

## NONLINEAR STOCHASTIC BIASING OF GALAXIES AND DARK HALOS IN COSMOLOGICAL HYDRODYNAMIC SIMULATIONS

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### ABSTRACT

We perform an extensive analysis of nonlinear and stochastic biasing of galaxies and dark halos in a spatially flat, low-density cold dark matter universe ( $\Omega_0 = 0.3$ ,  $\lambda_0 = 0.7$ ,  $h = 0.7$ , and  $\sigma_8 = 1$ ) using cosmological hydrodynamic simulations. We identify galaxies by linking cold and dense gas particles that satisfy the Jeans criterion. We compare their biasing properties with the predictions of an analytic halo biasing model. Dark halos in our simulations exhibit reasonable agreement with the predictions only on scales larger than  $\sim 10 h^{-1}$  Mpc; on smaller scales, the volume exclusion effect of halos due to their finite size becomes substantial. Interestingly, the biasing properties of galaxies are better described by extrapolating the halo biasing model predictions. The clustering amplitudes of galaxies are almost independent of the redshift between  $z = 0$  and 3, as reported in previous simulations. This in turn leads to a rapidly evolving biasing factor; we find that  $b_{\text{cov}} \approx 1$  at redshift  $z \approx 0$  and  $b_{\text{cov}} \approx 3-4$  at  $z = 3$ , where  $b_{\text{cov}}$  is a biasing parameter defined from the linear regression of galaxy and dark matter density fields. Those values are consistent with the observed clustering of Lyman break galaxies. We also find the clear dependence of galaxy biasing on formation epoch; the distribution of old populations of galaxies tightly correlates with the underlying mass density field while that of young populations is slightly more stochastic and antibiased relative to dark matter. The amplitude of the two-point correlation function of old populations is about 3 times larger than that of young populations. Furthermore, the old population of galaxies resides within massive dark halos while the young galaxies are preferentially formed in smaller dark halos. Assuming that the observed early- and late-type galaxies correspond to the simulated old and young populations of galaxies, respectively, all of these segregations of galaxies are consistent with observational ones for early- and late-type galaxies such as, e.g., the morphology-density relation of galaxies.

*Subject headings:* dark matter — galaxies: clusters: general — galaxies: formation — galaxies: halos — large-scale structure of universe — methods: numerical

### 1. INTRODUCTION

Ongoing galaxy redshift surveys such as the Sloan Digital Sky Survey and the Two-Degree Field aim at revealing the large-scale structure of the universe with unprecedented precision. Gravitational instability is the key process of *dark matter clustering*, and this is now well understood from numerical simulations and several empirical theoretical models (Davis et al. 1985; Hamilton et al. 1991; Suto 1993; Mo & White 1996; Navarro, Frenk, & White 1997). In fact, once the underlying cosmological models are specified, the two-point correlation functions of dark matter, which are the most conventional and widely used statistics describing the large-scale structure, can be predicted fairly accurately even with redshift distortion and light cone effects (Peacock & Dodds 1996; Suto et al. 1999; Suto, Magira, & Yamamoto 2000; Hamana, Colombi, & Suto 2001).

On the other hand, it is widely believed that the distribution of galaxies is somewhat biased with respect to the underlying dark matter. For instance, Lyman break gal-

axies at redshift  $z \approx 3$  (Steidel et al. 1998; Adelberger et al. 1998; Giavalisco et al. 1998) exhibit strong clustering, and the galaxy biasing with respect to dark matter is time dependent. Also, galaxy clustering is dependent on galaxy morphology and environment (Dressler 1980; Postman & Gellar 1984; Loveday et al. 1995; Hermit et al. 1996; Dressler et al. 1997; Tegmark & Bromley 1999), indicating that galaxy biasing is sensitive to many physical processes and is thus *stochastic*. Clearly the relation between galaxy and dark matter clustering is far from simple and not yet fully understood either observationally or theoretically. This is the primary difficulty in properly interpreting the observational data of the upcoming large-scale redshift surveys.

So far several models of galaxy biasing have been proposed, adopting simplifying assumptions; Fry (1996) and Tegmark & Peebles (1998) discuss the evolution of biasing assuming that the number of galaxies does not change. Mo & White (1996) presented a model for the nonlinear biasing of virialized dark halos using the extended Press-Schechter

formalism (Bond et al. 1991). Jing (1998) tested and improved the formula for the biasing of halo correlation functions, originally proposed by Mo & White (1996), using high-resolution  $N$ -body simulations. Dekel & Lahav (1999) developed a fundamental framework to quantify the nonlinearity and stochasticity in galaxy biasing. Their formulation was subsequently applied to several numerical simulations (Blanton et al. 1999, 2000; Somerville et al. 2001). The biasing of dark halos was also investigated by Kravtsov & Klypin (1999) using high-resolution  $N$ -body simulations. Note that their definition of *dark halos* is different from the conventional one used in the Press-Schechter formalism but rather close to *dark matter cores* in our analysis below. Recently, Taruya & Suto (2000, hereafter TS) proposed a first physical and analytical model for nonlinear and stochastic halo biasing combining the biasing model of Mo & White (1996) and the formation epoch distribution of Kitayama & Suto (1996).

More realistic approaches to galaxy biasing employ state of the art numerical simulations, including the mesh-based hydrodynamical simulations (Blanton et al. 1999, 2000; Cen & Ostriker 2000) and  $N$ -body simulations combined with semianalytic modeling of galaxy formation (Benson et al. 2000; Somerville et al. 2001). In what follows we use cosmological smoothed particle hydrodynamics (SPH) simulations (Yoshikawa, Jing, & Suto 2000) of the cold dark matter (CDM) universe to examine galaxy biasing. In particular, we focus on the comparison of the biasing characteristics of simulated objects (galaxies and dark halos) with the halo biasing model of TS. In addition, we investigate the dependence of galaxy biasing properties on their formation history as an origin of galaxy morphology. Our simulation of galaxy formation directly follows hydrodynamic and radiative processes; the evolution of galaxies is not so properly modeled as those combined with a semianalytic method of galaxy formation (Somerville et al. 2001). Owing to the Lagrangian nature of the SPH technique, the spatial resolution of our simulations is better than that in the mesh-hydrodynamic simulations by Blanton et al. (1999, 2000) and we can resolve galaxies as distinct and isolated objects; their treatment of the thermal process and the metal enrichment is more realistic. Thus, our method is complementary to previous investigations that use different approaches.

The rest of the paper is organized as follows. In § 2 we describe the detail of our numerical simulation and the procedures to identify galaxies, dark matter (DM) cores, and dark halos. In § 3 we present a brief summary of the biasing description following TS and compare several properties of the biasing in the one-point statistics of galaxies and dark halos. Then we discuss the biasing in terms of its two-point correlation functions. The dependence of galaxy biasing on formation history is examined in § 4. Finally, we summarize our major findings in § 5.

## 2. METHODOLOGY

### 2.1. Cosmological Smoothed Particle Hydrodynamics Simulation

Our numerical simulation code is a hybrid of a particle-particle-particle-mesh  $N$ -body Poisson solver (Hockney & Eastwood 1981) and an SPH algorithm (Yoshikawa et al. 2000). The simulation presented in this paper adopts  $N_{\text{DM}} = 128^3$  dark matter particles and the same number of gas particles for SPH. We use the spline functional form for

gravitational softening (Hockney & Eastwood 1981), and the softening length is set to  $\epsilon_{\text{grav}} = L_{\text{box}}/(10N_{\text{DM}}^{1/3})$  and kept constant in comoving coordinates, where  $L_{\text{box}}$  is the comoving size of the simulation box. We set the minimum of SPH smoothing length to  $h_{\min} = \epsilon_{\text{grav}}/4$  and adopt the ideal gas equation of state with an adiabatic index  $\gamma = 5/3$ . The effect of radiative cooling is included, adopting the metallicity of  $[\text{Fe}/\text{H}] = -0.5$ . We use the cooling rate described in Sutherland & Dopita (1993). Thacker et al. (2000) reported that artificial overcooling occurs under the presence of radiative cooling in SPH simulations owing to overestimates of hot gas density in the vicinity of cooled gas clumps due to the smoothing scheme of the SPH algorithm. In order to avoid this numerical artifact, we implement a modification of the SPH algorithm: “cold gas decoupling,” following Pearce et al. (1999). The detail of this prescription is presented in § 2.2.

We consider a spatially flat low-density CDM (LCDM) universe with  $\Omega_0 = 0.3$ ,  $\lambda_0 = 0.7$ ,  $\sigma_8 = 1.0$ , and  $h = 0.7$ , where  $\Omega_0$  is the mean mass density parameter,  $\lambda_0$  is the dimensionless cosmological constant,  $\sigma_8$  is the rms density fluctuation on a scale of  $8 h^{-1}$  Mpc, and  $h$  is the Hubble constant in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . This particular model satisfies both the *COBE* normalization (Bunn & White 1997) and the abundance of X-ray clusters of galaxies (Kitayama & Suto 1997). We assume the mean baryon mass density parameter to be  $\Omega_b = 0.015 h^{-2}$  (Copi, Schramm, & Turner 1995). The simulation is carried out in a periodic cube of  $(75 h^{-1} \text{ Mpc})^3$ , with the gas and dark matter mass per particle being  $2.4 \times 10^9$  and  $2.2 \times 10^{10} M_\odot$ , respectively. The initial condition is created at  $z = 25$  using the COSMICS package (Bertschinger 1995), which is evolved up to  $z = 0$ .

### 2.2. Cold Gas Decoupling and Identification of Galaxies

In order to avoid the numerical overcooling of gas particles mentioned above, we decouple cold gas particles that

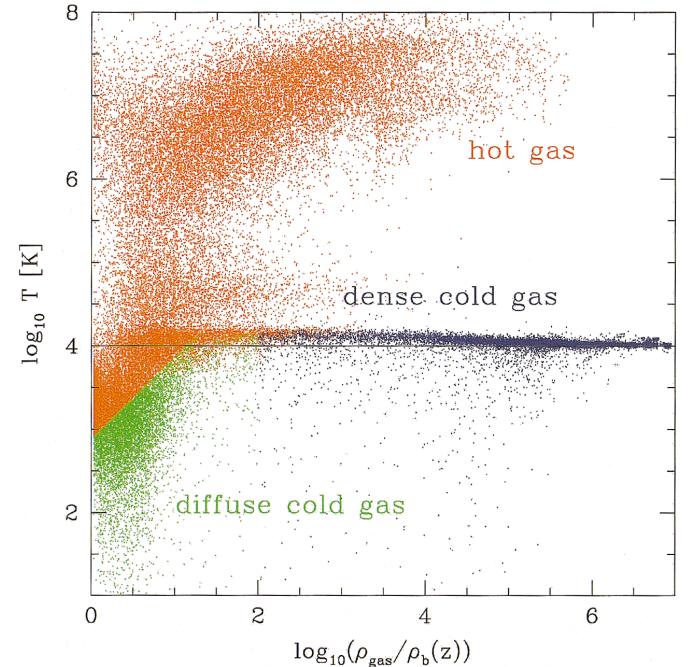


FIG. 1.—Scatter plot of gas particles at  $z = 0$  in  $\log \rho_{\text{gas}}-\log T$  plane. Cold and dense gas particles that satisfy criteria (1) and (2) are indicated by blue points, diffuse cold gas with  $\rho_{\text{gas}} > 10^2 \bar{\rho}_b(z)$  by green points, and the rest by red points.

satisfy the following Jeans condition (Yoshikawa et al. 2000):

$$h_{\text{SPH}} > \frac{c_s}{(\pi G \rho_{\text{gas}})^{1/2}}, \quad (1)$$

where  $h_{\text{SPH}}$  is the smoothing length of gas particles,  $c_s$  is the sound speed,  $G$  is the gravitational constant, and  $\rho_{\text{gas}}$  is the gas density of gas particles. Except for the fact that these cold gas particles are ignored in computing the gas density of hot gas particles, all other SPH interactions are left unchanged. This decoupling scheme is a phenomenological treatment of multiphase gas dynamics and should be interpreted as an approximate prescription of galaxy formation.

Galaxies in our simulations are identified as clumps of cold and dense gas particles that satisfy criterion (1) and

$$\rho_{\text{gas}} < 10^2 \bar{\rho}_b(z), \quad (2)$$

where  $\bar{\rho}_b(z)$  is the mean baryon density at redshift  $z$ . Figure 1 shows the scatter plots of gas particles in the density-

temperature plane. The blue points indicate the cold and dense gas particles satisfying criteria (1) and (2), green points indicate diffuse cold gas particles that satisfy criterion (1) and

$$\rho_{\text{gas}} < 10^2 \bar{\rho}_b(z),$$

and red points represent all other hot gas particles. This indicates that the above criteria for the galaxy particles properly segregate the cold and dense gas particles. We group these particles using the friend-of-friend (FOF) algorithm (Davis et al. 1985) with linking length  $b_g = 0.0164(1+z)\bar{l}$  and identify the resulting clumps as “galaxies,” where  $\bar{l} = L_{\text{box}}/N_{\text{DM}}^{1/3}$  is the comoving mean particle separation. The proper choice of linking length is not clear, and we simply adopt the value of Pearce et al. (1999) here. In this paper we consider only galaxies with masses greater than  $M_{\text{min},g} = 10^{11} M_{\odot}$ , which is equivalent to 40 times each gas particle mass and is close to a nominal mass resolution of

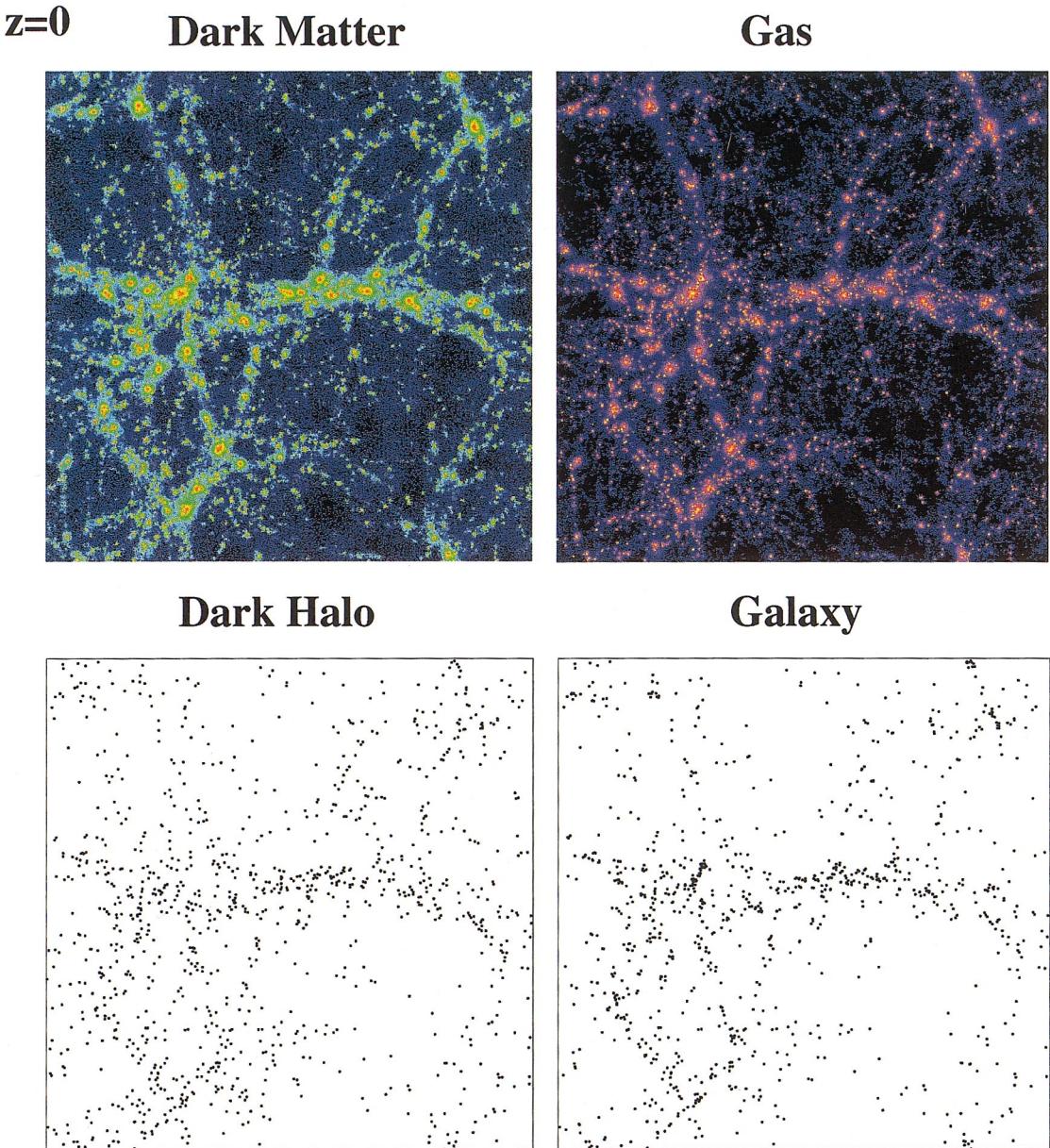
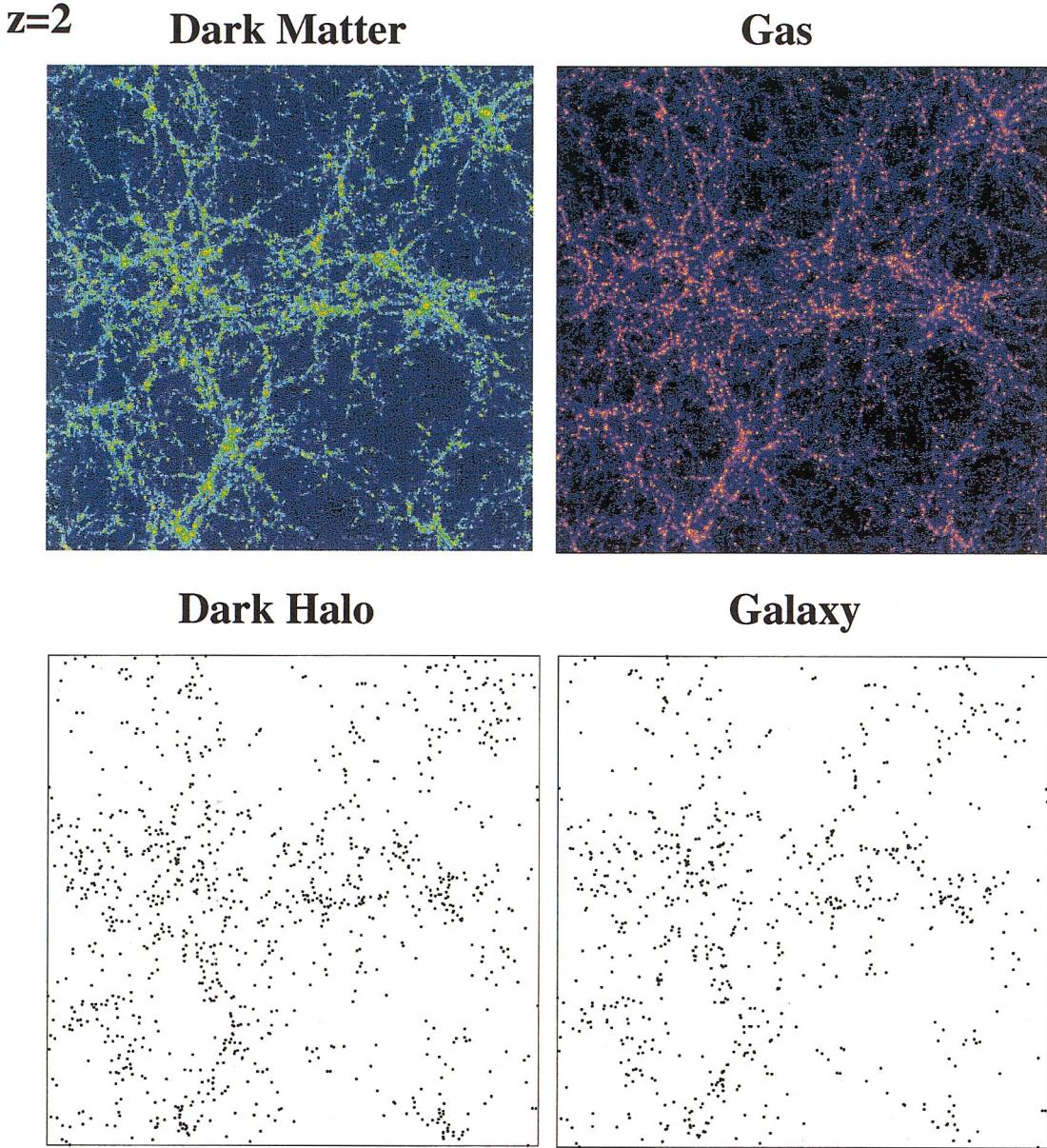


FIG. 2.—Distribution of gas particles, dark matter particles, galaxies, and dark halos in the volume of  $75 \times 75 \times 30 (h^{-1} \text{Mpc})^3$  model at  $z = 0$ . *Upper right*, gas particles; *upper left*, dark matter particles; *lower right*, galaxies; *lower left*, DM cores.

FIG. 3.—Same as Fig. 2, but for  $z = 2$ 

baryonic matter.<sup>1</sup> As noted in § 2.3, the mass functions of simulated galaxies are roughly consistent with those from semianalytic modeling of galaxy formation, which justifies our galaxy criteria empirically to some extent. We show the number of galaxies identified in our simulation and the adopted linking length (in parentheses) in Table 1.

### 2.3. Identification of Dark Halos and Dark Matter Cores

The FOF algorithm is also applied in identifying dark halos. The linking length  $b_h$  for dark halos is set to satisfy the equation

$$\frac{\Delta_c(z)}{18\pi^2} = \left(\frac{b_h}{0.2\bar{l}}\right)^{-3}, \quad (3)$$

<sup>1</sup> SPH gas density is smoothed over about 30 nearest neighbor gas particles.

where  $\Delta_c(z)$  is the mean overdensity of spherically virialized objects formed at redshift  $z$ . We compute  $\Delta_c(z)$  at each redshift using a fitting formula by Kitayama & Suto (1996). At  $z = 0$ , for instance,  $\Delta_c = 335$  and  $b_h = 0.164\bar{l}$ .

We also identify the surviving high-density substructures in dark halos, which we call DM cores. Identification of substructures in dark halos is a technically challenging problem, and several objective methods have been proposed so far (Gelb & Bertschinger 1994; Eisenstein & Hut 1998; Klypin et al. 1999; Springel et al. 2000). In order to identify DM cores in our simulation, we adopt the hierarchical FOF (HFOF) method (Gottlöber, Klypin, & Kravtsov 1999). In the HFOF method we apply the conventional FOF method with a set of different linking length:  $b_c = l_{\max}/4$ ,  $l_{\max}/2$ , and  $l_{\max}$ , where  $l_{\max}$  is the maximum linking length. For each linking length, gravitationally bound groups with more than 20 particles are identified as DM cores. The maximum linking length is set to  $l_{\max} = 0.05\bar{l}$ .

TABLE 1  
NUMBER AND MASS RANGE OF IDENTIFIED OBJECTS AND ADOPTED LINKING LENGTH FOR FOF ALGORITHM

DARK HALO			GALAXY			DM CORE		
REDSHIFT	N	Mass ( $M_{\odot}$ )	N	Mass ( $M_{\odot}$ )	N	Mass ( $M_{\odot}$ )		
0.0 .....	1797 (0.164 $\bar{l}$ )	$10^{12}$ – $8.6 \times 10^{14}$	1604 (0.0164 $\bar{l}$ )	$10^{11}$ – $9.5 \times 10^{12}$	1525 (0.05 $\bar{l}$ )	$4.3 \times 10^{11}$ – $2.0 \times 10^{14}$		
0.5 .....	2105 (0.184 $\bar{l}$ )	$10^{12}$ – $3.5 \times 10^{14}$	1936 (0.0246 $\bar{l}$ )	$10^{11}$ – $6.8 \times 10^{12}$	1721 (0.05 $\bar{l}$ )	$4.3 \times 10^{11}$ – $6.3 \times 10^{13}$		
1.0 .....	2201 (0.192 $\bar{l}$ )	$10^{12}$ – $2.3 \times 10^{14}$	1861 (0.0328 $\bar{l}$ )	$10^{11}$ – $3.6 \times 10^{12}$	1543 (0.05 $\bar{l}$ )	$4.3 \times 10^{11}$ – $2.9 \times 10^{13}$		
2.0 .....	1859 (0.197 $\bar{l}$ )	$10^{12}$ – $8.2 \times 10^{13}$	1360 (0.0492 $\bar{l}$ )	$10^{11}$ – $2.0 \times 10^{12}$	765 (0.05 $\bar{l}$ )	$4.3 \times 10^{11}$ – $9.8 \times 10^{12}$		
3.0 .....	1165 (0.199 $\bar{l}$ )	$10^{12}$ – $3.8 \times 10^{13}$	996 (0.0656 $\bar{l}$ )	$10^{11}$ – $1.4 \times 10^{12}$	278 (0.05 $\bar{l}$ )	$4.3 \times 10^{11}$ – $4.2 \times 10^{12}$		

NOTE.—Values in parentheses are the adopted linking length for the FOF algorithm.

In this paper we consider the dark halos with masses greater than  $10^{12} M_{\odot}$  ( $\simeq \Omega_b/\Omega_0 \times M_{\min, g}$ ) and DM cores with more than 20 dark matter particles (equivalent to  $4.3 \times 10^{11} M_{\odot}$ ). In Table 1 the number of identified objects and adopted linking lengths are also shown. Figures 2 and 3 show the distribution of dark matter particles, gas particles, dark halos, and galaxies at  $z = 0$  and 2. At  $z = 0$  galaxies are more strongly clustered than dark halos while at  $z = 2$  those two objects show similar spatial distribution.

Figures 4 and 5 show close-up snapshots of the most massive cluster at  $z = 0$  with mass  $M \simeq 8 \times 10^{14} M_{\odot}$  and a relatively poor cluster with  $M \simeq 10^{14} M_{\odot}$ , respectively. In each figure the upper panels depict the distribution of dark matter and gas particles and the lower panels show the distributions of DM cores and dense cold gas particles that satisfy criteria (1) and (2). Circles in the lower panels indicate the positions of galaxies identified in our simulation. We can see that for the richer cluster, the distribution of

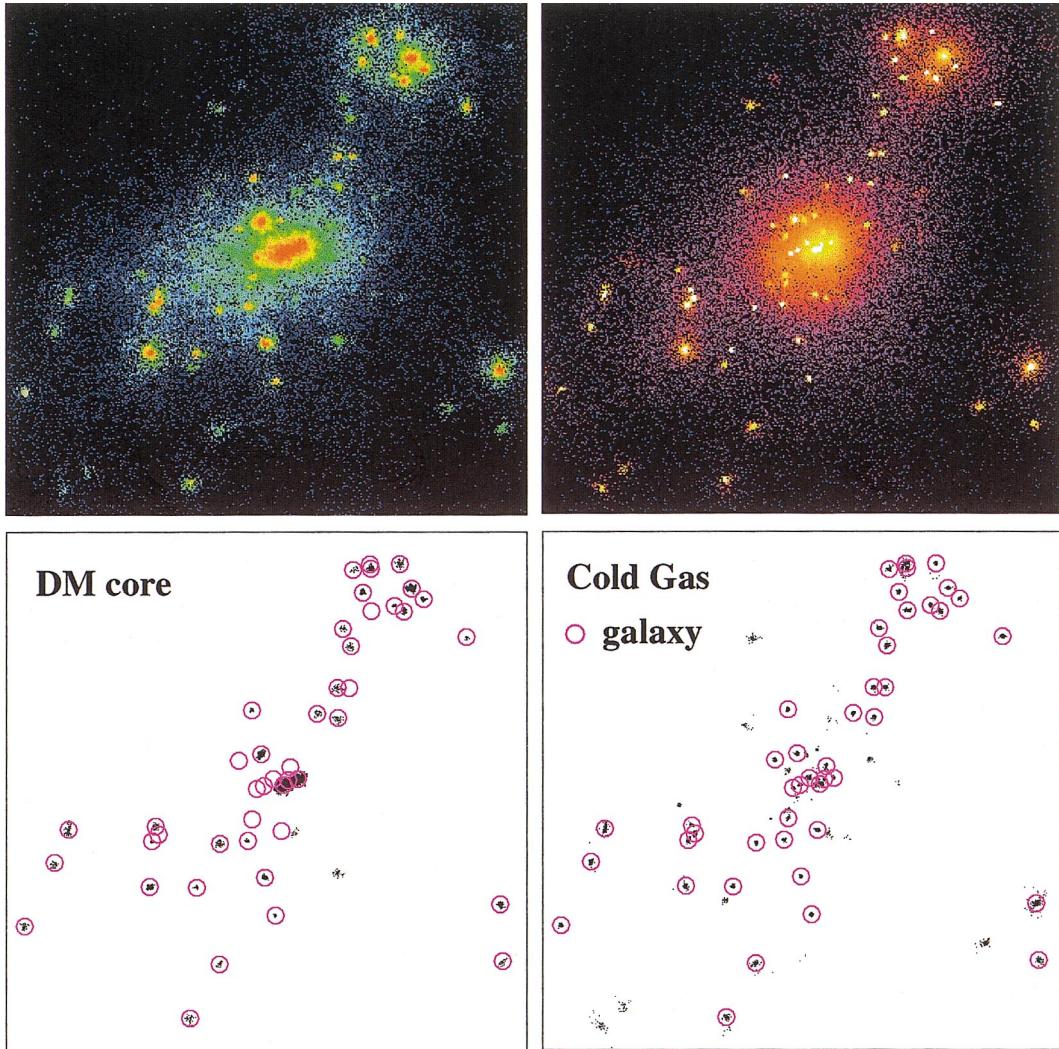
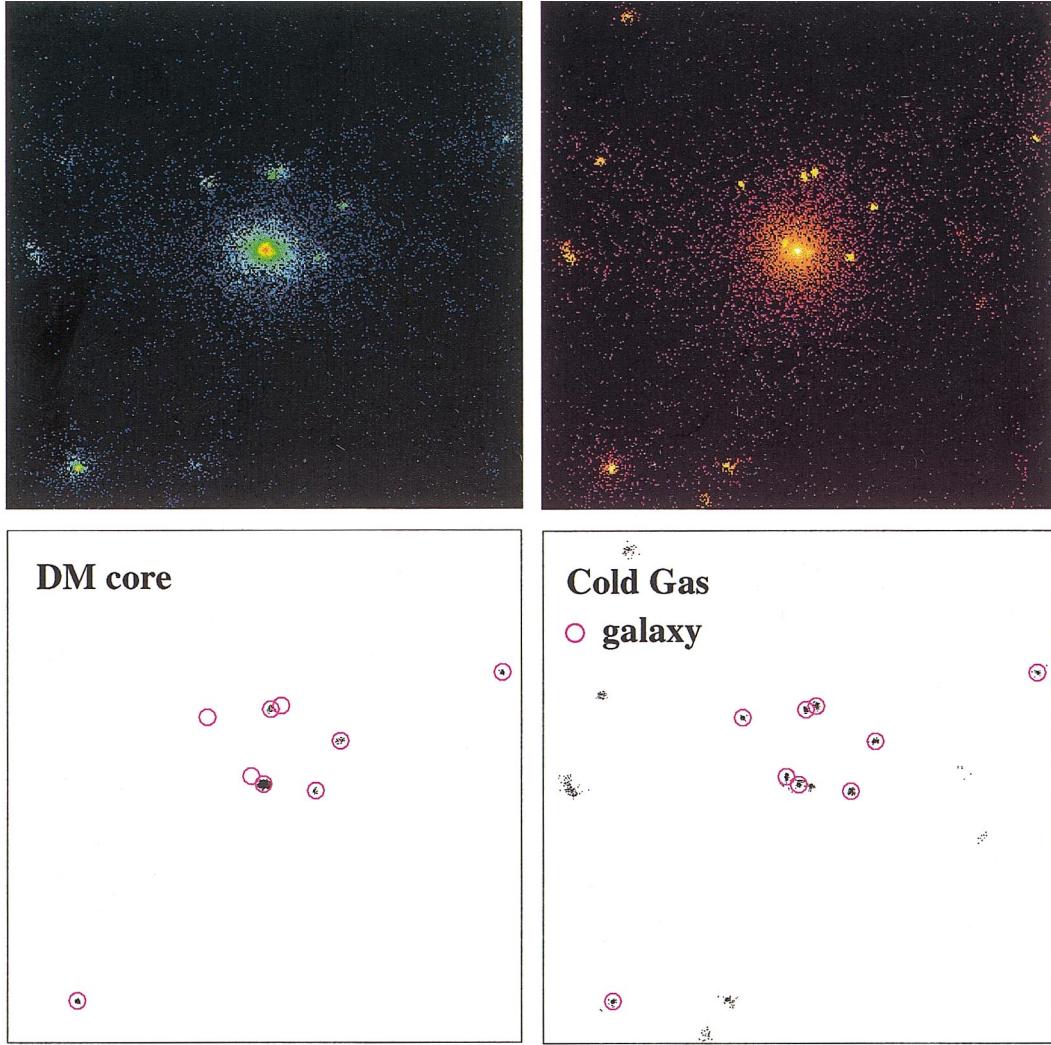


FIG. 4.—Snapshots of the most massive cluster ( $M \simeq 8 \times 10^{14} M_{\odot}$ ) in the simulation at  $z = 0$ . Upper left, dark matter; upper right, gas particles; lower left, DM cores; lower right, cold gas. Circles in lower panels indicate the positions of galaxies identified according to our criteria. The comoving size of the box is  $6.25 h^{-1} \text{Mpc}$  per side.

FIG. 5.—Same as Fig. 4, but for a poorer cluster with  $M \approx 10^{14} M_\odot$ 

DM cores is in relatively good agreement with that of galaxies except for the cluster center, where the tidal radius is much shorter than our numerical resolution. On the other hand, galaxies or cold gas clumps in the smaller cluster are not necessarily hosted by DM cores. This is probably because DM cores in our simulation significantly suffer from artificial overmerging, which is severer for poorer dark halos owing to a small number of particles while galaxies represented by dissipative gas particles are less affected by this overmerging. This is why DM cores at higher redshift are much less abundant than galaxies and dark halos (see Table 1). This problem is intrinsically related to the question of whether substructures within dark halos identified in high-resolution  $N$ -body simulations (Klypin et al. 1999; Colín et al. 1999) really correspond to the real galaxies. Unfortunately, the resolution of our current simulations is not sufficiently good to answer this issue in a reliable manner, but we hope to revisit this with another SPH run with  $N = 256^3$  particles (K. Yoshikawa, Y. P. Jing, & Y. Suto, in preparation).

Figure 6 shows the mass function of dark halos and galaxies at  $z = 0$  and 2. We find that the mass function of simulated dark halos (*upper panels*) agrees better to the fitting formula of Jenkins et al. (2001; *dashed lines*) than to that of Press & Schechter (1974; *solid lines*). Galaxy mass

functions in our simulations (*lower panels*) are roughly consistent with those from other SPH simulations and semi-analytic models (Benson et al. 2001) but slightly less abundant at  $M_{\text{galaxy}} \lesssim 10^{11} M_\odot$  because of limited mass resolution.

### 3. BIASING PROPERTIES OF GALAXIES AND DARK HALOS

The most natural form of galaxy biasing is the relation between overdensity fields of galaxies  $\delta_g$  and dark matter  $\delta_m$ . In this section we compute the density fields of galaxies and dark halos from our simulation and study their statistical properties and evolution.

#### 3.1. Formulation and Computation of Biasing Parameters

A biasing scheme relates the density field of dark matter with those of galaxies and dark halos, which are defined for a given smoothing scale  $R_s$  as

$$\delta_m(x, R_s) = \frac{\rho(x, R_s)}{\bar{\rho}} - 1 , \quad (4)$$

$$\delta_g(x, R_s) = \frac{n_g(x, R_s)}{\bar{n}_g} - 1 , \quad (5)$$

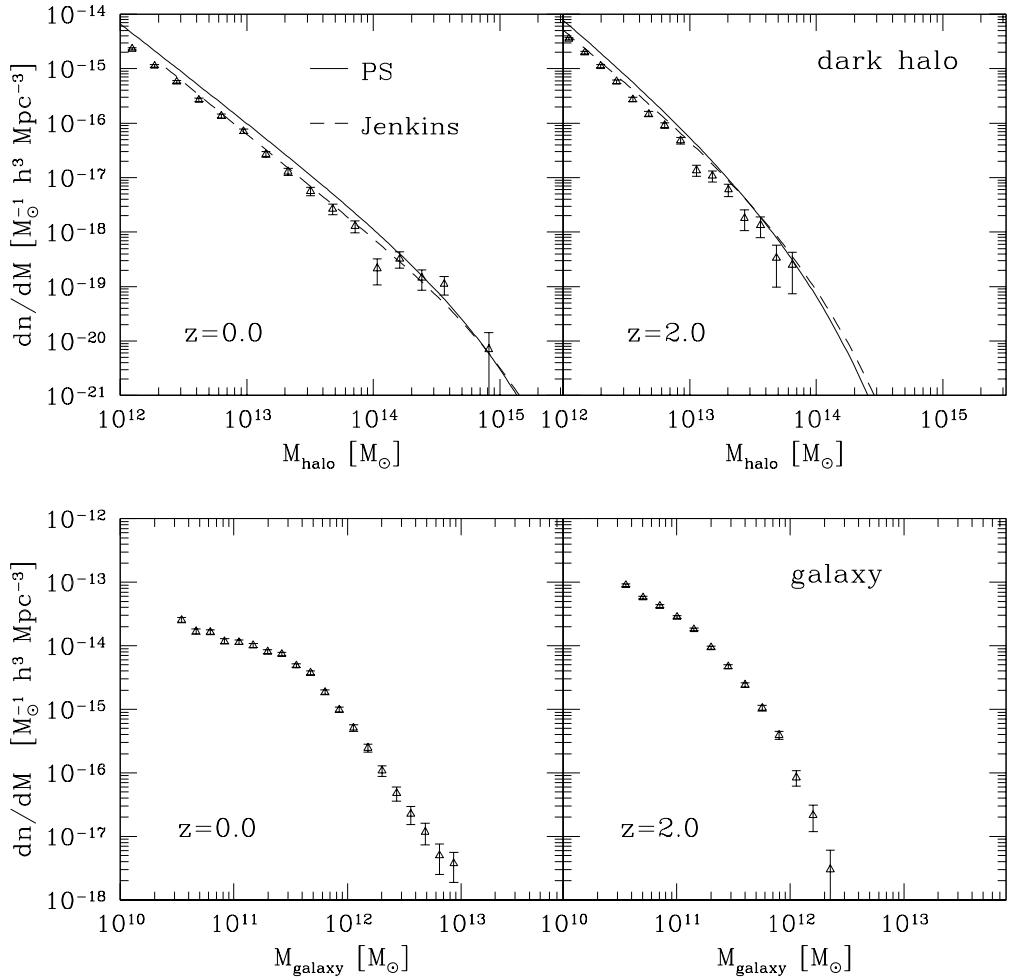


FIG. 6.—Mass functions of dark halos and galaxies at redshifts  $z = 0$  and 2. Solid lines: Theoretical predictions of Press-Schechter mass function. Dashed lines: Fitting formula by Jenkins et al. (2001).

$$\delta_h(x, R_s) = \frac{n_h(x, R_s)}{\bar{n}_h} - 1, \quad (6)$$

where  $\rho(x, R_s)$ ,  $n_g(x, R_s)$ , and  $n_h(x, R_s)$  denote the mass, galaxy, and halo number densities smoothed over the top-hat window radius  $R_s$ ; the overbar indicates the mean over the entire universe. We briefly summarize several parameters describing the nonlinear stochastic nature of biasing introduced by TS for later convenience.

The joint probability distribution function (PDF)  $P(\delta_m, \delta_i)$  characterizes the statistical properties of  $\delta_m$  and  $\delta_i$ , where the subscript  $i$  indicates two different objects:  $g$  for galaxies and  $h$  for dark halos. By definition,  $\delta_m$  and  $\delta_i$  have zero mean, and their variances are related to the joint PDF as

$$\sigma_m^2 = \langle \delta_m^2 \rangle = \int \int P(\delta_m, \delta_i) \delta_m^2 d\delta_m d\delta_i, \quad (7)$$

$$\sigma_i^2 = \langle \delta_i^2 \rangle = \int \int P(\delta_m, \delta_i) \delta_i^2 d\delta_m d\delta_i, \quad (8)$$

where the angle brackets denote the joint average over  $\delta_i$  and  $\delta_m$ . The statistical relation between  $\delta_i$  and  $\delta_m$  is described by the conditional PDF  $P(\delta_i | \delta_m)$ . The conditional

mean of  $\delta_i$ ,  $\bar{\delta}_i(\delta_m)$ , for a given  $\delta_m$  is then calculated from

$$\bar{\delta}_i(\delta_m) = \int \delta_i P(\delta_i | \delta_m) d\delta_i, \quad (9)$$

yielding the following biasing parameter (TS):

$$b_{\text{cov}, i} \equiv \frac{\langle \bar{\delta}_i(\delta_m) \delta_m \rangle}{\sigma_m^2} = \frac{\langle \delta_i \delta_m \rangle}{\sigma_m^2}. \quad (10)$$

The nonlinearity of the biasing is quantified by

$$\epsilon_{\text{nl}, i}^2 \equiv \frac{\langle \delta_m^2 \rangle \langle \bar{\delta}_i^2 \rangle}{\langle \bar{\delta}_i \delta_m \rangle^2} - 1 = \frac{\sigma_m^2 \langle \bar{\delta}_i^2 \rangle}{\langle \bar{\delta}_i \delta_m \rangle^2} - 1, \quad (11)$$

which vanishes only when the biasing is linear (i.e., the ratio  $\bar{\delta}_i/\delta_m$  is independent of  $\delta_m$ ) and is otherwise positive. Similarly, the stochasticity of the biasing is characterized by

$$\epsilon_{\text{scatt}, i}^2 \equiv \frac{\langle \delta_m^2 \rangle \langle (\delta_i - \bar{\delta}_i)^2 \rangle}{\langle \bar{\delta}_i \delta_m \rangle^2} = \frac{\sigma_m^2 (\sigma_i^2 - \langle \bar{\delta}_i^2 \rangle)}{\langle \bar{\delta}_i \delta_m \rangle^2}. \quad (12)$$

This parameter vanishes for the deterministic bias where  $\delta_i = \bar{\delta}_i(\delta_m)$ . In terms of the above biasing parameters, a somewhat more conventional biasing coefficient  $b_{\text{var}, i} \equiv \sigma_i/\sigma_m$  is written as

$$b_{\text{var}, i} = b_{\text{cov}, i} (1 + \epsilon_{\text{nl}, i}^2 + \epsilon_{\text{scatt}, i}^2)^{1/2}. \quad (13)$$

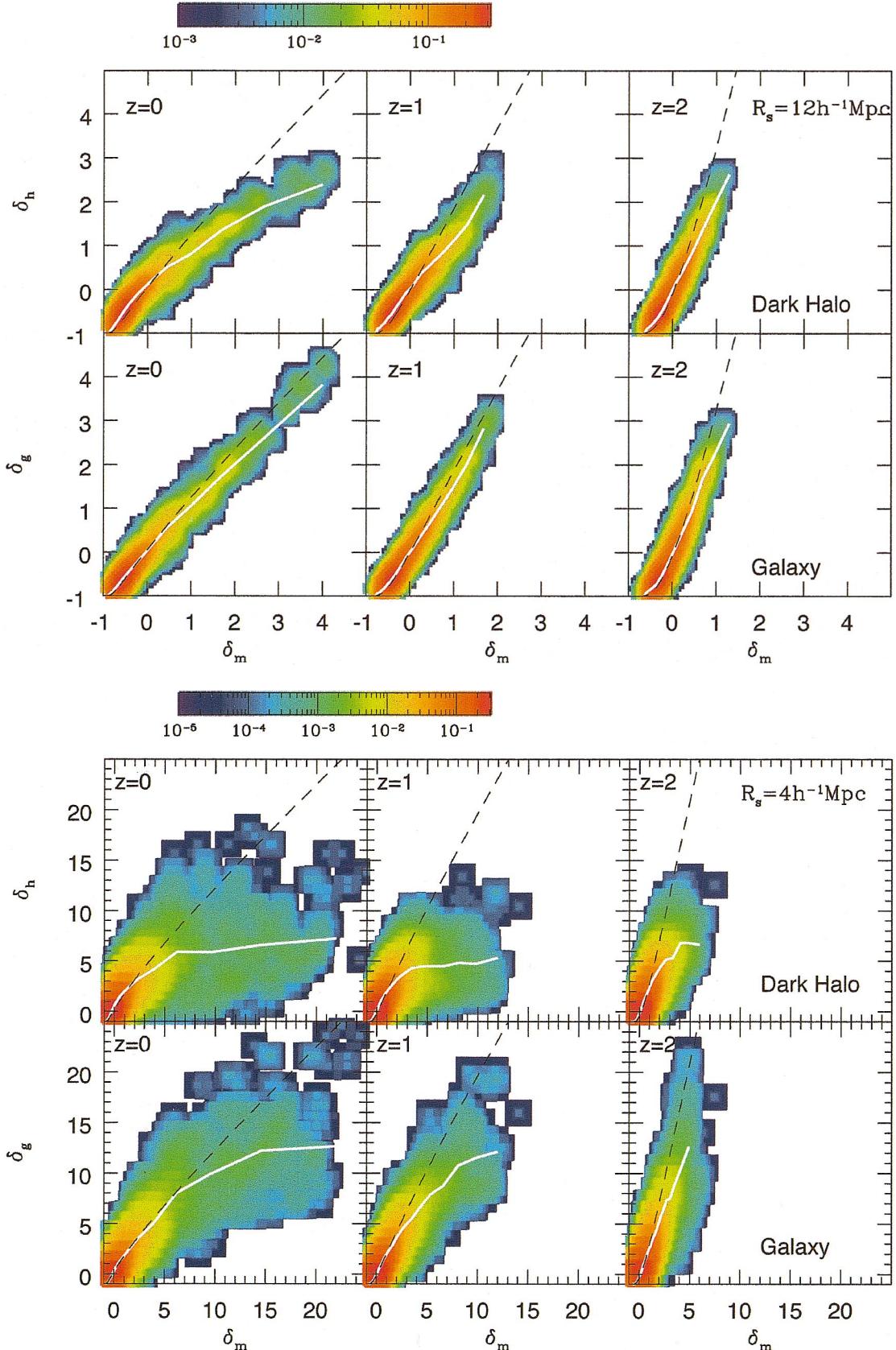


FIG. 7.—Joint probability distributions of overdensity fields for dark halos and galaxies with dark matter overdensity smoothed over  $R_s = 12 h^{-1} \text{ Mpc}$  (upper panels) and  $R_s = 4 h^{-1} \text{ Mpc}$  (lower panels) at redshifts  $z = 0, 1$ , and  $2$ . Solid lines: Conditional mean  $\bar{\delta}_i(\delta_m)$  for each object. Dashed lines: Theoretical prediction of conditional mean by TS.

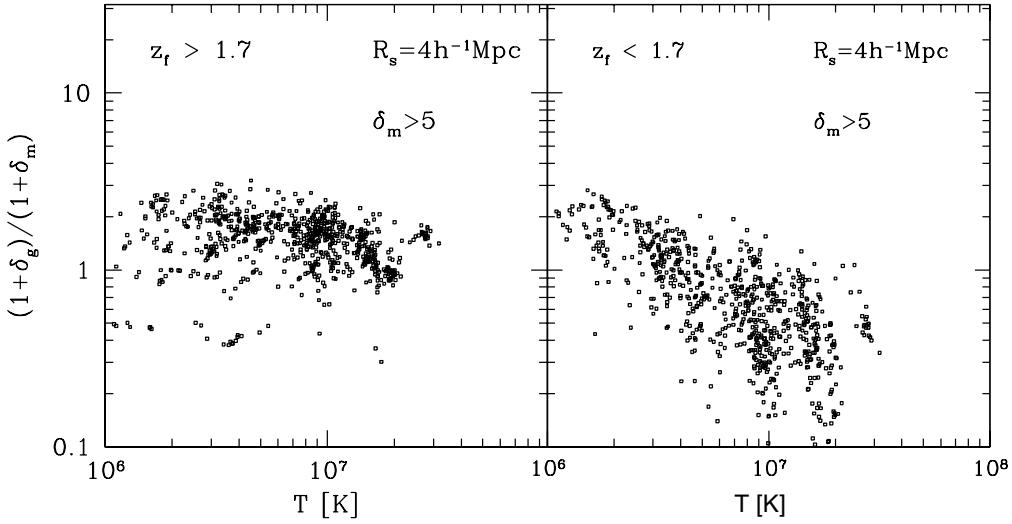


FIG. 8.—Relation between environmental temperature and the ratios of dark matter overdensity with that of galaxies with  $z_f > 1.7$  (left panel) and  $z_f < 1.7$  (right panel) in the high-density regions ( $\delta_m > 5$ ). Each point corresponds to the randomly selected point in the simulation box. Smoothing scale is set to  $R_s = 4 h^{-1}$  Mpc.

Finally, the correlation coefficient  $r_{\text{corr},i}$  (Dekel & Lahav 1999) is given by

$$r_{\text{corr},i} \equiv \frac{\langle \delta_i \delta_m \rangle}{\sigma_i \sigma_m} = \frac{1}{(1 + \epsilon_{\text{scatt},i}^2 + \epsilon_{\text{nl},i}^2)^{1/2}}. \quad (14)$$

We compute the biasing parameters  $b_{\text{cov},i}$ ,  $b_{\text{var},i}$ ,  $\epsilon_{\text{nl},i}$ ,  $\epsilon_{\text{scatt},i}$ , and  $r_{\text{corr},i}$  for dark halos and galaxies with smoothing scales  $R = 4, 8$ , and  $12 h^{-1}$  Mpc. We obtain many pairs of the values  $[\delta_i(x, R_s), \delta_m(x, R_s)]$  for randomly selected points  $x$  in the simulation volume and evaluate the biasing parameters using equations (7)–(14) by replacing the joint averages with averages over all selected points. The number of randomly selected points is 1000 for the top-hat smoothing scale  $R_s = 12 h^{-1}$  Mpc, 5000 for  $R_s = 8 h^{-1}$  Mpc, and 30,000 for  $R_s = 4 h^{-1}$  Mpc. Since our simulation volume is  $75 h^{-1}$  Mpc per side, most of the selected sampling points are not fully independent. Nevertheless, we decided to make oversampling in evaluating the mean and the variance of the density fields. Thus, our quoted error bars below may rather correspond to those in a bootstrap resampling method.

### 3.2. Comparison of Biasing of Galaxies and Dark Halos

Figure 7 shows the joint distribution of  $\delta_h$  and  $\delta_g$  with mass density field  $\delta_m$  at redshifts  $z = 0, 1$ , and  $2$ , smoothed over  $R_s = 12 h^{-1}$  Mpc (upper panels) and  $4 h^{-1}$  Mpc (lower panels). We plot the conditional mean relation  $\bar{\delta}_i(\delta_m)$  from our simulation results (solid lines) and from the theoretical prediction of halo biasing by TS (dashed lines). In computing theoretical predictions, we adjust the range of dark halo mass as our simulated dark halos (Table 1).

Consider first the results for dark halos. For a given smoothing scale, the simulated halos exhibit positive biasing for relatively small  $\delta_m$  in agreement with the predictions. On the other hand, they tend to be underpopulated for large  $\delta_m$ , or *antibiased*. This is mainly due to the exclusion effect of dark halos because of their finite volume size, as previously discussed in Taruya et al. (2001) using purely *N*-body simulations. The theoretical model of TS does not take this effect into account, and thus the discrepancy

between the predictions and the simulations becomes more substantial for smaller  $R_s$  and/or at lower  $z$  as expected.

Since our identified galaxies have smaller spatial extent than the halos, the exclusion effect is not so serious. This is clearly illustrated in the lower panels of Figure 7. In fact, they seem to show much better agreement with the TS predictions despite the fact that the models are formally valid only for dark halos defined according to the Press-Schechter manner.

A more careful look at the results for galaxies, however, reveals that  $\bar{\delta}_g(\delta_m)/\delta_m$  decreases slightly at larger  $\delta_m$ , especially for smaller smoothing scale  $R_s = 4 h^{-1}$  Mpc. While this tendency may be partially explained by their volume exclusion effect, their typical sizes seem to be sufficiently small to account for this. Rather, we consider two possible origins of this tendency. One is the suppression of galaxy formation at very high temperature and thus high-density regions as pointed out in Blanton et al. (1999, 2000). Figure 8 shows the dependence of galaxy overdensity on the surrounding gas temperature separately for galaxies with different formation redshifts (see § 4 for details) and supports this interpretation; the ratio  $(1 + \delta_g)/(1 + \delta_m)$  is anticorrelated with the surrounding gas temperature. Comparing the left and right panels in Figure 8 indicates that the anticorrelation with gas temperature is much stronger for galaxies that form relatively late ( $z_f < 1.7$ ). On the other hand, those formed earlier show very weak anticorrelation at most, which is natural because they should have collapsed and formed much before the surrounding gas acquires the current high temperature. Another possibility is that there is an intrinsic difference in formation epoch of galaxies between over- and underdense regions. Since in hierarchical formation scenarios objects in overdense regions tend to form earlier than those in underdense regions, it is expected that young galaxies with  $z_f < 1.7$  form relatively low density and thus low-temperature regions, which is also consistent with Figure 8. The similar analysis for DM cores will distinguish these two possibilities. Although we notice that the same correlation exists even for DM cores, we suspect that this is mainly due

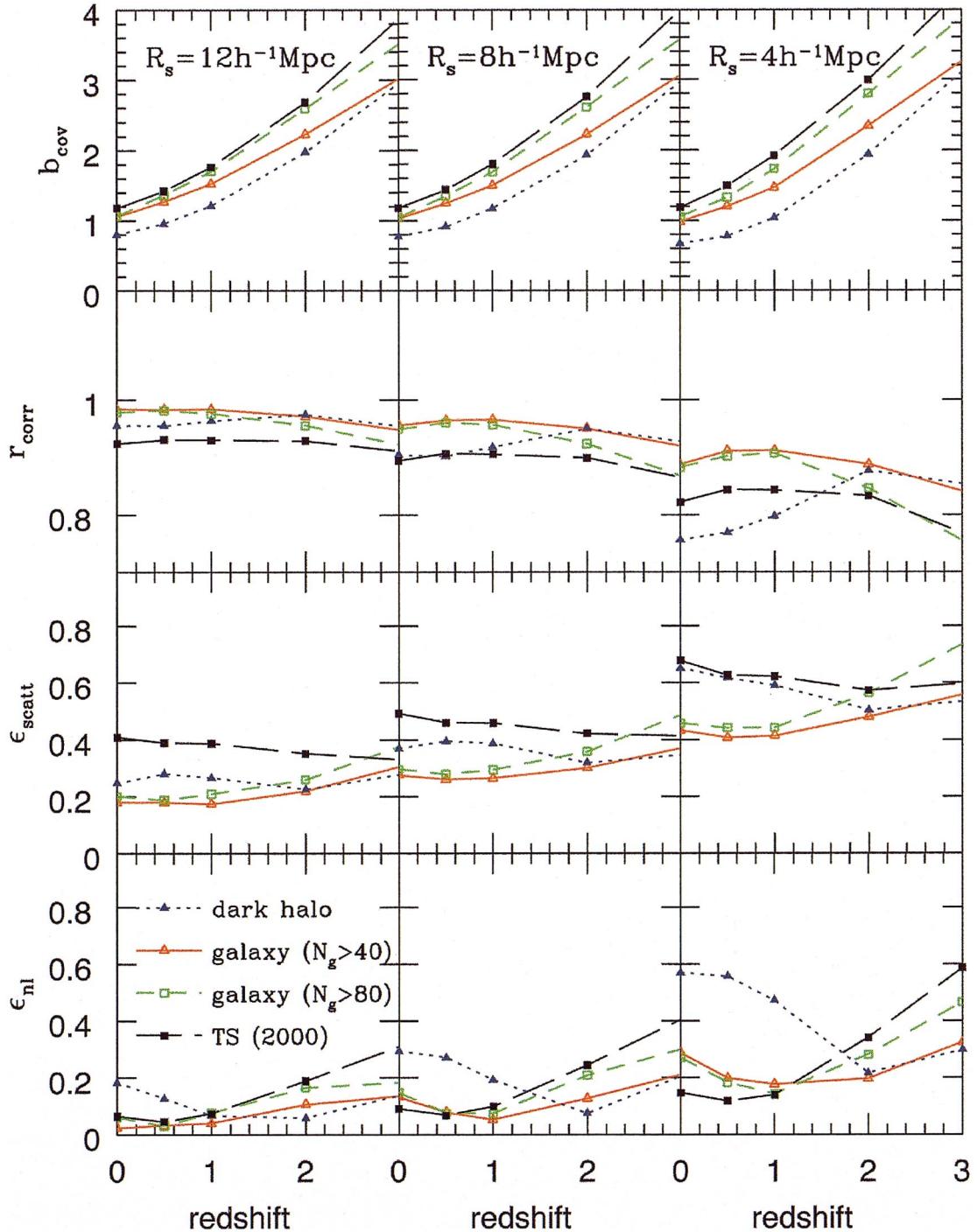


FIG. 9.—Evolution of biasing parameters  $b_{\text{cov}}$ ,  $r_{\text{corr}}$ ,  $\epsilon_{\text{scatt}}$ , and  $\epsilon_{\text{nl}}$  for galaxies (solid lines), dark halos (dotted lines), and the theoretical predictions by TS (long-dashed lines).

to the artificial overmerging effect as we discussed in § 2.3 and will revisit this topic in a future paper with another simulation with higher resolution (K. Yoshikawa, Y. P. Jing, & Y. Suto 2001, in preparation).

Incidentally, in order to check the dependence of the simulated galaxy biasing on the lower mass limit of our criteria,  $M_{\text{galaxy}} > 10^{11} M_\odot$  (or equivalently  $N_{\text{gas}} > 40$ ), we construct another set of galaxy samples adopting a higher mass cutoff,  $N_{\text{gas}} > 80$ , and compare their biasing properties. We find that the joint probability distribution of  $\delta_m$  and  $\delta_g$  for the galaxy sample selected with  $N_{\text{gas}} > 80$  does

not significantly change from those of the original galaxy sample.

### 3.3. Stochasticity and Nonlinearity in Biasing of Galaxies and Dark Halos

The stochasticity and nonlinearity in galaxy and halo biasing are clearly identified in Figure 7. For a more quantitative discussion, we plot in Figure 9 the evolution of their biasing parameters  $b_{\text{cov}}$ ,  $r_{\text{corr}}$ ,  $\epsilon_{\text{scatt}}$ , and  $\epsilon_{\text{nl}}$  for three different smoothing radii.

Consider first  $b_{\text{cov}}$ . This biasing parameter exhibits strong

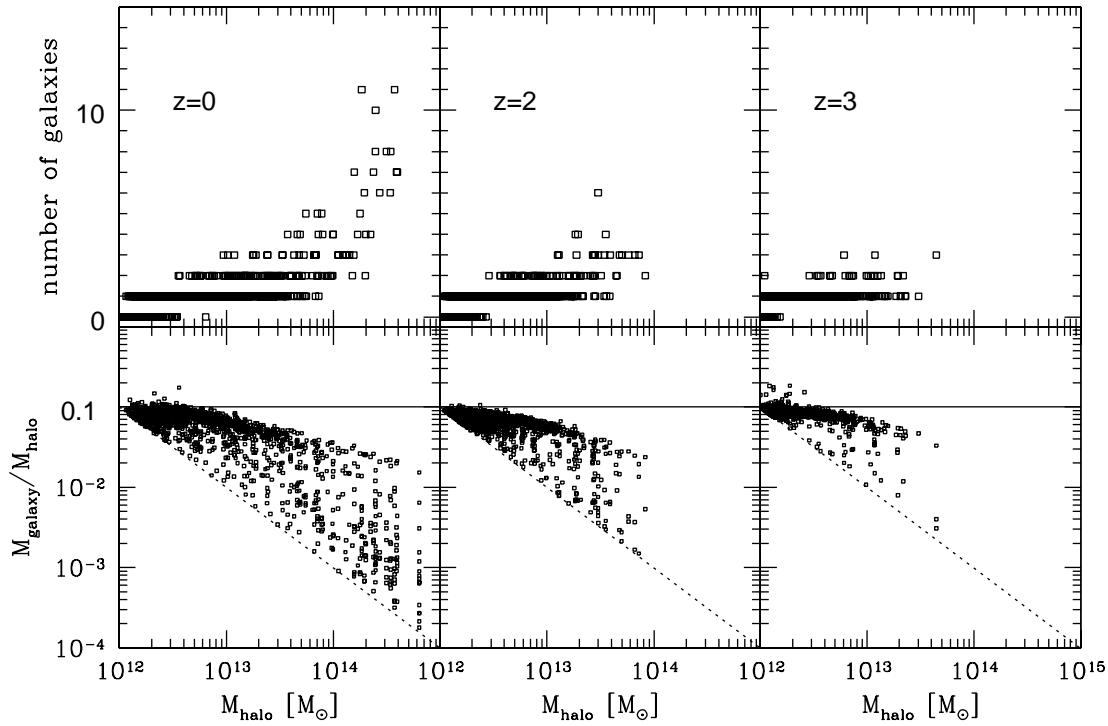


FIG. 10.—Number of galaxies that reside in a dark halo (*upper panels*) and distributions of mass ratio between galaxies and dark halos that host them (*lower panels*) at redshifts  $z = 0$  and  $2$ . In lower panels, solid lines indicate the mean baryon fraction ( $\Omega_b/\Omega_0$ ) and dashed lines indicate the resolution limit constrained by the minimum mass of galaxies in their definition (see § 2.2).

time dependence; the biasing is stronger in the past. This is consistent with analytic biasing models (Mo & White 1996; TS) and previous numerical simulations (Kravtsov & Klypin 1999; Somerville et al. 2001; Pearce et al. 1999) and in fact explains the recent observations of Lyman break galaxies (Giavalisco et al. 1998; Adelberger et al. 1998) using the halo biasing model (Mo & White 1996; Jing & Suto 1998). On the other hand, the scale dependence of  $b_{\text{cov}}$  is very weak, as in the case of the biasing parameter defined through the two-point correlation function (see § 3.4).

Both  $\epsilon_{\text{scatt}}$  and  $\epsilon_{\text{nl}}$  in our simulated catalogs are somewhat smaller than the TS prediction, but their qualitative behavior is consistent with the model: larger on small scales and almost independent of  $z$ . The biasing becomes a linear and deterministic relation, and the volume exclusion is less effective for larger smoothing scales. The current degree of stochasticity and nonlinearity hardly affects the amplitude of clustering (see eq. [13]), but the topology of the iso-density contours is sensitive to the nonlinearity even at this level (Hikage, Taruya, & Suto 2001).

It is interesting to notice that the biasing parameters for galaxies show similar behavior that is closer to the predicted behavior. In addition, all biasing parameters for dark halos and galaxies behave very similarly at high redshifts of  $z \simeq 2\text{--}3$ . This indicates that the spatial distribution of galaxies and dark halos is statistically similar and can be understood by the fact that we have one-to-one correspondence between dark halos and galaxies at  $z \simeq 2\text{--}3$  as shown below.

Figure 9 also shows that the evolution of biasing is almost independent of the lower mass limit of the galaxies. This might be interpreted as our simulated galaxy sample being nearly complete for the present purpose.

Figure 10 shows the number of member galaxies that reside within the virial radius of their hosting dark halos (*upper panels*) and the distribution of their mass ratios (*lower panels*) at redshifts  $z = 0, 2$ , and  $3$ . Solid and dashed lines in the lower panels indicate the cosmic mean baryon fraction  $\Omega_b/\Omega_0$  and the resolution limit of galaxy mass ( $M_{\text{galaxy}} = 10^{11} M_{\odot}$ ), respectively. One can see that most dark halos at  $z = 3$  host only one galaxy, explicitly justifying the *empirical* assumption of one-to-one correspondence between dark halos and Lyman break galaxies around  $z = 3$  found in previous studies (Jing & Suto 1998; Steidel et al. 1998). The subsequent evolution of dark halos involves several merger processes and thus dark halos at lower redshifts tend to host multiple member galaxies.

#### 3.4. Biasing in Terms of the Two-Point Correlation Function

The previous subsections discuss only the biasing parameters defined from one-point statistics. In this subsection we turn to a more conventional biasing parameter defined through the two-point statistics:

$$b_{\xi,i}(r) \equiv \left[ \frac{\xi_{ii}(r)}{\xi_{mm}(r)} \right]^{1/2}, \quad (15)$$

where  $\xi_{ii}(r)$  and  $\xi_{mm}(r)$  are two-point correlation functions of objects  $i$  and of dark matter  $m$ , respectively. While the above biasing parameter is ill-defined where either  $\xi_{ii}(r)$  or  $\xi_{mm}(r)$  becomes negative, that is not the case at clustering scales of interest ( $< 10 h^{-1} \text{ Mpc}$ ). The relation of one-point and two-point biasing parameters is also investigated in detail by Taruya et al. (2001) for density peaks and dark halos.

Figure 11 shows two-point correlation functions of dark matter, galaxies, dark halos, and DM cores (*upper and middle panels*) and the profiles of biasing parameters  $b_{\xi}(r)$  for

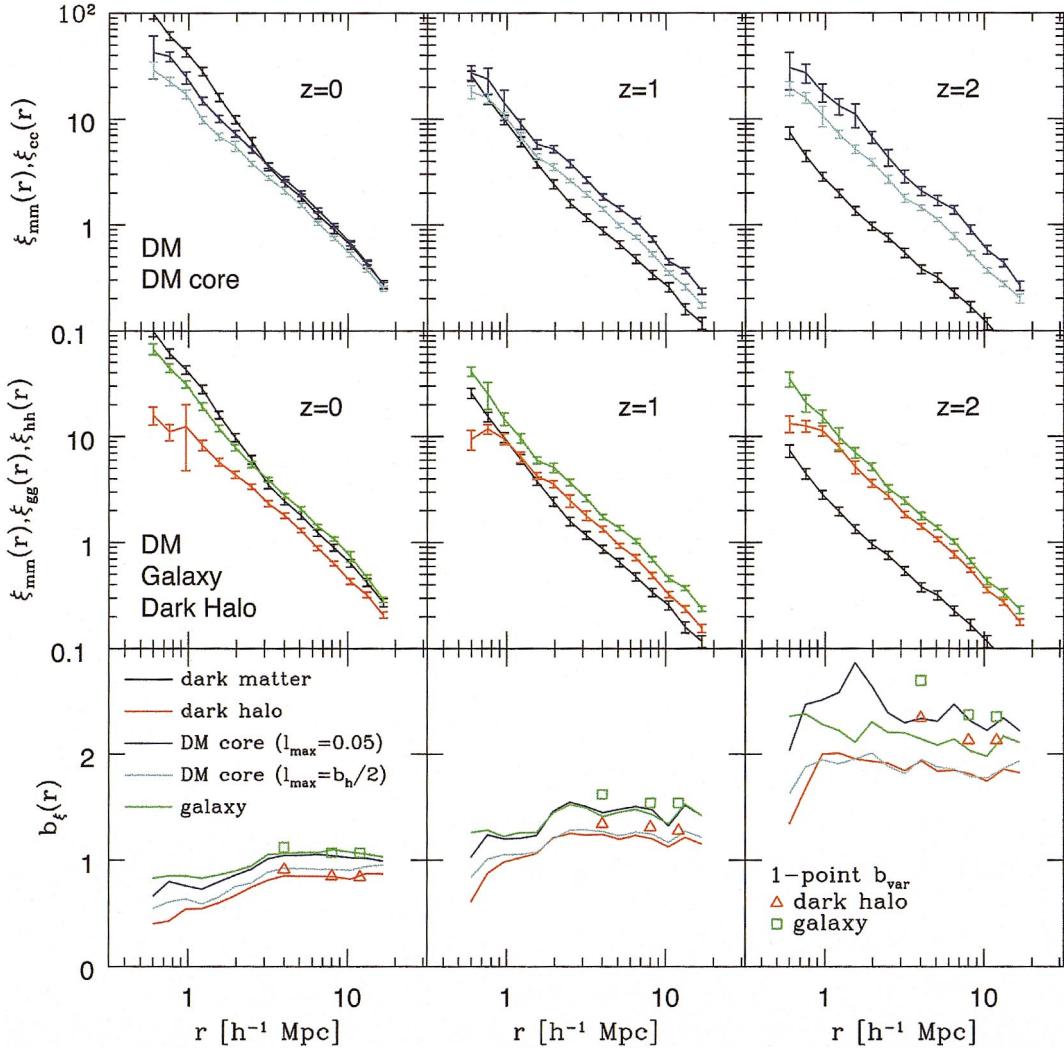


FIG. 11.—*Upper panels:* Two-point correlation functions for dark matter and DM cores at redshifts  $z = 0, 1$ , and  $2$ . *Middle panels:* Two-point correlation functions for dark matter, galaxies, and dark halos. *Lower panels:* Profiles of biasing parameter  $b_\xi(r)$  for dark halos, DM cores, and galaxies at  $z = 0, 1$ , and  $2$ ; we also plot the parameter  $b_{var}$  on the smoothing scales  $R_s = 4, 8$ , and  $12 h^{-1}$  Mpc at  $r = R_s$  for each kind of object by different symbols.

those objects (*lower panels*) at  $z = 0, 1$ , and  $2$ . In the upper panels we show the correlation functions of DM cores identified with two different maximum linking lengths:  $l_{max} = 0.05$  as presented in § 2.3 and  $l_{max} = b_h/2$ . Correlation functions of DM cores identified with  $l_{max} = 0.05$  are similar to those of galaxies. On the other hand, those identified with  $l_{max} = b_h/2$  exhibit much weaker correlation and are rather similar to those of dark halos. This is due to the fact that the HFOF algorithm with larger  $l_{max}$  tends to pick up lower mass halos that are poorly resolved in our numerical resolution.

The correlation functions of galaxies are almost unchanged with redshift, and those of dark halos only slightly evolve between  $z = 0$  and  $2$ . By contrast, the amplitude of the dark matter correlation function evolves rapidly by a factor of  $\sim 10$  from  $z = 2$  to  $0$ . The biasing parameter  $b_{\xi,g}$  is larger at higher redshifts, e.g.,  $b_{\xi,g} \simeq 2-2.5$  at  $z = 2$ . These results are consistent with the numerical studies by Bagla (1998), Colín et al. (1999), and Pearce et al. (1999) and also qualitatively explain the clustering of Lyman break galaxies (Giavalisco et al. 1998). The biasing parameter  $b_{\xi,h}$  for dark halos is systematically lower than that of galaxies and DM cores, again owing to the volume exclusion effect.

At  $z = 0$  galaxies and DM cores are slightly antibiased relative to dark matter at  $r \simeq 1 h^{-1}$  Mpc, which is also consistent with previous numerical simulations (Pearce et al. 1999; Colín et al. 1999; Benson et al. 2000; Somerville et al. 2001) as well as with the observational results from the Las Campanas Redshift Survey (Jing, Mo, & Börner 1998). In the lower panels we also plot the one-point biasing parameter  $b_{var,i} \equiv \sigma_i/\sigma_m$  at  $r = R_s$  for comparison. In general we find that  $b_{\xi,i}$  is very close to  $b_{var,i}$  at  $z \sim 0$  but systematically lower than  $b_{var,i}$  at higher redshifts.

#### 4. THE FORMATION EPOCH AS AN ORIGIN OF MORPHOLOGICAL TYPE GALAXIES

It is fairly established that there exists a certain correlation between the morphology of galaxies and their star formation history: early-type galaxies form via initial star bursts at high redshifts while late-type galaxies experience a continuous and relatively mild star formation history (Roberts & Haynes 1994; Kennicutt 1998). This implies that the galaxy morphology is empirically related to its formation epoch. On the basis of this interpretation, one can examine the morphology-dependent clustering of galaxies

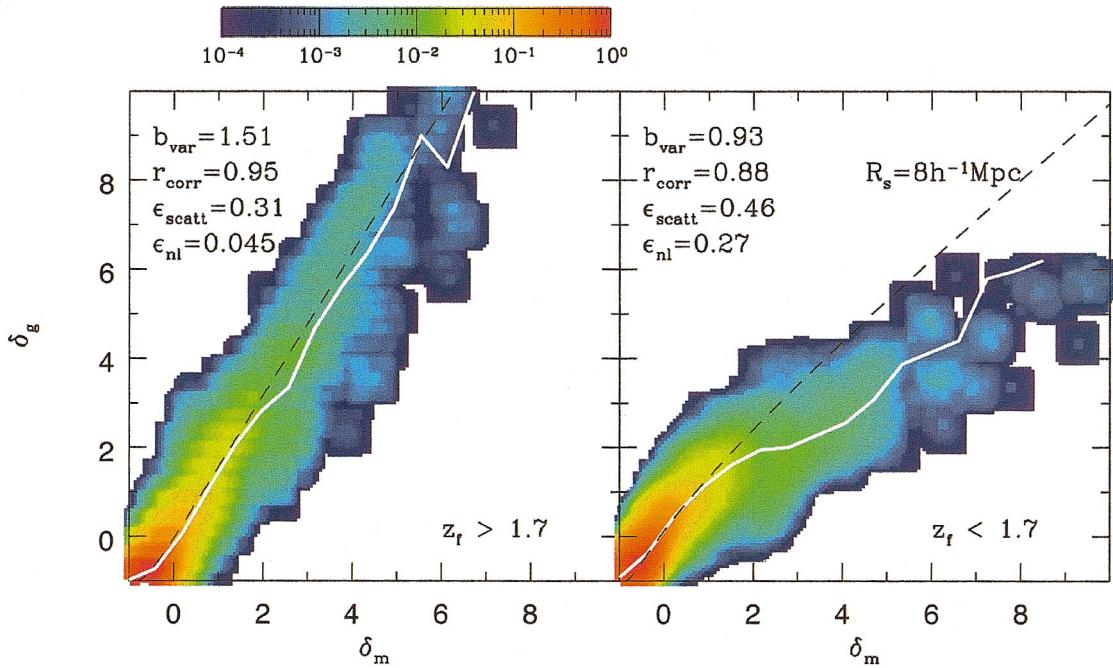


FIG. 12.—Joint probability distributions of density fields of dark matter and galaxies with different formation epochs on the scale of  $R_s = 8 h^{-1} \text{ Mpc}$ . Left panel: galaxies with  $z_f > 1.7$ ; right panel: galaxies with  $z_f < 1.7$ . Solid lines: Simulated mean relations. For comparison, the predictions of mean biasing for dark halos with formation redshift greater and less than 1.7 are shown in left and right panels, respectively.

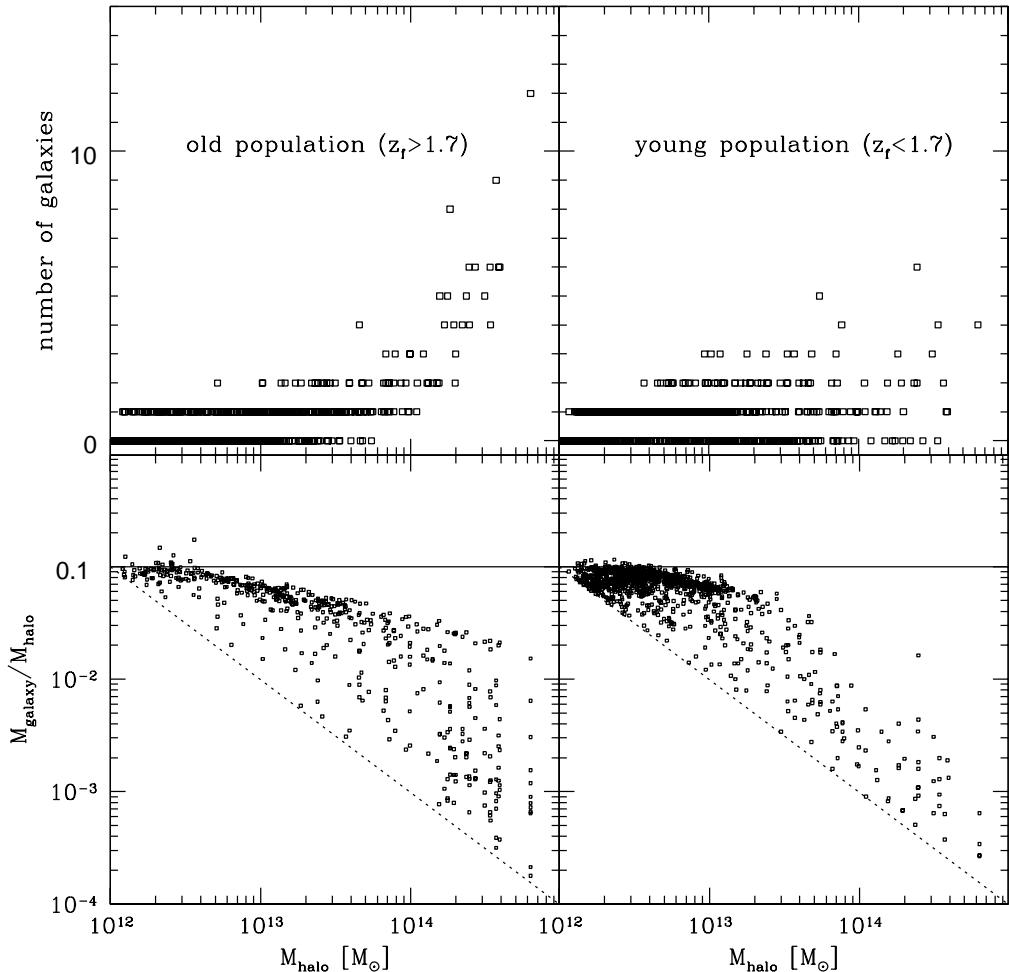


FIG. 13.—Same as Fig. 10, but for old (left panels) and young (right panels) populations of galaxies at  $z = 0$

by classifying our simulated galaxies according to their formation epoch.

We have 50 outputs of all simulation particles at different redshifts between  $z = 9$  and 0. For each galaxy identified at  $z = 0$ , we define its formation redshift  $z_f$  by the epoch when half of its *cooled gas particles* satisfy criteria (1) and (2). Roughly speaking,  $z_f$  corresponds to the median formation redshift of stars in present-day galaxies. We divide all simulated galaxies at  $z = 0$  into two populations (young population with  $z_f < 1.7$  and old population with  $z_f > 1.7$ ) so as to approximate the observed number ratio of 3/1 for late-type and early-type galaxies (Loveday et al. 1995).

Figure 12 shows the joint probability distribution of  $\delta_m$  and  $\delta_g$  for the old (*left panel*) and young (*right panel*) populations, respectively. They exhibit clear differences in their clustering properties. Their biasing parameters are  $\sigma_g = 1.73$ ,  $b_{\text{var},g} = 1.51$ , and  $r_{\text{corr},g} = 0.95$  for the old population and  $\sigma_g = 1.06$ ,  $b_{\text{var},g} = 0.93$ , and  $r_{\text{corr},g} = 0.88$  for the young population. These results qualitatively agree with Blanton et al. (1999); Somerville et al. (2001) also showed a similar result that red galaxies are biased and blue galaxies are antibiased compared to the overall population, where galaxies with color  $B - V > 0.8$  are defined as red galaxies and the remainder as blue galaxies. The dashed lines in the left and right panels indicate the TS predictions of the mean biasing for dark halos, restricting the formation epochs as  $z_f > 1.7$  and  $z_f < 1.7$ , respectively; the old population shows excellent agreement with the halo biasing prediction while the young population behaves rather differently. This indicates that early-type galaxies preferentially reside in the center of the massive halos almost in a one-to-one manner while late-type galaxies avoid the dense environment, which is consistent with the observed morphology-density relation (Dressler 1980; Postman & Gellar 1984; Dressler et al. 1997).

This interpretation is directly confirmed in Figure 13. Massive halos have a larger fraction of the old population

of galaxies while the young population of galaxies mainly reside in smaller halos. This segregation may be understood by the same mechanisms of antibias of galaxies at high-density regions. As discussed in § 3.2, owing to the suppression of galaxy formation in high-temperature regions at lower redshift and/or a different formation epoch for over- and underdense regions, we have the deficiency of the young population of galaxies within massive dark halos at  $z = 0$ , and galaxies formed at high redshift trapped within the gravitational potential of dark halos gradually tend to trace the distribution of underlying dark matter.

The difference between clustering amplitudes of these two populations can also be quantified by their two-point correlation functions at  $z = 0$  as plotted in Figure 14. The old population indeed clusters more strongly than the mass, and the young population is antibiased. The relative bias between the two populations  $b_{\xi,g}^{\text{rel}} \equiv (\xi_{\text{old}}/\xi_{\text{young}})^{1/2}$  ranges between 1.5 and 2 for  $1 h^{-1} \text{ Mpc} < r < 20 h^{-1} \text{ Mpc}$ , where  $\xi_{\text{young}}$  and  $\xi_{\text{old}}$  are the two-point correlation functions of the young and old populations. Again this is completely consistent with the observational indications that the clustering of early-type galaxies is stronger than that of late-type galaxies by a factor of 3–4 in terms of the amplitude of two-point correlation functions (Loveday et al. 1995; Hermit et al. 1996).

All of the above results suggest that the old and young populations of galaxies in our simulations may be interpreted as the early-type and late-type galaxies in the present universe and that the formation epoch and the hydrodynamical environment play the important role in determining the morphology of galaxies. We note here that the above result is fully consistent with the recent analysis of the *IRAS* Point Source Catalog Redshift Survey galaxy sample by Jing, Börner, & Suto (2001), who found a strong antibias of the *IRAS*-selected galaxies (and thus mainly late type). The degree of the detected bias is accounted for by the phenomenological cluster underweight bias model (Jing, Mo, & Börner 1998) and also by the semianalytic modeling of galaxy formation, which assumes that the galaxy morphology is determined by the frequency of the major merger of halos (Kauffmann, Charlot, & White 1996; Kauffmann, Nusser, & Steinmetz 1997; Kauffmann et al. 1999).

## 5. CONCLUSIONS AND DISCUSSION

Using a cosmological SPH simulation we directly simulate the formation of galaxies via radiative cooling of baryonic component and identify galaxies as isolated and distinct groups of cold gas particles. We calculated the biasing of galaxies and dark halos and, in particular, compared their properties with the theoretical prediction of the halo biasing model proposed by TS.

Our major findings are summarized as follows:

1. The clustering of dark halos suffers from the volume exclusion effect because of their finite size, especially at small scales. On the other hand, the halo biasing model by TS can reasonably account for the clustering of “galaxies” at large scales. At smaller scales, however, galaxies are antibiased relative to dark matter at high-density and thus high-temperature environments.

2. The biasing parameters are strongly time dependent. At  $z \sim 3$  our galaxies exhibit strong biasing:  $b_{\text{cov},g} \simeq 3$  and  $b_{\xi,g} \simeq 3\text{--}4$ , which is consistent with the observed clustering of Lyman break galaxies (Adelberger et al. 1998; Giavalisco et al. 1998; Steidel et al. 1998).

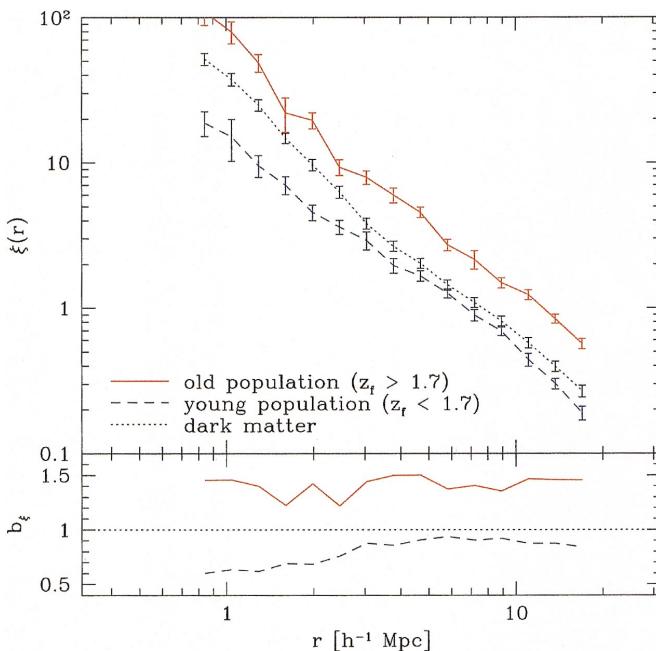


FIG. 14.—Two-point correlation functions for old and young populations of galaxies at  $z = 0$  as well as that of dark matter distribution. The profiles of bias parameters  $b_\xi(r)$  for both populations are also shown in the lower panel.

3. The formation epoch  $z_f$  is the major parameter in determining the morphological type of galaxies. In our specific example, galaxies identified at  $z = 0$  with  $z_f > 1.7$  and  $z_f < 1.7$  can be roughly regarded as early-type and late-type galaxies, respectively. The former tightly correlate with the massive host halos and show stronger clustering while the latter are antibiased and more stochastic. This suggests that biasing properties of galaxies identified by different photometric bands or color selections should be significantly different, which should be kept in mind in comparing the galaxy clustering from different galaxy catalogues.

Our current definition of galaxies in simulation data is admittedly rather phenomenological. Apparently, more observationally oriented classification of galaxies, e.g., using the color or magnitude of galaxies, is necessary for direct comparison with observations. We plan to implement more realistic prescriptions of galaxy formation and evolution including star formation, feedback, and UV background heating in due course. Nevertheless it is quite encouraging that even the simple scheme described here explains the major properties of galaxy clustering in the universe.

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