in the SDSS sample. We have found an impressive agreement between our mock galaxies and the SDSS galaxies in the dependence of central velocity dispersion on the local density and luminosity.

Subject headings: dark matter — galaxies: halos — galaxies: luminosity function, mass function — methods: n-body simulations

Online material: color figures

1. INTRODUCTION

The current galaxy formation paradigm can be characterized as “hierarchical clustering”: in this scenario, massive dark matter halos form by the merger of less massive halos and/or by accreting ambient matter, and a dark matter halo governs the evolution of the galaxy residing inside. Most galaxies are believed to be surrounded by dark matter halos, because the halos can provide a deep potential well in which baryonic matter can condense and cool down. This in turn leads to a triggering of star formation; gas accumulating sufficiently in the halo potential center begins to experience many hydrodynamic processes, such as radiative cooling, star formation, supernova explosion, and chemical enrichments. All of these processes play an important role in ultimately making visible galaxies. Because galaxies as building blocks of large-scale structure consequently follow the evolution of their host halos over cosmic history, understanding the gravitational evolution of dark halos is very important for the study of galaxy formation and evolution.

Over the past few decades, cosmological simulations have proved useful for the study of structure formation. Simulations have facilitated many investigations of nonlinear structure evolution, and their results have been extensively compared to observations in various areas of interest. Many studies have reported successful recovery of observed features of the galaxy distribution, such as the two-point correlations of galaxies (Conroy et al. 2006; Kravtsov et al. 2004; Berlind & Weinberg 2002; Cooray 2006), topology (Park et al. 2005a, 2005b; Gott et al. 2008), and the environmental dependence of spin distributions (Cervantes-Sodi et al. 2008).

Detailed modeling of galaxy evolution and an understanding of galaxy properties have become possible with the recent advent of huge redshift surveys such as the Sloan Digital Sky Survey (SDSS) and the Two Degree Field Galaxy Redshift Survey (2dFGRS). These larger surveys provide rich information on the formation and evolution of galaxies. To establish a relation between simulated structures and observed galaxies, many techniques have been introduced. The semianalytic model (SAM) of galaxy formation is based on the hierarchical clustering of halos whose merging history trees are built either by generating a set of Gaussian random numbers (Cole et al. 1994; Kauffmann et al. 1997; Baugh 2006) or by tracing the evolution of halos in N-body simulations (Kang et al. 2005; De Lucia et al. 2004; Springel et al. 2001). Numerous SAM parameters are implemented in the merging history to reflect the hydrodynamic processes of heating, cooling, star formation, and aging of the stellar populations. Their parameter values are fine-tuned to provide the best description of the collective properties of observed galaxies. However, as the number of observational constraints increases, the number of parameters also increases, and SAM becomes much more complicated.

Hydrodynamical simulations employ direct formulations of hydrodynamic processes (Weinberg et al. 2008). Two types of hydrodynamical simulations are now widely adopted, the Lagrangian (Monaghan 1992; Hernquist & Katz 1989) and Eulerian methods (Tasker & Bryan 2006; Tart structures, and gas grids in the system of interest, then gas dynamics
are taken into account by calculating the hydrodynamic interactions between neighbor particles or by solving differential hydrodynamic equations between adjacent grids. This general method has several weak points; it suffers from the same lack of resolution in space and mass as in the \(N\)-body simulations, and in most cases, star formation and supernova explosions are far beyond the simulation resolution. In addition, some processes, such as radiative transfer, star formation, supernovae feedback, and the initial stellar mass function, are not thoroughly understood, and are difficult to parameterize in a well-established way.

There have been several previous studies of galaxy-halo clustering. While they did not directly target galaxy formation, we are able to infer the background physics of galaxy formation and evolution from information on the hierarchical clustering of matter and the biasing between dark halos and galaxies. One galaxy clustering model is the halo occupation distribution (HOD; Zheng et al. 2005; Seljak 2000; Berlind & Weinberg 2002) model. The HOD model relates the mass of the friends-of-friends (FoF) or other self-consistently defined halo to the number of subhalos (or galaxies) it contains, using a conditional probability \(P(N|M)\), where \(M\) is the halo mass and \(N\) is the number of subhalos inside the halo. This probability function is obtained from numerical simulations (Kravtsov et al. 2004; Berlind & Weinberg 2002; Jing et al. 1998) or from observations (Zehavi et al. 2004; Abazajian et al. 2005; Zheng et al. 2007), fitting the model to the observed two-point correlation functions.

There is another approach to studying the connection between galaxies and subhalos. This model adopts a one-to-one monotonic correspondence between galaxy luminosity and subhalo mass (Marinoni & Hudson 2002; Vale & Ostriker 2004, 2006; Shankar et al. 2006). This method is often called the “correspondence model.” It is simpler than other methods, because it has only two prerequisites: the luminosity function of galaxies and the mass function of subhalos. Its key assumption that a more massive subhalo hosts a brighter galaxy is consistent with the hierarchical clustering picture. As the halo mass grows, its luminosity is also expected to grow, in general because the merging of halos may be followed by the merging of galaxies. Matching these two functions allows the subhalo mass to be mapped to galaxy luminosity.

However, sometimes a galaxy may survive the merger event, because the baryonic component of a galaxy is usually more concentrated and more tightly bound than its dark counterpart. These “orphan” galaxies (Gao et al. 2004), which have no separate corresponding halos, could exist in cluster regions. Halos of mass below a certain characteristic scale also may not provide baryonic matter with a strong enough gravitational attraction to resist supernova explosions, which can tear up small-mass systems. Even if such cases are common, it is reasonable to expect that the galaxy census will be closely related to the population of subhalos, because most of the observed galaxies are field galaxies that have their own dark halos. It is thus worth investigating the hypothesis of the subhalo-to-galaxy correspondence model of galaxy formation.

In this paper, we apply the subhalo-galaxy correspondence model to a large \(N\)-body simulation and compare the statistical properties of mock galaxies with those of galaxies observed by the SDSS. We organize this paper as follows. In § 2, we describe our simulation and the subhalo finding method. In § 3, we implement the subhalo-galaxy correspondence model and show how to assign morphological types to mock galaxies. In § 4, the local density is introduced to quantify local environments, and the local density distributions of mock and SDSS galaxies are investigated. We also compare the luminosity distributions of mock galaxies with those of the SDSS galaxies in § 4.3. The environmental dependence of central velocity distributions is studied for the mock and SDSS galaxies in § 4.4, and discussions and conclusions follow in § 5.

2. SIMULATION AND HALO FINDING

We have carried out a cosmological \(N\)-body simulation of the universe with the Wilkinson Microwave Anisotropy Probe (WMAP) 3 year cosmological parameters. We ran 1024\(^3\) cold dark matter particles using an improved version of the GADGET code (Dubinski et al. 2004). The code adopts a dynamical domain decomposition for the particle-mesh part, with a variable width of the \(z\)-directional domain slabs. It also uses more compact and efficient oct-sibling tree walks, reducing the computational cost for the short-range force update, which consumes about 90% of the total run time. As a result, this new version outperforms the previous version by about a factor of 3 in speed. The simulation was run on a Beowulf-type system installed at the Korea Institute for Advanced Study. The Linux cluster consists of 256 AMD cores and 1 terabyte of main memory.

The simulation and cosmological parameters adopted in this study are listed in Table 1. The number of time steps in the simulations is empirically predetermined to satisfy the requirement that the maximum displacement of particles in a step should be less than the force resolution, which is 0.1 times the mean interparticle separation (\(d_{\text{mean}}\)). The starting epochs of simulations are chosen such that no particle will overshoot its neighbors when the Zel’dovich displacement is made. We further set the bias factor \(b = 1.314\), defined as the inverse of \(\sigma_8\) measured at the present epoch.

| Parameter | Value |
|-----------|-------|
| \(N_p\)   | 1024\(^3\) |
| \(N_m\)   | 1024\(^3\) |
| \(L_{\text{box}}\) | 256 \(h^{-1}\) Mpc |
| \(N_{\text{step}}\) | 3800 |
| \(z_i\)   | 95 |
| \(h\)     | 0.732 |
| \(\Omega_m\) | 0.238 |
| \(\Omega_b\) | 0.042 |
| \(\Omega_{\Lambda}\) | 0.762 |
| \(n_s\)   | 0.958 |
| \(b\)     | 1.314 |
| \(m_{\text{halo}}\) | \(1.0 \times 10^9 h^{-1} M_\odot\) |
| \(c\)     | 25 \(h^{-1}\) kpc |

\* Spectral power index.
\* Particle mass.
\* Force resolution.

Subhalos are identified by the physically self-bound (PSB) method (Kim & Park 2006). The method applies the FoF algorithm to identify dark matter particle groups, adopting the standard linking length, \(l_{\text{link}} = 0.2d_{\text{mean}}\). Then it divides each FoF halo into subhalos. This two-stage halo finding is in common with other methods (Springel et al. 2001; Shaw et al. 2006). In the second stage, we build a particle density field, using a coordinate-free method, as is usually done in smoothed particle hydrodynamics (Monaghan 1992). This adaptive kernel implementation is intended to resolve tight clusterings of particles. Then we search for 26 nearest neighbors of each particle. To construct an isodensity contour, we move along the neighbor positions in a manner similar to that used in the original physically self-bound (PSB) method (for details, see Kim & Park 2006). Self-bound and tidally
stable subhalos are identified by measuring the tidal radius of the subhalos and total energies of their member particles; member candidates are selected if their distance to the center of a subhalo is less than the tidal radius of the subhalo. Among these particles, gravitationally unbound particles are discarded. The resulting subhalos are used to allocate galaxies. We call the most massive subhalo a “central” halo and other subhalos “satellite” halos in the FoF group; the group of particles found by the FoF method is named the “FoF group” or “FoF halo.”

3. THE SUBHALO-GALAXY CORRESPONDENCE MODEL

We use a monotonic one-to-one correspondence model between galaxies and subhalos; there is one and only one galaxy in each subhalo, and a more massive subhalo hosts a more luminous galaxy. We apply this model to assign galaxies within our simulation box.

The one-to-one correspondence model is formalized in the following way. We first measure the mass function $\Phi(M_\text{h})$ of PSB subhalos. We then take the observed luminosity functions of the early-type (E/S0) and late-type (S/Irr) galaxies. The relation between halo mass and the corresponding absolute magnitude limit is given by

$$\int_{M_{\text{h}}}^{\infty} \Phi(M') dM' = \int_{-\infty}^{M_{\text{c}}(M_\text{h})} \phi_E(M') dM' + \int_{M_{\text{c}}(M_\text{h})}^{\infty} \phi_L(M') dM', \quad (1)$$

where $\Phi$ is the subhalo mass function, and $\phi_E$ and $\phi_L$ are the luminosity functions of early- and late-type galaxies, respectively. In this equation, we separate the full luminosity function of subhalos into early and late types to take into account the difference in mass of the halos associated with galaxies of different morphological type.

Two models are proposed to utilize the simple mass and luminosity scaling ratios between different morphological types at fixed luminosity and at fixed mass, respectively. The first model uses

$$L_L(M_\text{h}) = L_E(\kappa M_\text{h}), \quad (2)$$

where $M_\text{h}$ is the subhalo mass and $L_L$ and $L_E$ are the luminosities of late and early types, respectively. This means that at equal luminosity, the early-type galaxy is $\kappa$ times more massive than the late-type galaxy. This model is based on the findings of Park et al. (2007), who have confirmed that early-type galaxies brighter than $M_\text{r} = -19.5$ have about $\sqrt{2}$ times higher central velocity dispersion and pairwise peculiar velocity difference than late-type galaxies of the same brightness. This implies $\kappa \approx 2$ if $(M_\text{h}/L_\text{E})_\text{E} = (M_\text{h}/L_\text{E})_\text{L}. \quad$ Another convincing piece of observational evidence for $\kappa = 2$ can be found in Mandelbaum et al. (2006), who obtained the same result for halos of mass greater than $10^{11} h^{-1} M_\odot$ from an analysis of galaxy-galaxy weak lensing of the SDSS sample. Equation (2) then makes equation (1) a one-to-one relation between halo mass and galaxy luminosity. From here on, we call it the $\kappa$ model.

The second model uses a constant factor for luminosity rather than mass. This relation can be formulated as

$$L_L(M_\text{h}) = \beta L_E(M_\text{h}), \quad (3)$$

which says that late-type galaxies are brighter than early-type galaxies residing in halos of the same mass by a factor of $\beta$. We call this the $\beta$ model.

For the galaxy luminosity distribution, we use the Schechter function

$$\phi(M) = (0.4 \ln 10) \phi^* 10^{-0.4(M-M^*)(\alpha+1)} \times \exp \left[-10^{-0.4(M-M^*)}\right], \quad (4)$$

where we adopt the type-specific Schechter function parameters $M^*_E - 5 \log h = -20.23$, $\phi^*_E = 7.11 \times 10^{-3} h^3 \text{Mpc}^{-3}$, and $\alpha_E = -0.53$ for early-type galaxies and $M^*_L - 5 \log h = -20.12$, $\phi^*_L = 12.27 \times 10^{-3} h^3 \text{Mpc}^{-3}$, and $\alpha_L = -0.90$ for late-type galaxies (these values are given in Table 2 of Choi et al. (2007) for the SDSS galaxies brighter than $M_\text{r} = -19.0$). (Hereafter, we drop the term $5 \log h$ in the absolute magnitude and the magnitudes are all in r-band.) These values are quite different from those given by Blanton et al. (2001, 2003), mostly because we are using the type-specific functions. The reduction of the effects of internal extinction by Choi et al. (2007) also makes a significant difference in the $\alpha$ parameter compared to Blanton et al.’s (2003) results, as does the size of the data set (DR4+ vs. DR1), adopted cosmology ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ vs. $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$), and sample definition (volume limited vs. apparent magnitude limited).

The $\beta$ model can be easily solved by using the relation $M_L(M_\text{h}) = M_E(M_\text{h}) - 2.5 \log \beta$ in equation (1), but the $\kappa$ model is a bit tricky to solve and needs a few assumptions. The $\kappa$ model can be solved by a chain of equations whose left-hand side of eq. [5] is

$$\int_{M_\text{h}/\kappa}^{M_\text{h}} \Phi(M) dM = \int_{M_{L,2}}^{M_{L,1}} \phi_L(M) dM + \int_{M_{L,1}}^{M_{L}} \phi_E(M) dM, \quad (5)$$

where $M_{L,2} \leq M_{L,1} \leq M_\text{h}$ and

$$M_\text{h}(M_{L,2}) = M_\text{h}(M_{E,n-1}) \equiv m, \quad (6)$$

$$M_\text{h}(M_{L,1}) = M_\text{h}(M_{E,n}) = m/\kappa \quad (7)$$

for $\kappa > 1$. Here $M_\text{h}(M_\text{L})$ and $M_\text{h}(M_\text{E})$ denote the halo masses of late-type and early-type galaxies of absolute magnitude $M_\text{L}$, respectively. If $M_{L,2}$, $M_{L,1}$, and $M_{E,n}$ are given, then $M_\text{h}$ can be derived. Figure 1 depicts the relations among the three magnitudes described above. The solid and dashed curves show the luminosity functions of early and late types, respectively, and the dotted line connects the same subhalo mass for the two morphological types. The shaded areas denoted by $A_N$ and $B_N$ are the integrated number densities of galaxies of magnitude between $M_{L,2}$ and $M_{L,1}$ for the late types and between $M_{E,n-1}$ and $M_{E,n}$ for the early types. Therefore, the sum of the two shaded areas should be equal to the integral of the subhalo mass function (the left-hand side of eq. [5]).

By making a stride to the next mass scale, which is smaller by $1/\kappa$ times, we can get a chain of equations and derive the scaling relation between subhalo mass and galaxy luminosity. To solve this chain of equations, we set initial conditions under the plausible assumption that the late-type contributions to the number density at the high-mass (or bright) end are negligible compared to those of early types (or $0 \simeq A_1, A_2 \ll B_1, B_2$). This setting is quite fair, given the fact that early-type galaxies dominate the
bright end of the galaxy population. Then, we are able to solve
the series of equation (5) from the initial conditions where only the early-type contribution to number density is dominant.

Now we investigate the early-type fractions as a function of the hosting subhalo mass. The probability $f_E(M_h)$ that a galaxy of hosting subhalo mass $M_h$ is early type can be derived by solving

$$
\int_{M_h}^{\infty} dM_h f_E(M_h) = \int_{M_h}^{\infty} dM_h \phi_E(M_h),
$$

where $\phi(M)$ is the number density of galaxies residing in the subhalo mass $M_h$. This equation should be satisfied for all $M_h$. Using $\phi(M_h) = \phi(M) \cdot dM_h/dM_h$, equation (8) leads to

$$
f_E(M_h) = \frac{\phi_E(M; M_h) dM_h}{\phi_E(M; M_h) dM_h + \phi_L(M; M_h) dM_L},
$$

where the denominator is the number density of all galaxies hosted by subhalos of mass $M_h$, and the numerator is the number density of early-type galaxies hosted by subhalos of mass $M_h$. In the $\beta$ model, this equation simply reduces to $f_E = \phi_E(\phi_E + \phi_L)$, because $(dM_h/dM_h) = (dM_h/dM_h)$ for all $M_h$. However, this relation does not hold in the $\kappa$ model, because $\mathcal{M}_e(M_h) = \mathcal{M}_e(M_h)$. Therefore, we numerically calculate $(dM_h/dM_h)$ and $(dM_L/dM_h)$ at $M_h$. Figure 2 shows the early-type fractions for the $\kappa$ and $\beta$ models. Using $f_E$, we are able to randomly assign a morphological type to each mock galaxy in accordance with its subhalo mass. For a larger value of $\beta$, early-type galaxies tend to dominate the population down to lower mass scales ($M_h$); below $M_h$, $f_E$ drops more rapidly. However, for the $\kappa$ model these changes in $f_E$ are not so steep. In this plot we also note that there is a more dramatic change of $f_E$ in the $\beta$ model than in the $\kappa$ model.

Figure 3 shows the relation between the subhalo mass $M_h$ and absolute magnitude $M$ of early-type (solid lines) and late-type (dashed lines) galaxies derived from equation (1), and the luminosity functions of the SDSS galaxies in the $\kappa$ (top) and $\beta$ (bottom) models. Here we only show the cases $\beta = 2$ (thick lines) and $1.5$ (thin lines) and $\kappa = 2$ (thick lines) and $3$ (thin lines). For comparison, the characteristic minimum mass of subhalos hosting the central subhalos at each absolute magnitude limit estimated by Zheng et al. (2007) based on the HOD model is shown by filled circles. They obtained the magnitude-to-mass relation of the central subhalo, but ignored the morphological types of the galaxies. The HOD model is quite consistent with our $M_h$-$\mathcal{M}$ relation for the early-type galaxies with $\beta = 2$ and $\kappa = 2$ and $3$.

The bottom panel of Figure 4 shows the mass-luminosity relation (solid line) for the early-type galaxies. Here we adopt $M_l = 4.64 - 5 \log h$ (Blanton & Roweis 2007) to transform the magnitude to luminosity in the $r$-band filter. Note that galaxy luminosity drops steeply at the low-mass end and rises as a power-law relation at the high-mass end. Taking these features into account, we propose a function

$$
L(M) = \frac{M^*}{\Psi_{ml}} \left( \frac{M^*}{M} \right)^{\gamma - 1} e^{-(M^*/M)},
$$

as a fitting function for the subhalo mass versus early-type galaxy luminosity relation. We apply $\chi^2$ fitting to the relation and obtain the best-fit values of $\Psi_{ml} = 38.3 \ M_0/L_0$, $M^* = 2.04 \times 10^{11} \ h^{-1} \ M_0$, and $\gamma = 0.644$ for early types in the $\beta = 2$ model. In the $\kappa = 2$ model, we obtain $\Psi_{ml} = 39.8 \ (20.3) \ h \ M_0/L_0$, $M^* = 4.83 \ (1.52) \times 10^{11} \ h^{-1} \ M_0$, and $\gamma = 0.667 \ (0.719)$ for the early (late) types. Only the fitting result for the early types in the $\beta = 2$ model is shown in Figure 4 (short-dashed line).

The top panel of Figure 4 shows the mass-to-light ratios of the early types (solid curve) in the $\beta = 2$ model, while the long-dashed
and dotted curves show them for early- and late-type galaxies in the \( \kappa = 2 \) model. In the \( \beta = 2 \) model, there is an upturn of the mass-to-light ratio of early types around \( M_e = 3 \times 10^{11} h^{-1} M_\odot \) (for those measured in other bands, see van den Bosch et al. 2003; Yang et al. 2003; Eke et al. 2006), which means that the star formation in galaxies is strongest at this mass scale. A fitting formula for the mass-to-light ratio can be derived from

\[
\Upsilon \equiv \frac{M}{L} = \Psi_{\text{ml}} \left( \frac{M}{M^*} \right)^{\gamma} \left( \frac{M^*}{M} \right).
\]

Using this equation, the mass scale corresponding to the minimum mass-to-light ratio can be related to the shape parameters as \( M_e = M^*/\gamma \), and the minimum mass-to-light ratio is \( \Upsilon_{\text{ml}}(E) = \Psi_{\text{ml}}(e/\gamma)^{\gamma} \approx 100 \ h \ (M_\odot/L_\odot) \) for early-type galaxies and \( \Upsilon_{\text{ml}}(L) \approx 50 \ h \ (M_\odot/L_\odot) \) for late types in the \( \beta = 2 \) model.

According to our results, the mass-to-light ratio of the brightest galaxies reaches \( \Upsilon(E) \approx 1450 \ h \ (M_\odot/L_\odot) \) at \( M_h = 5.8 \times 10^{13} h^{-1} M_\odot \). This value is slightly larger than or comparable to those reported in the literature. For example, Mandelbaum et al. (2006) noted that the mass-to-light ratio of central early types reaches \( M_h/L_c = 963 \ h \ (M_\odot/L_\odot) \) for their brightest samples of \( M_h \approx 5.8 \times 10^{13} h^{-1} M_\odot \) (see their Table 4). Zheng et al. (2007) found \( M_h/L_c = 1500 \ h \ (M_\odot/L_\odot) \) for halos of \( M_h \approx 6 \times 10^{13} h^{-1} M_\odot \). From Figure 1 of Vale & Ostriker (2008), the modeled galaxies have \( M_h/L_c \approx 1000 \ h \ (M_\odot/L_\odot) \) around \( M_h \approx 3 \times 10^{13} h^{-1} M_\odot \) in the \( b_1 \)-band and \( M_h/L_c \approx 1000 \ h \ (M_\odot/L_\odot) \) around \( M_h \approx 2 \times 10^{14} h^{-1} M_\odot \) in the \( K \) band.

In those papers considering the collective mass or total luminosity, the reported values are significantly lower than ours. In the \( b_1 \)-band, Vale & Ostriker (2006) reported \( \Upsilon \approx 425 \ h \ (M_\odot/L_\odot) \) for a cluster halo of mass \( M_h = 10^{15} h^{-1} M_\odot \). Because their results are for the cluster mass-to-light ratio, their value is usually smaller than the galaxy mass-to-light ratio investigated here. It is also known that the cluster mass-to-light ratio may depend on the magnitude limits of the satellite galaxy sample (see Fig. 6 of Tinker et al. 2005). On the other hand, Cooray & Milosavljevic (2005a, 2005b) reported a ratio of central galaxy luminosity to total halo mass as low as \( M_h/L_c = 370 \ h \ (M_\odot/L_\odot) \) for \( M_h = 10^{14} h^{-1} M_\odot \), using lensing and cluster BCG data in 2MASS. The main reasons for these lower values are the different definitions of mass or luminosity and the different bandpass adopted in their analyses.

4. ENVIRONMENTAL EFFECTS ON GALAXY DISTRIBUTION

4.1. Definition of the Local Density

For a comparative study of the environmental effects on the spatial and luminosity distributions of observed and mock galaxies, a quantitative measure of the local environment is needed.
To minimize the parameterizations and maximize the spatial resolution, we use the spline kernel to obtain the smooth galaxy number density field. It is given by

\[
W(q) = \begin{cases} 
\left(1 - \frac{3}{2}q^2 + \frac{3}{4}q^3\right)/\left(\pi h_s^3\right) & \text{for } 0 < q \leq 1, \\
\left(2 - q\right)^3/(4\pi h_s^3) & \text{for } 1 < q \leq 2, \\
0 & \text{otherwise},
\end{cases}
\]

where \(q \equiv r/h_s\). The kernel is centrally weighted more than the Gaussian and has only one parameter, \(h_s\). It is smooth to second order and has a finite tail out to \(2h_s\). Throughout this paper, we set \(h_s = d_{20}/2\), where \(d_{20}\) is the distance to the 20th nearest neighbor galaxy. Because of these features and the adaptive nature of \(h_s\), the resulting galaxy density map represents the observed distribution of galaxies better than the Gaussian, particularly in voids and clustered regions. To compare the observed and mock galaxy samples, it is necessary to make the number density of the density tracers the same. We use galaxies brighter than \(M = -20\) as the galaxy density tracers. This selection differs slightly from that adopted by Park et al. (2007), who chose \(-21 < M < -20\). We removed the bright cut to better resolve the centers of clusters, where galaxies brighter than \(L_\ast\) are concentrated.

4.2. Number Density Distributions

The local density at galaxy positions is measured in our SDSS volume-limited samples. The density estimate is corrected for boundary effects when the kernel sphere of radius \(d_{20}\) overlaps the survey boundary. Late-type galaxies with axis ratios \(b/a < 0.6\) are removed from the sample to reduce the effects of internal absorption on luminosity. After this exclusion, we give a weight of 1/0.505 to late-type galaxies to correct the galaxy number density for the missing inclined galaxies, where 0.505 is the fraction of late types with \(b/a > 0.6\) in a sample containing galaxies down to \(M = -17.5\) (the CM sample of Choi et al. 2007).

The correction for boundary effects is unnecessary for mock galaxies, since their distribution is periodic in all directions. The redshift distortion effects caused by the peculiar velocities are mimicked by shifting the mock galaxies along the \(x\)-axis using \(x' = x + v_x/H_0\), where \(v_x\) is the \(x\)-component of peculiar velocity and \(H_0\) is the Hubble constant.

Figure 5 shows the distribution of local density (open circles) at the location of galaxies in two volume-limited SDSS samples with absolute magnitude limits of \(-20.0\) (sample D5) and \(-18.5\) (sample D2). Also plotted are the local density distributions of mock galaxies selected by the same magnitude-limit criteria for the \(\beta = 2\) and \(\kappa = 2\) models. Note that the local density distributions of the SDSS galaxies and the corresponding mock galaxies match each other closely at all densities except high densities. These distributions for the \(\kappa = 2\) model are also shown in Figure 6, with the same criteria.

Ostriker et al. (2003) employed a lognormal function to fit the one-point distribution of dark matter density and luminosity density in their hydrodynamical simulation. A spherical top-hat filter of constant radius was adopted in their study. They found a good agreement between the simulated density distributions and the lognormal distribution, while the distribution of luminosity density showed a poor fit. We check how well the galaxy density distribution, rather than dark matter or luminosity, is described by the nonnormalized lognormal function

\[
\Xi(\Delta) \equiv \frac{dN(\Delta)}{d\log \Delta} = \frac{A}{\sqrt{2\pi}\sigma}e^{-(\ln \Delta - \rho)^2/2\sigma^2},
\]

where \(\Delta \equiv \rho/\rho_0\), and \(A\) is the amplitude of the distribution. The mean number density of galaxies is \(n = A \log e\). The best-fitting results are shown by dashed lines in each panel of Figure 5, and the fitting parameter values for various magnitude-limit (\(M_{\text{lim}}\)) samples are listed in Table 2. As can be seen, brighter galaxies tend to be located at higher local densities. The local density distribution also becomes broader for brighter subsamples if viewed in the linear overdensity scale, or has nearly a constant width (width(\(\sigma\)) \(\approx 1.29\)) in log scale.

Figures 7 and 8 show the distribution of local density at locations of early-type (circles) and late-type (stars) galaxies in the \(\beta = 2\) and \(\kappa = 2\) models, respectively. Open symbols are for the SDSS samples, and the rest are for the mock galaxies. The local density distributions of the simulated early- and late-type galaxies are very well matched with observations at low and intermediate densities (\(\rho/\rho_0 < 10\)), even though there is only one input parameter in our model. Late-type galaxies dominate these regions. From these figures, it appears that the galaxy morphology depends only on the halo mass and does not directly depend on environment. However, the number density analysis alone is not sufficient to
allow any definite conclusions as to the environmental effect. We will further investigate this effect in the next section by comparing the luminosity functions of the SDSS sample with those of mock galaxies in various environments.

In the high-density regions our model gives too few galaxies, probably due to the resolution of the simulation, which is insufficient to maintain small subhalos within clusters, and to the lack of gas physics.

4.3. Luminosity Function

There have been several works reporting on the environmental dependence of the galaxy luminosity function (Park et al. 1994, 2007 in observations; Mo et al. 2004 in the HOD model). It has been found that the characteristic galaxy luminosity \( L^* \) is an increasing function of the local density, and that the faint-end slope \( \alpha \) of the luminosity function is insensitive to the local density. However, Park et al. (2007) used a spline kernel weighting to estimate local densities, and Mo et al. (2004; also Cooray 2005) used a spherical top-hat filter of constant radius. For a quantitative comparison between observations and models, the same density estimation scheme is required.

In the previous section, we studied the one-point distribution of the local density at galaxy locations for each morphology sample of galaxies brighter than a certain absolute magnitude limit. In this section, we investigate the distribution of the absolute magnitude of early- and late-type galaxies located in different local

| \( M_{\text{min}} \)  | Sample | \( A \) \((h^{-1} \text{Mpc})^{-3} \) | \( \mu \)  | \( \sigma \) |
|-----------------|-------|-----------------|--------|--------|
| -18.5           | D2    | \( 4.53 \times 10^{-2} \) | 0.662  | 1.27   |
| -20             | D5    | \( 1.47 \times 10^{-2} \) | 0.949  | 1.34   |
| -20.5           | D5    | \( 7.44 \times 10^{-3} \) | 1.11   | 1.30   |
| -21             | D5    | \( 2.76 \times 10^{-3} \) | 1.23   | 1.26   |

Fig. 6.—As in Fig. 5, but for the \( \kappa = 2 \) model.

Fig. 7.—Local overdensity distributions for the two morphological types in the \( \beta = 2 \) model. The distributions of local overdensity of mock and SDSS galaxies (D5 and D2) are shown for two magnitude-limit samples, \( M < -20 \) (top) and \( M < -18.5 \) (bottom). Open circles and open stars mark the distributions of overdensity of the early-type and late-type SDSS galaxies. Filled circles and asterisks denote mock galaxies for the corresponding types. We label each panel with the magnitude criteria of the sample in the upper-left corner.
ing the MINUIT packages, which employ the maximum likelihood method. The fitting of the measured luminosity functions measured from the D3 sample produces the observed luminosity functions at different local densities and for different morphological types. For this comparison, we use the luminosity functions measured from the D3 sample of Park et al. (2007), because this absolute magnitude–limited sample covers both bright and faint magnitudes well, relative to other volume-limited samples. The fitting of the measured luminosity functions to the Schechter formula is carried out using the MINUIT packages, which employ the maximum likelihood method.

Figures 9 and 10 show a comparison of the luminosity functions in four different local density regions in the $\beta = 2$ and $\kappa = 2$ models. The resulting environment- and morphology-specific luminosity functions reproduce the observations surprisingly well. However, there are notable disagreements between the two cases. At very high densities ($\rho/\bar{\rho} > 10$), the abundance of faint early-type galaxies is significantly low in the simulation. This is again probably due to the lack of small subhalos, which were destroyed in the high-density environment. Another problem is seen at low densities ($\rho/\bar{\rho} < 1$), where the early-type galaxies are too few at the bright end of the luminosity function. It seems that the morphology transformation to bright early types in underdense regions through close interactions and mergers is more efficient in nature than in our model (see Park et al. 2008 for observational evidence). In the high-density regions, the $\kappa = 2$ model describes the number distribution of faint late-type galaxies better than the $\beta = 2$ model, while this $\kappa$ model shows a slight overestimation in the population of faint late types in the mean fields $[0.4 < \log (\rho/\bar{\rho}) < 1]$ compared to the observation.

Figures 11 and 12 compare the parameter of the Schechter function best fit to the SDSS data (open symbols) and mock galaxy samples (filled symbols) as a function of local density in the $\beta = 2$ and $\kappa = 2$ models. The dependence of both $M_{\ast}$ and $\alpha$ on local density is qualitatively well reproduced by the simulation. However, the characteristic magnitude $M_{\ast}$ of the early types is significantly fainter at $\rho/\bar{\rho} < 2$ in the simulation. This is due to the paucity of bright early-type galaxies in low-density regions, as mentioned above. The parameter $\alpha$ of the simulation is quite different from the observation at $\rho/\bar{\rho} > 2$ for early-type galaxies. This is again due to the flat faint-end slope of the luminosity function of the simulated early-type galaxies.

4.4. Central Velocity Dispersion

Figure 13 shows the central velocity dispersion of early-type galaxies in the D3 sample. The gray symbols with connecting lines are the relations between $\sigma$ and the local density for early-type galaxies in four subsamples with absolute magnitude limits of $-19.0 > M > -19.3$ (bottom curve), $-19.3 > M > -20.1$, $-20.1 > M > -20.5$, and $M < -20.5$ (top curve with filled circles). The curves delineate the median value of $\sigma_0$ in each local density bin, which monotonically increases as luminosity increases. We also plot, with black symbols, the scaled one-dimensional velocity dispersion of the early-type mock galaxies in the $\beta = 2$ model. Because the observed velocity dispersion is obtained by sampling the inner part ($\leq 1.5r_e$) of the galaxy, we have to apply a scaling factor to the mock galaxy velocity dispersions. Because for our purposes we do not need to derive the exact value of the scaling factor and apply it to the related analysis, we make a rough estimation of the relation between $\sigma_{\text{los}}$ and $V_v$, where $\sigma_{\text{los}}$ is the line-of-sight aperture velocity dispersion and $V_v$ is the virial velocity. According to Lokas & Mamon (2001), the resulting scaling ratio of the velocity dispersions, $f_v(\equiv \sigma_{\text{los}}/V_v)$, is

$$0.5 \leq f_v \leq 3$$  \hspace{1cm} (13)

for the acceptable ranges of the velocity anisotropy and the concentration parameter in $0 < (r_e/R_v) < 1$, where $r_e$ is the comoving aperture radius. Here we assume that $V_v = \sigma_0$, where $\sigma_0$ is the three-dimensional velocity dispersion and $V_v = (2GM/H_0)^{1/2}$. In the range of $f_v$ written in equation (13), we simply set $f_v = 0.8$ ($M < -20.5$), $f_v = 1.0$ ($-20.5 < M < -20.1$), $f_v = 1.1$ ($-20.1 < M < -19.3$), and $f_v = 1.2$ ($-19.3 < M < -19.0$) to match the mean amplitudes of velocity dispersions for each mock and SDSS sample pair. At a fixed luminosity, the velocity dispersion of the early-type mock galaxies increases as the local density increases for bright galaxies, and the slopes decrease for the faint sample. It is reassuring that this trend is exactly the kind of phenomenon found in the observation (gray symbols). While the

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5 Documentation for MINUIT is available at http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html.
Fig. 9.—Luminosity functions of mock (curves) and SDSS (symbols) galaxies in the $\beta = 2$ model. Each line shows the luminosity functions of the mock galaxies: solid lines, all galaxies; dotted lines, early-type galaxies; dashed lines, late-type galaxies. For comparison, we show the luminosity densities of the SDSS subsamples divided by the same density cuts. The sample selection criteria are based on the log scale of local density and are written in the lower-right corner of each panel.
Fig. 10.—As in Fig. 9, but for the $\kappa = 2$ model.
switch of the slope in the faintest SDSS samples is not clearly ob-
served in the mock sample (it shows a nearly flat slope in the local
environments), the changes of slope are similar. Both observations
and our model show that the mass-to-light ratio of the early-type
galaxies is a function of environment, and that this dependence, in
turn, is a function of luminosity. The mass-to-light ratio of the early
types decreases as the local density increases for galaxies brighter
than about $M_{C3}$, but increases for those fainter than about
$M_{C3} + 1.

4.5. Effects of Scatterings in the $M_L$-L Relation

Many researchers have investigated the effects of scatter in the
mass-to-luminosity relations on the mock galaxy distributions in
their models of $L(M_h)$. Therefore, it is valuable to check whether
the introduction of scatter in the relation can provide a cure for the
paucity of modeled galaxy populations in the cluster regions, leav-
ing the distributions unchanged in other regions. We use a log-
normal function for the probability distribution, $\varphi$, for a subhalo
of mass $M_h$ to have a galaxy luminosity $L$ around $L_0$:

$$
\varphi(L|M_h) dL = \frac{1}{\sqrt{2\pi} \sigma_{LN}} \exp\left(-\frac{\ln^2[L/L_0(M_h)]}{2\sigma_{LN}^2}\right) d\ln \left(\frac{L}{L_0}\right),
$$

where $L_0(M_h)$ is the deterministic mass-to-light relation and
$\int_{-\infty}^{\infty} \varphi \, dL = 1$ for all $M_h$. Cooray & Milosavljevic (2005b) used a
similar form to describe the conditional luminosity function,
$\varphi_c(L|M_h) = \varphi(L|M_h)\Phi_h(M_h)/\ln(10)$, where $\Phi_h(M_h)$ is the halo
mass function and $\varphi_c$ is the conditional central galaxy luminosity
function. Here $\ln(10)$ is included to account for the different log-
arithmic scales applied to define $\varphi_c(L)$ and $\Phi_h(M_h)$. They applied
this equation to measure $L_0(M_h)$ and $\sigma_{LN}$ by fitting the resulting
modeled luminosity functions to the observations.

On the other hand, we already have a well-defined $L_0(M_h)$, so
we can simply apply small deviations to the relation, checking
whether the galaxy populations in the cluster regions are recovered
accordingly. For this test, we adopt constant values of $\sigma_{LN} = 0.25$
(Cooray & Milosavljevic 2005b; Vale & Ostriker 2008) and
$\sigma_{LN} = 1$, where the latter value is taken for an extreme case of
the model. Then, the scattered magnitude, $M'$, is obtained by

$$
M' = M_0 - 2.5\sigma_{LN} R_G \log e,
$$

where $R_G$ is the generated Gaussian random number of a unit
standard deviation. Using this equation, we remeasure the mag-
nitudes of mock galaxies and apply them to the number density
and the luminosity function analyses.

As shown in Figure 14, the effect of the scatter on the number
density distribution is almost negligible for both scattering mod-
els. This is because the applied sample is not differential but
cumulative, so the scattering effect is significant only at the sam-
ple boundary. As a result, the total effect on the sample is too
small to create any change in the distributions. Next, we investigate the changes in the luminosity functions of both models. Figure 15 shows the luminosity functions in the \( \kappa = 2, \sigma_{\text{LN}} = 0.25 \) model. Compared to the no-scatter model (Fig. 10), there is no gain for the cluster regions. We still observe underpopulations of galaxies in both types. However, there are small positive changes; bright populations in the exponential decay are increased compared to those in the no-scatter models, with a slightly better match for the observations. This is also noted by Vale & Ostriker (2008), who argued that the scattering effect is more significant in the steep regions than in the flat regions. For the \( \kappa = 1 \) model, the bright mock galaxies are seriously overproduced by a factor of several compared to the observed populations, and no change is obtained for the cluster regions. Therefore, we confirm that the scatter in the \( L(M_h) \) relation should be around \( \sigma_{\text{LN}} = 0.25 \) and not as high as \( \sigma_{\text{LN}} = 1 \). We also conclude that the underpopulation of the mock galaxies in cluster regions is not relieved by this simple scattering model.

5. SUMMARY AND CONCLUSIONS

We have proposed a model to assign galaxy luminosity and morphology to the dark subhalos directly identified in cosmological \( N \)-body simulations. It is assumed that galaxy luminosity is a monotonic function of the host halo mass. In the \( \kappa \) model, we assume that the halo masses of early- and late-type galaxies of equal luminosity have a constant ratio. An alternative model is the \( \beta \) model, which assumes a constant luminosity ratio between galaxies of different types residing in subhalos of the same mass. This model has been proposed by Marinoni & Hudson (2002), who found that the observed \( B \)-band luminosity function of galaxies can be reproduced from the Press-Schechter (PS) function, assuming double power-law mass-to-light ratios and derived halo occupation numbers. It has been expanded by Vale & Ostriker (2004, 2006), who adopted satellite halo mass functions and directly linked subhalos to the observed galaxies. Cooray & Milosavljevic (2005b) combined this double power-law ratio with the conditional luminosity function \( \Phi(L|M_h) \) to relate the halo mass to the luminosity distribution of the central galaxies. In this paper, we have introduced the ratio of the luminosity of early and late morphological type galaxies at a given halo mass, and derived type-specific mass-to-light ratios as a function of subhalo mass. These are used to assign luminosity and morphology to subhalos. The mass-to-light ratio of the early-type galaxies derived in this way has a minimum value of \( \gamma_b \simeq 100 h (M_\odot/L_\odot) \) at the scale of \( M_\odot \approx 3 \times 10^{11} h^{-1} M_\odot \) in the \( \beta = 2 \) model. The mass-to-light ratio starts to increase exponentially below \( M_\odot \) and increases as a power law above \( M_\odot \).

We use the large-scale background galaxy number density as an environmental parameter. The smooth galaxy density field is obtained by using the adaptive spline kernel, which enables us to resolve crowded regions well. The local density distribution of the SDSS galaxies is well described by the lognormal function. The lognormal parameter values obtained indicate that brighter galaxies tend to be located in dense regions. The local density distribution.

Fig. 13.—Median distribution of central velocity dispersions of SDSS (gray symbols) galaxies and scaled one-dimensional velocity dispersions of mock (black symbols) galaxies of early types in the four magnitude-limit samples divided by four magnitude cuts. The magnitude ranges of the subsamples are \( M < -20.5, -20.5 < M < -20.1, -20.1 < M < -19.3, \) and \( -19.3 < M < -19 \), from top to bottom.

Fig. 14.—Number density distributions for the models with scatterings of \( \sigma_{\text{LN}} = 0.25 \) (top) and \( \sigma_{\text{LN}} = 1 \) (bottom) in the \( \kappa = 2 \) model. The sample magnitude is set at \( M < -18.5 \).
of the mock galaxies is quite similar to that of the SDSS galaxies in voids and moderate-density regions for both morphological types.

The underestimation of the mock galaxy population in clusters is believed to be due to the evaporation of subhalos by dynamical friction and tidal stripping. This may explain the discrepancy in the luminosity functions of early- and late-type galaxies in high-density regions. Several authors (Conroy et al. 2006; Vale & Ostriker 2006) have already considered this effect in cluster environments. Rather than using current subhalo mass, they adopt the mass or mass-related circular velocity at the time of accretion to measure the luminosity in the present epoch. It is plausible that a galaxy may sustain its luminosity during the merging event, while the mass of its hosting subhalo could be significantly reduced by the merging process. However, in our N-body simulation, we are unable to keep track of individual subhalos, because the output of the simulation is not complete in time. In future simulations, we will check whether the preaccretion mass could play a role in completely saving the model in the cluster regions.

A scattering in the relation between the galaxy luminosity and subhalo mass has been adopted by several researchers (Tasitsiomi et al. 2004; Conroy et al. 2006; Vale & Ostriker 2006; Cooray & Milosavljevic 2005b). Cooray & Milosavljevic (2005b) claimed that this intrinsic scatter helped their model to reproduce the exponential decay of the Schechter function toward the bright end. Conroy et al. (2006) noted that some scatter in the mass and luminosity relation is necessary to describe the spreads of data in the Tully-Fisher and Faber-Jackson relations (for a full discussion, see their paper). Vale & Ostriker (2006) argued that the scattering over the average relation is reasonable from the plotted observational data, and this makes the mock catalogs more realistic. We also found that the \( \sigma_{\text{L}} = 0.25 \) model predicted galaxy populations similar to observations in the voids and mean fields, but it is still unable to recover the galaxy populations in the cluster regions.

In this work, we fix \( \kappa \) and \( \beta \) over all mass ranges of subhalos. This assumption is based on observational evidence. The central velocity dispersion for different galaxy types in the SDSS observation shows a constant shift over the available magnitude range (Park et al. 2007). However, it would be valuable to study the effect of a variable \( \kappa \) or \( \beta \) on the model distributions. We will investigate this issue in a future work.

Recently, Gott et al. (2008) measured the genus statistic from a large sample of SDSS galaxies and compared it to those of mock galaxies created by three distinctive methods: the semianalytic galaxy formation model applied to the Millenium run (Springel et al. 2005), a hydrodynamic simulation, and the subhalo-galaxy correspondence model adopted in this paper. It was found that the observed topology of large-scale structure was best reproduced by the subhalo-galaxy correspondence model, even though other models were also consistent with observations. However, the observed

![Fig. 15.](image-url)
topology was marginally inconsistent with all simulations, in the sense that it showed a strong meatball topology at the significance level of 2.5 σ at the scale studied. The prominence of isolated high-density regions in the observation seems to be due to the Sloan Great Wall, which was a dominant structure in the sample analyzed.

We have found an impressive agreement between our mock galaxies and the SDSS galaxies in the dependence of central velocity dispersion on local density and luminosity. The early-type galaxies tend to have higher σ, or higher mass in high-density regions at a given luminosity when they are brighter than about $M_{\text{lim}}$. In other words, these bright galaxies tend to become relatively fainter in high-density regions at a given halo mass.

This interesting dependence of the mass-to-light ratio on environment was successfully reproduced by our subhalo-galaxy correspondence model of galaxy formation. A more detailed study of this phenomenon will be presented in a forthcoming paper.

C. P. and Y.-Y. C. acknowledge the support of the Korea Science and Engineering Foundation (KOSEF) through the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC). Funding for the SDSS and SDSS-II was provided by the Alfred P. Sloan Foundation, the SDSS participating institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The participating institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington. The authors would like to acknowledge the use of the Linux cluster, QUEST, at the Korea Institute for Advanced Study (KIAS). Its huge computing power was indispensable for the study, and we thank the system managers for their efforts in providing stable and comfortable computation resources during the simulation and subsequent analysis.

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