MOIRCS Deep Survey. II.
Clustering Properties of K-Band Selected Galaxies in GOODS-North Region

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(Received 2007 January 29; accepted 2007 July 13)

Abstract

We present the first measurement of clustering properties of low-mass galaxies with a stellar mass down to \( M_* \sim 10^8 M_\odot \) at \( 1 < z < 4 \) in 24.4 arcmin\(^2\) of the GOODS-North region with a depth of \( K_{AB} \sim 25 \). Luminous galaxies in the K-band have a larger correlation length than faint galaxies. For color-selected samples at \( 2 < z < 4 \), distant red galaxies with \( J - K > 1.3 \) show a large bias of \( b \sim 7.2 \pm 1.3 \) on scales of up to \( \theta \sim 100'' \) or 3.1 comoving Mpc, while blue galaxies with \( 0.5 < J - K < 1.3 \) have a weak clustering signal on large scales, but a possible strong small-scale excess at \( \theta < 10'' \). For massive galaxies with \( M_* \gtrsim 10^{10} M_\odot \), we estimate the correlation length and bias to be \( r_0 \sim 4.5 h^{-1} \) Mpc and \( b = 1.9 - 3.5 \), which are much larger than those of low-mass (\( M_* \sim 10^8 - 10^{10} M_\odot \)) galaxies. The comparison of our measurements with analytic CDM models constrains the properties of hosting dark halos, and indicates that the low-mass galaxies would be progenitors of galaxies with a typical luminosity of \( L \lesssim L_\ast \) in the local Universe. The blue galaxies in low-mass samples are more strongly clustered in more massive halos with higher occupation numbers than low-mass red galaxies. This fact suggests an environment effect due to the halo mass on the star-formation activity at high-z.

Key words: cosmology: large-scale structure of universe — cosmology: observations — galaxies: evolution — galaxies: high-redshift — infrared: galaxies

1. Introduction

The spatial correlation of galaxy distributions with that of the underlying dark matter is one type of fundamental information to understand galaxy evolution. Under a fixed cosmological framework of cold dark matter models, a comparison of observed clustering properties of galaxies to the theoretical predictions allows us to obtain, in a statistical manner, typical masses of the dark matter halos hosting galaxies, even at a high-z Universe (e.g., Moustakas & Somerville 2002; Ouchi et al. 2004; Hamana et al. 2006). Therefore, the evolution of galaxy clustering strength and stellar mass assembly in galaxies as a function of redshift will give us clues about the assembly history of not only the stellar mass, but also dark halos. Thus, it allows us to study ancestor-descendant connections of galaxies at different redshifts.

Previous studies of galaxy evolution at high-z have been limited mainly to massive galaxies with stellar mass of \( M_* > 10^{10} M_\odot \). According to hierarchical clustering models, low-mass galaxies played an important role in the high-z Universe as building blocks, merging into massive galaxies. Therefore, a comparison of the clustering properties of massive and lower mass galaxies will give us a more general view of galaxy evolution in dark matter. In this context, we have performed deep near-infrared (NIR) imaging observations (Kajisawa et al. 2006) to measure the properties of high-z galaxies based on a K-selected catalog, while focusing on low-luminous (or low-mass) galaxies in comparison with massive galaxies.

The clustering properties have been well studied at \( z \lesssim 1 \) in the optical band with spectroscopic redshift data (e.g., Zehavi et al. 2002, 2005; Norberg et al. 2002; Coil et al. 2004; Meneux et al. 2006; Li et al. 2006). For higher redshifts, where spectroscopic redshift data are limited to bright galaxies, multicolor selection techniques have efficiently revealed an abundant population of galaxies. Optically selected UV luminous Lyman break galaxies (LBGs) (Steidel et al. 1996) and NIR selected galaxies, such as distant red galaxies (DRGs) (Franx et al. 2003), BzK galaxies (Daddi et al. 2004) are among the galaxies selected by such color selection techniques for high-z galaxies. It is important to notice that the clustering properties of galaxy samples would be sensitive to the selection criteria. LBGs are generally biased to UV luminous active star-forming galaxies, and may give biased samples in terms of stellar mass (van Dokkum et al. 2006). On the other hand, galaxy catalogs compiled with NIR data allow us to construct a mass-selected sample because NIR emission is less affected by dust extinction, and closely traces the total stellar mass.
Thus, a NIR selection may give a suitable sample to study the clustering properties of galaxies based on the stellar mass. Nonetheless, previous studies at high-z on the basis of NIR observations have been limited in a deep (K < 25) but small field of view (4.5 arcmin²) (Labbé et al. 2003), or in shallow (K < 23.5) and wide fields (> 30 arcmin²) (e.g., Glazebrook et al. 2004; Quadri et al. 2007; Foucaud et al. 2007; Grazian et al. 2006b).

To examine the clustering properties of galaxies at 1 < z < 4, we discuss in this paper the medium deep (K < 25) and wide-field (28 arcmin²) NIR data taken with MOIRCS on the Subaru Telescope (Kajisawa et al. 2006), and publicly available data in the Great Observatory Origins Deep Survey North (GOODS-N) region (Giavalisco et al. 2004). Although the depth (K = 25.1 at 90% completeness) is shallower than K = 25.7 of Daddi et al. (2003), the field of view is 5.5-times larger. The limiting magnitude, ~1.5 mag deeper than that of e.g., Grazian et al. (2006b), will give us data statistically robust in number and with a smaller field variance for the clustering properties of low-luminous (or low mass) galaxies.

By applying analytic models for the spatial clustering of dark matter to the observational results, we estimate the mass of dark matter halos hosting massive and low-mass galaxies from any bias of the galaxy-dark matter distribution (Bullock et al. 2002; Moustakas & Somerville 2002; Allen et al. 2005).

The present paper is organized as follows. In section 2, we present a brief account of the observations and data reduction. The photometric redshift and stellar mass of the observed galaxies are given. We describe in section 3 the angular clustering estimates, and the dependence on color, flux, and mass of galaxies at z = 1−4. Summarizing the result in comparison with previous studies, we estimate in section 4 the clustering properties of low-luminous (or low mass) galaxies. By applying analytic models for the spatial clustering of dark matter to the observational results, we estimate the mass of dark matter halos hosting massive and low-mass galaxies from any bias of the galaxy-dark matter distribution (Bullock et al. 2002; Moustakas & Somerville 2002; Allen et al. 2005).

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The field of view of MOIRCS is divided into two 4 × 3.5 fields, and focuses on two separate focal-plane arrays (Ichikawa et al. 2006). Excluding the edge area of each frame, where S/N is lower than the center due to dithering or pixel defects, we obtained images with the K ~ 25.0 limiting magnitude uniform over a field of 24.4 arcmin², which is smaller than the original observation area (28 arcmin²). The final catalog used for the present study contains 1959 galaxies to a 90% completeness limit of K = 25.

Our survey area is covered by deep ACS images with the F435W, F606W, F775W, and F850LP bands of HST in the GOODS-N region (Giavalisco et al. 2004). (For convenience, we designate them as B, V, i, and z when referring to the filters, respectively.) A deep U-band image taken with the KPNO 4 m telescope is available in Capak et al. (2004), though the PSF is much larger than those of ACS and MOIRCS. Using our MOIRCS data and a public dataset, we have produced a high-quality multicolor catalog of galaxies in the GOODS-N region.

The ACS images and our K and H images were convolved with a Gaussian kernel to match the PSF to 0.′42 of the J-band, which has the largest PSF in the present image set, except...
for the $U$-band. For color measurements, we used a 0″.85 aperture (2 × FWHM). However, we measured the flux in a 2″.8 aperture for the $U$-band because the PSF was much larger (FWHM = 1″.3). An aperture correction to 0″.85 aperture photometry was made using the flux with the same aperture on the $B$ image convolved with FWHM = 1″.3, and assuming the same intrinsic profile of galaxies in the $B$ and $U$-bands. The less-reliable photometry for the $U$-band could be partly the origin of the large photo-$z$ error and outliers (see below).

### 2.2. Photometric Redshift and Stellar Mass

We compiled spectroscopic redshifts for 527 galaxies in the present region from the literature (Wirth et al. 2004; Cowie et al. 2004; Barger et al. 2003; Cohen et al. 2000; Cohen 2001; Treu et al. 2005; Erb et al. 2004; Steidel et al. 2003; Dawson et al. 2001; Reddy et al. 2006), excluding several unreliable identifications. (Note that the spectroscopic redshifts are available for only 7 DRGs among 115 DRGs in the present region.) For all of the detected objects, we estimated their redshifts photometrically with the photometric data of $UBVizJHK$ by fitting the observed flux with model SEDs, following a method described in Kajisawa and Yamada (2005). We used the model SEDs of Bruzual, Charlot synthetic library (GALAXEV: Bruzual & Charlot 2003), the Calzetti extinction law (Calzetti et al. 2000), and HI absorption (Madau 1995). The free parameters used in the fitting were the redshift, spectral type, age, and extinction. We assumed a star formation rate (SFR) that decays exponentially with time, $SFR \propto e^{-t/t^*}$, where $t^*$ is the time scale between 0.01 and 30 Gyr. The metallicity is changed from 0.005 to 2.5 solar values. The initial mass function (IMF) of Chabrier (2003) is adopted with lower and upper mass cutoffs of $m_1 = 0.1 M_\odot$ and $m_u = 100 M_\odot$.

We checked the accuracy of our photometric redshift measurement using objects with available spectroscopic redshifts. Figure 1 compares the spectroscopic and photometric redshifts. There are several outliers at $z_{\text{sp}} \sim 0.5$ and $2 < z < 4$, for which the difference is as large as $|\Delta z| \sim 2$. The error distribution (the inset of the lower panel of figure 1) is nearly Gaussian and scatters around zero with an rms error of $\Delta z/(1 + z_{\text{sp}}) \sim 0.06$. Excluding $|\Delta z|/(1 + z_{\text{sp}}) > 0.5$, we obtained an rms error of $\sim 0.12$, which is comparable with the results (0.12, 0.09, and 0.05) of Quadri et al. (2007), Rudnick et al. (2003), and Grazian et al. (2006a). The outliers are possibly caused by confusion concerning the Lyman break and the 4000 Å/Balmer break in the photometric redshift technique. We discuss the influence of the outliers on an evaluation of the clustering properties of galaxies in section 3. Figure 2 gives the redshift distribution of the present $K$-band selected galaxies. We hereafter use the spectroscopic redshifts whenever available.

Since GALAXEV gives the stellar mass-to-light ratio ($M_*/L$) and rest-frame colors for each template, we can obtain the total stellar mass ($M_*$) of the galaxies using the total absolute magnitude in the rest-frame $V$ band, corrected for dust extinction. Note that our stellar mass estimate with the Chabrier (2003) IMF is systematically about 1.8-times smaller than that with the Salpeter IMF (Salpeter 1955). We plot the mass distributions as a function of redshift in figure 3, where the galaxies are divided into three groups with colors $J - K \geq 1.3$, $0.5 \leq J - K < 1.3$, and $J - K < 0.5$. All 52 LBGs of Steidel et al. (2003), which are located in the present region, are identified in our $K$-selected catalog. The colors of most LBGs are distributed in $0.5 < J - K < 1.3$. Therefore, we divide the blue galaxies into two groups by $J - K = 0.5$ for the following described analysis. We can see in figure 3 that most DRGs ($J - K \geq 1.3$) are massive galaxies ($3.6 \times 10^{10} M_\odot$ on average) residing at $2 < z < 4$. 

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**Fig. 1.** Upper panel: the spectroscopic ($z_{\text{sp}}$) vs. photometric ($z_{\text{photo}}$) redshifts for 527 galaxies in the present region. Lower panel: relative scatter ($z_{\text{photo}} - z_{\text{sp}})/(1 + z_{\text{sp}})$ as a function of $z_{\text{sp}}$. The inset histogram shows the distribution of the photometric redshift error. The error distribution is approximated by a Gaussian centered at 0.004 with an rms of 0.06 (solid line).

**Fig. 2.** Redshift distributions for 1959 galaxies with $K \leq 25.0$. The spectroscopic samples for 527 galaxies are depicted by the filled histogram.
Fig. 3. Stellar mass as a function of redshift for our galaxies with $K \leq 25.0$. DRGs ($J - K \geq 1.3$), the galaxies with $0.5 \leq J - K < 1.3$ and $J - K < 0.5$ are depicted with filled circles, open circles, and crosses, respectively. The typical error for each $z$ bin is shown by a thin line.

Note that even $K$-band selection would not closely trace the mass in the redshift range considered in the present study, especially for star-forming galaxies in the high-redshift range, because of the large fluctuation in the mass-to-stellar luminosity ratio in the galaxies (e.g., Dickinson et al. 2003). In fact, the uncertainty in our mass estimates are comparatively large at $z > 3.5$ (see figure 3), primarily because the $K$-band measurement samples only rest-frame optical wavelengths in the $B$-band or a bluer wavelength range.

The sky distributions of the sample galaxies are represented in figure 4, where we can see, as a visual impression, the difference in the distributions between different sampling criteria by the redshift, color, and stellar mass. In what follows, we examine the differences in a quantitative manner.

3. Angular Correlation Function

We quantitatively measured the clustering properties of galaxy distributions using the angular two-point correlation function (ACF), $w(\theta)$ (Peebles 1980). To examine the dependence on the galaxy properties, we defined a variety of different subsamples based on the redshift, flux, color, and stellar mass (see the following section for definitions).

We adopted the minimum-variance Landy-Szalay estimator (Landy & Szalay 1993):

$$w(\theta) \equiv \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)},$$

where $DD(\theta)$ is the observed number of galaxy pairs with separation $\theta$, $DR(\theta)$ the number of pairs between the observed galaxies and random samples, and $RR(\theta)$ the number of pairs in the random catalog. In the calculation, we distributed the same number of random samples as of the observed samples in the same geometrical constraint of the observations. To reduce the noise in the random pair counts, we repeated the measurement until the random sample count became over 100000. We computed $w(\theta)$ in logarithmic bins of width $\Delta \log(\theta) = 0.4$. The ACF errors were estimated by a bootstrap re-sampling technique (e.g., Ling et al. 1986). Note that our error estimate does not include field variance.

The ACFs measured in a finite sky region are influenced by the so-called integral constraint $IC$, which is expressed by

$$IC \approx \frac{1}{\Omega} \int d\Omega_1 d\Omega_2 w_T(\theta),$$

where $w_T(\theta)$ is the true ACF and $\Omega$ is the solid angle of the field (Groth & Peebles 1977). We assumed a power-law ACF of the form $w(\theta) = A_w \theta^{-\beta}$, and determined its amplitude, $A_w$, by fitting the function

$$w(\theta) = A_w \theta^{-\beta} - IC$$

to the observations. Our measurement, however, could not significantly constrain the slope of the correlation function because of the relatively small number of pairs and small angular range. Therefore, we took a fixed slope of $\beta = 0.8$. The amplitude $A_w$ was computed by fitting the ACF over the range $1'' - 100''$, because the finite-size effect was serious for a larger separation, and our aperture photometry size of $0.85''$ would hardly separate close pairs in $\theta < 1''$, if any. We estimated the integral constraint numerically as

Fig. 4. Sky distributions of the galaxies at (a) $1 < z < 2$ and (b) $2 < z < 4$. The galaxies with $J - K \geq 1.3$, $0.5 \leq J - K < 1.3$ and $J - K < 0.5$ are depicted with filled circles, open circles, and crosses, respectively. The large and small symbols represent the galaxies with stellar mass $M_*>10^{10}M_\odot$ and $M_* = 10^{9-10}M_\odot$, respectively.
following Roche et al. (2002).

Since ACF quantifies the clustering properties of galaxies projected on the sky, it reflects the combination of the redshift distribution of selected galaxies and the clustering in three-dimensional space. The spatial correlation is usually expressed by a power law as
\[
\xi = (r/r_0)^{-\gamma},
\]
where \( r \) is the spatial separation between objects, \( r_0 \) the correlation length, and \( \gamma \) the slope of the power law. The slope \( \beta \) of ACF is related to \( \gamma \) with \( \gamma = \beta + 1 \). We used the Limber equation (Limber 1953) to infer \( r_0 \) from \( w(\theta) \) in comoving units:
\[
w(\theta) = \frac{\theta^{1-\gamma} I(\gamma) \int_0^\infty \frac{dN}{dz} \left( \frac{dN}{dr} \right)^2 [r(z)]^{1-\gamma} \frac{dz}{dr} dz}{N_{\text{obj}}^2},
\]
where \( N_{\text{obj}} \) is the number of galaxies in a sample, and \( dN/dz \) is the redshift selection function of sampled galaxies. For \( dN/dz \), we used the actual redshift distribution of each subsample.

Since the scatter in the photometric redshifts was very small, as shown in the previous section, the error in the photometric redshifts does not have a significant influence on our results. The outliers of the photometric redshift act as contaminants. If the contaminants had a uniform distribution, the measured redshifts does not have a significant influence on our results.

Section 4. Results from Clustering Measurements

We present results of clustering measurements for subsamples in the present \( K \)-selected galaxy catalog with \( K \leq 25 \). We define subsamples by (1) \( K \) flux, (2) \( J-K \) color, (3) \( B-z \) colors, (4) stellar mass \( M_\star \), and (5) rest frame \( U-V \) color. Also, in the ACF analysis, we divide the catalog into two redshift bins of \( 1 < z < 2 \) and \( 2 < z < 4 \) to investigate the redshift evolution of galaxy clustering. The redshift intervals were chosen so that each sample would have roughly the same number of galaxies (\( \sim 500 \)) and similar time intervals (\( \sim 2 \) Gyr).

In figure 5, the observed \( w(\theta) \) and the best-fit power-law model with a fixed slope of \( \beta = 0.8 \) and galaxy-dark matter bias \( b \) are depicted. It can be seen from the figure that the clustering bias of the present sample increases with \( z \). In a higher redshift sample, the bias excess at small scales (\( \theta < 8' \)) is distinctly observed. In the galaxy catalog with a flux limit, various populations of galaxies are likely to be mingled. Populations uniformly distributed in space would smear out any actual strong clustering of some populations, if any. To see what populations are contributed to the large bias or small-scale excess, we disentangle the populations using different selection criteria as described below.

4.1. Clustering on \( K \)-Band Flux Selection

We show the dependence of the clustering length on \( K \) magnitude in redshift bins of \( 1 < z < 2 \) and \( 2 < z < 4 \) in figure 6, where the ACF analysis was made with limiting magnitudes of \( K = 23,24,25 \) for our sample. In this figure, we see that the clustering length increases with the \( K \)-band luminosity in both redshift bins; more luminous galaxies tend to be more strongly clustered. The result conflicts with a previous study by Daddi et al. (2003), based on a \( K \leq 26 \) sample in the 4.5 arcmin\(^2 \) HDF-S field, in which they concluded that the clustering length declined only slightly from \( K \sim 20 \) and remained as high as \( r_0 \sim 5 \) down to \( K \sim 26 \). Fluctuations in the clustering amplitude due to field variance could affect their estimate derived in the small HDF-S field.

Quadr et al. (2007) studied in 300 arcmin\(^2 \) the angular correlation functions of \( K \)-selected galaxies with \( 2 < z < 3.5 \) and \( K < 22.8 \). Their clustering measurement based on shallow, but wide-field data is statistically more robust than ours at a bright magnitude of \( K \leq 23 \). The correlation length for their sample is \( r_0 = 6.0_{-1.0}^{+0.9} \) h\(^{-1} \) Mpc with \( \gamma = 1.8 \), which is in good agreement with our result of \( r_0 = 4.8_{-2.0}^{+2.4} \) h\(^{-1} \) Mpc with the same selection criteria (\( K < 23 \)), even though our error is much larger due to the small area and small number (\( N = 54 \)) of galaxies. The bias \( b = 4.1 \pm 2.0 \) for our \( K < 23 \) sample is also consistent with that of Quadr et al. (2007) \( (b = 3.3 \pm 0.5) \) within a \( 1 \sigma \) error. They found no dependence of the correlation lengths on the \( K \) magnitudes, whereas our deeper observations have revealed a strong dependence on the \( K \) flux at a fainter
the correlation lengths on the redder studies (Quadri et al. 2007; Foucaud et al. 2007; Grazian et al. 2006b). We compare their results with ours in figure 8. As shown in this figure, our result \( r_0 = 9.2_{-0.1}^{+2.1} h^{-1} \text{Mpc} \) for the sample with \( J - K \geq 1.3 \) at \( 2 < z < 4 \) agrees with their results within a 1<sup>σ</sup> error \( r_0 = 12.0_{-1.0}^{+0.9} h^{-1} \text{Mpc} \), Quadri et al. 2007; \( r_0 = 11.1_{-3.8}^{+3.8} h^{-1} \text{Mpc} \), Foucaud et al. 2007; \( r_0 = 13.4_{-3.0}^{+3.0} h^{-1} \text{Mpc} \), Grazian et al. 2006b). We note, however, that a marginal tendency of a larger correlation length for a brighter sample is observed among the results.

Daddi et al. (2003) found color segregation of clustering at \( 2 < z < 4 \), dividing the catalog into \( J - K > 1.7 \) and bluer galaxies, so that the number of the galaxies became similar. \( (J - K = 1.7 \) in Vega corresponds to \( J - K = 0.74 \) in AB of MOIRCS photometric system.) Although their sample is 0.7 mag deeper than our data at the same 90% completeness level, our catalog is expected to well sample those galaxies with \( J - K > 0.74 \) at \( 2 < z < 4 \). In fact, the surface number density, \( 11.0 \pm 0.7 \text{ galaxies arcmin}^{-2} \), in our catalog is very consistent with their sample (10.9 ± 1.6 arcmin<sup>−2</sup>). To check the consistency with the result of Daddi et al. (2003), we subsampled the galaxies of our catalog by \( J - K = 0.74 \) and measured the correlation lengths. For the redder sample \( (J - K > 0.74) \), we obtained \( r_0 = 5.3_{-0.4}^{+0.4} h^{-1} \text{Mpc} \), which is much smaller than the value provided by Daddi et al. (2003) \( (3.5_{-1.7}^{+1.7} h^{-1} \text{Mpc}) \). For the bluer sample, we obtained \( r_0 = 2.5_{-2.4}^{+1.4} h^{-1} \text{Mpc} \), which is slightly smaller than that of Daddi et al. (3.5_{-1.7}^{+1.7} h^{-1} \text{Mpc}), though the difference is within a 1<sup>σ</sup> error. The discrepancy may likely arise from the field-to-field variation, as discussed in the previous subsection.

In addition to \( J - K \) color segregation of the clustering, it is important to notice that the sample with \( 0.5 < J - K < 1.3 \), which includes most of the LBGs, clearly shows excess clustering at small scales (\( \theta < 8'' \)), while the sample has a weaker clustering amplitude at \( 8'' < \theta < 100'' \). Interestingly, the correlation length \( (r_0 = 4.1_{-1.9}^{+1.3} h^{-1} \text{Mpc}) \) and bias \((b = 2.6 \pm 0.4) \) for \( 0.5 < J - K < 1.3 \) galaxies

**Fig. 5.** Upper panel: The ACFs, \( w(\theta) \), of the \( K \)-band selected galaxies at (a) \( 1 < z < 2 \) and (b) \( 2 < z < 4 \). The filled circles show observations with a 1<sup>σ</sup> bootstrap error. The solid curve with a dotted 1<sup>σ</sup> error range is the best-fit power-law \( A_w \theta^{-\beta} - IC \) with a fixed \( \beta = 0.8 \) for \( 1''-100'' \). The dash curve shows the ACF of dark matter predicted by a nonlinear model of Peacock & Dodds (1996). Lower panel: Galaxy-dark matter bias \( b \), defined as \( b(\theta) = \sqrt{w(\theta)}/w_{DM} \). The thin line with dotted lines of ±1<sup>σ</sup> error indicates the average bias and the dispersion in the bins with \( 8'' < \theta < 100'' \).

**Fig. 6.** Dependence of the clustering length on the \( K \) magnitude at \( 1 < z < 2 \) (left) and \( 2 < z < 4 \) (right). The open circles represent the results of the present study. The square and triangle show the results of Daddi et al. (2003) (FIRES) and Quadri et al. (2007) (Q07), respectively.

magnitude of \( K > 23 \). The result that at high-z dependence of the correlation lengths on the \( K \) flux is weak for bright galaxies (Quadri et al. 2007), whereas that for faint galaxies is strong (this study), suggests an opposite tendency for those galaxies at the local Universe (e.g., Norberg et al. 2002; Li et al. 2006) or for LBGs at \( z \sim 4 \) (Ouchi et al. 2005).

**4.2. Clustering of DRGs and Bluer Galaxies at \( 2 < z < 4 \)**

To study the color dependence of the clustering properties, we present the results of an ACF analysis based on \( J - K \) color selection in figure 7. It is found from figure 7 that the bias increases with the \( J - K \) color; stronger clustering occurs for the redder \( J - K \) color.

The clustering lengths of DRGs were measured in previous studies (Quadri et al. 2007; Foucaud et al. 2007; Grazian et al. 2006b). We compare their results with ours in figure 8. As shown in this figure, our result \( r_0 = 9.2_{-0.1}^{+2.1} h^{-1} \text{Mpc} \) for the sample with \( J - K \geq 1.3 \) at \( 2 < z < 4 \) agrees with their results within a 1<sup>σ</sup> error \( r_0 = 12.0_{-1.0}^{+0.9} h^{-1} \text{Mpc} \), Quadri et al. 2007; \( r_0 = 11.1_{-3.8}^{+3.8} h^{-1} \text{Mpc} \), Foucaud et al. 2007; \( r_0 = 13.4_{-3.0}^{+3.0} h^{-1} \text{Mpc} \), Grazian et al. 2006b). We note, however, that a marginal tendency of a larger correlation length for a brighter sample is observed among the results.

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are consistent with those of LBGs for $L \gtrsim L^*$ at $\langle z \rangle = 3$ ($r_0 = 5.0^{+0.7}_{-0.7} h^{-1} \text{Mpc}$, $b = 2.7 \pm 0.4$) (Giavalisco & Dickinson 2001; Ouchi et al. 2004).

### 4.3. Clustering of BzK Galaxies

Daddi et al. (2004) proposed a simple two-color selection based on $B^*$, $z^*$, and $K$-band photometry in $K$-selected samples to effectively extract galaxies at $1.4 < z < 2.5$ and to classify them as star-forming (sBzK) or passive (pBzK) galaxies. In the $B - z'$ versus $z' - K$ plane, sBzK's are defined to be objects with $(z' - K) - (B - z') > -0.2$, while the criteria for pBzK's are defined as $(z' - K) - (B - z') < -0.2$ and $z - K > 2.5$. It has been shown that most star-forming galaxies at $1.4 < z < 2.5$ meet the criteria for sBzK's, irrespective of the amount of dust extinction (Daddi et al. 2004). Clustering has recently been examined using samples of bright BzK's from wide-field surveys (Kong et al. 2006; Hayashi et al. 2007); both pBzK's and sBzK's are found to be clustered strongly. However, the properties of faint, or low-mass, BzK's have remained unclear because of shallow imaging (e.g., Kong et al. 2006 for $K < 22$; Hayashi et al. 2007 for $K < 23.2$).

Our catalog includes 564 sBzK, while there are 3 pBzK galaxies. Therefore, it would be intriguing to study the clustering nature of sBzK in the present catalog, though our area is much smaller than those of the previous wide-field observations. The redshift distributions of bright ($K < 23$) and faint ($K < 25$) sBzK galaxies in figure 9 indicate that, although most sBzK galaxies are located in the redshift bin $1.4 < z < 2.5$, they include many outliers. (Note that two spikes in the histogram would have originated from a systematic photo-z error.) Although some outliers would be due to the photo-z error, most are red massive galaxies at $z > 2.5$ and blue low-mass galaxies at $z < 1.4$. To avoid contamination, we obtained the ACF using the BzK galaxies located at $1.4 < z < 2.5$. The correlation length, $r_0 = 9.7^{+1.7}_{-2.0} h^{-1} \text{Mpc}$, for $K < 23$ is inconsistent with that of Hayashi et al. (2007), $r_0 = 3.2^{+1.6}_{-0.7} h^{-1} \text{Mpc}$. (Even if we assume the Gaussian redshift distribution adopted by Hayashi et al. 2007, all 119 sBzK galaxies with $K < 23$ give $r_0 = 9.0^{+1.3}_{-1.3} h^{-1} \text{Mpc}$.)
inconsistency would come from the field variance due to our small field of view, or due to the contaminants outside of $1.4 < z < 2.5$ in the sample of Hayashi et al. (2007), which could dilute the strong clustering nature, if any.

4.4. Clustering on Stellar Mass Selection

Next, we consider the stellar mass dependence on galaxy clustering. We divide the sample into the two mass ranges of massive ($M_* > 10^{10} M_\odot$) and low-mass ($M_* = 10^{9-10} M_\odot$) populations. The result is presented in figure 10, which shows that massive galaxies have larger biases than low-mass galaxies in the same redshift ranges.

We examined which populations mainly contribute to massive galaxies. Some massive galaxies at $2 < z < 4$ would be overlooked by the standard DRG selection technique, as shown in figure 3 (see also Conselice et al. 2007; van Dokkum et al. 2006). We counted 124 galaxies with $M_* > 10^{10} M_\odot$ at $2 < z < 4$. Among them, 54 galaxies were found to be DRGs with $J - K > 1.3$. van Dokkum et al. (2006) showed that the fraction of DRGs at $2 < z < 3$ is 69% by number among massive galaxies with $M_* > 10^{11} M_\odot$, using the Salpeter IMF. At the same $2 < z < 3$, we counted 16 galaxies with $M_* > 6 \times 10^{10} M_\odot$ which corresponds $M_* > 10^{11} M_\odot$ with the Salpeter IMF. Among them, 13 galaxies (81%) are DRGs; the fraction is consistent with the result of van Dokkum et al. (2006), if the field variance is taken into account. LBGs are another population of massive galaxies (e.g., Rigopoulou et al. 2006). In fact, van Dokkum et al. (2006) studied the population of LBGs with $M_* > 10^{11} M_\odot$ at $2 < z < 3$. However, it is noted that the 52 LBGs of Steidel et al. (2003) in the present region have various stellar masses with a wide range of $7 \times 10^8 M_\odot \sim 9 \times 10^{10} M_\odot$. Among them, 12 LBGs have masses of $M_* > 10^{10} M_\odot$.

Counting DRGs and LBGs, we found that only 53% of massive galaxies are classified by the combination of color-selection techniques. In summary, massive galaxies, including the DRGs sample ($J - K > 1.3$) and a minor portion of LBGs in $2 < z < 4$, contribute a large bias at $\theta > 8''$ (or $> 0.25$ Mpc at $z \sim 3$) with a large correlation length. The redder massive galaxies are more strongly clustered, as discussed below.

4.5. Clustering on the Rest Frame $U - V$ Color

Finally, we examined the rest frame $U - V$ color dependence on the galaxy clustering. We divided the sample into the two subsamples by the rest frame $U - V = 0.7$. Note the color $U - V \sim 0.7$ in AB magnitude corresponds to the color of A0 type stars ($U - V \sim 0$ in Vega). Therefore, $U - V < 0.7$ galaxies are likely to be in active star formation. Also, it should be noted that most massive galaxies ($M_* > 10^{10}$) at $1 < z < 2$ have color redder than $U - V = 0.7$.

We summarize the results in table 1. The first column is the redshift range, in which we describe the clustering properties for each subsample. The second column contains selection criteria for subsampling. The number of galaxies, $N$, for each subsample is given in the third column. The average redshift $\langle z \rangle$ and stellar mass $\langle M_* \rangle$ were calculated and given for each subsample in columns 4 and 5, respectively. The sixth column is the best-fit parameter, $A_{\omega}$, in equation (3) and the 1σ error with a constrained slope of $\beta = 0.8$. Using the Limber equation (6), we converted the parameter to a comoving correlation.
length, $r_0$, in units of $h^{-1}$ Mpc and given the results in the seventh column. The eighth column is the bias averaged in the bins, where we use bins with $8^\circ < \theta < 100^\circ$ to avoid any small-scale excess. In the last column, we give the number density and the Poisson error on a comoving scale based on the $1/V_{\text{max}}$ method, where $V_{\text{max}}$ is the volume corresponding to the total redshift range over which the galaxy would be detected at the $K \sim 25$ flux limit.

4.6. Accuracy of the ACF Analysis

Some of the samples used in the present analysis are very small in size. For example, the number of DRGs is 83 in $2 < z < 4$. A concern would be that the strong clustering amplitude of the galaxies given in the above described analysis could have resulted from shot noise. To estimate the errors arising in a small sample, we used Monte-Carlo simulations. We generated 300 sets of mock catalogs, which had an intrinsic $w(\theta)$ equal to the best power-law fit to the DRG sample, $w(\theta) = 3.7\theta^{-0.8}$, for the same size and geometry. For each mock catalog, the best-fit analysis with the Landy-Szalay estimator [equation (1)] was applied in $\theta = 1^\circ$–$100^\circ$ bins, as for the DRG sample. The average of the best-fit $A_w$ values in equation (3) for 300 sets is $(A_w) = 2.8 \pm 1.2 \, \text{arcsec}^{0.8}$, which is within $1\sigma$ of the observation $A_w(\text{DRG}) = 3.7 \pm 2.1 \, \text{arcsec}^{0.8}$.

As a final check, we computed ACF of DRGs using the counts-in-cells (CIC), which is significantly less affected by shot noise than the pair count analysis (Porciani & Giavalisco 2002). The correlation function, $w(\theta)$, is expressed as
is the average count. We obtained $N$ to observations. The theoretical model in the CDM cosmology. In the previous halos that host galaxies and the halo occupation number from

4.7. Hosting Dark-Halos and Halo Occupation Number

Here, we examine the characteristic mass of dark-matter halos that host galaxies and the halo occupation number from the galaxy clustering and the number density compared with a theoretical model in the CDM cosmology. In the previous section, we gave the correlation length, $r_0$, obtained by fitting the power-law ACF to observations. The $r_0$ value would be a reasonable quantity to compare the observations with dark-matter models. However, it strongly depends on the assumed $\gamma$ and, moreover, could be affected by the small-scale excess in $\theta < 8''$ bins, as shown in the previous section. For this reason, here we adopt the bias instead of the correlation length.

We plot the observed bias parameter, $b$, against the number density of the galaxies in figure 12, where $b$ was obtained by averaging the observed biases in the bins with $8'' < \theta < 100''$ so as to avoid any small-scale excess (see table 1). For a comparison, we depict the results of other studies based on $K$-selected catalogs (Daddi et al. 2003; Quadri et al. 2007), and those of optical samples (LBGs: Lee et al. 2006; DEEP2: Conroy et al. 2007). The model predictions for the number density and the average bias of dark halos are defined as

$$n(z) = \int_{M_{\text{min},DH}}^{\infty} n(M,z) \, dM,$$

(12)

$$b(z) = \int_{M_{\text{min},DH}}^{\infty} b(M,z) n(M,z) \, dM/n(z),$$

(13)

where the number density, $n(M,z)$, and the bias, $b(M,z)$, of dark halos with mass $M$ at $z$ are given by Sheth and Tormen (1999). $M_{\text{min},DH}$ is the minimum mass of dark-halo hosting galaxies. If there were to be a one-to-one correspondence between halos and galaxies, the observed points and the model prediction would coincide. The discrepancy indicates that the number densities of galaxies and dark halos are not in a one-to-one correspondence. We define the occupation number, $N_{oc}$, as the ratio of the number density to that of the dark halos.

For a given redshift and mass range, we summarize in table 2 the results of the minimum halo mass, $M_{\text{min},DH}$, for which the average bias is the same as that of the galaxy sample, the occupation number, $N_{oc}$, the average halo mass, $\langle M_{DH} \rangle$, with the same bias as the galaxies ($b \simeq b_{DH}$), and the ratios of $M_{DH}$ to the average stellar mass, $\langle M_\star \rangle$.

4.8. Redshift Evolution of Galaxy Biases

In order to explore any ancestor-descendant connection of different galaxy populations at various redshifts from the viewponts of both stellar mass and dark-matter assembly, we compared our results of the bias and those from the literature with model predictions as a function of the redshift in figure 13. If the bias values were not available in the literature, we calculated the bias, $b_g$, by the following equation from the published $r_0$ and $\gamma$:

$$b_g = \sqrt{\frac{[h^{-1}\text{Mpc}/r_0]^{\gamma}}{\xi_{\text{DM}}(r = 8h^{-1}\text{Mpc})}},$$

(14)

where $\xi_{\text{DM}}$ is the two-point correlation function of underlying dark matter. We calculated $r_0$ of the dark matter using a nonlinear CDM correlation function (Peacock & Dodds 1994). For a comparison, we give the bias values of clusters of galaxies (Bahcall et al. 2003) and groups of galaxies (Padilla et al. 2004; Girardi et al. 2000) in the local Universe. The bias value of local galaxies with the typical luminosity, $M_\star \sim -20.5$ (Zehavi et al. 2005), which corresponds to $M_\star \sim 3.8 \times 10^{10} M_\odot$ using $M_\star/L \sim 3$ (Kauffmann et al. 2003), is also given along with the bias range for galaxies with $-23 < M_\star < -17$.

If the motion of galaxies is purely caused by gravity, and merging does not take place, the bias value of galaxies would decrease as the Universe evolves with time, according to

$$b_z = 1 + (b_0 - 1)/D(z),$$

(15)
Fig. 12. Relationship between the galaxy number density and the bias of the galaxies at $1 < z < 2$ (left) and $2 < z < 4$ (right), divided into groups by the stellar mass and color. The large open circles and squares show the bias averaged in $8^\circ < \theta < 10^\circ$ bins for massive ($>10^{10} M_\odot$) and low-mass ($10^9 / NUL 10 M_\odot$) galaxies, respectively. The small filled and open circles (squares) depict the color-selected subsample for massive (low mass) galaxies. For a comparison, the results of FIRES (Daddi et al. 2003), Quadri et al. (2007), LBGs (Lee et al. 2006), and DEEP2 (Conroy et al. 2007) are depicted. The solid lines indicate the number density and the average bias of the dark-halo given by Sheth and Tormen (1999) integrated with the minimum mass ($M_{\text{min}}^{\text{DH}}$), shown at the upper-side of the figures with tick marks in units of $M_\odot$. At the right side for each figure, halo masses ($M_{\text{DH}}$) corresponding to $b$ are marked.

Table 2. Hosting dark-halos.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$M_{\text{DH}}^{\text{min}}$</th>
<th>$N_{\text{oc}}$</th>
<th>$\langle M_{\text{DH}} \rangle$</th>
<th>$\langle M_{\text{DH}}/\langle M_{\odot} \rangle \rangle$</th>
<th>$\langle M_{\text{DH}}/\langle M_{\odot} \rangle \rangle$</th>
<th>$b_{\text{DH}}^0$</th>
<th>$\Delta b_{\text{DH}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 &lt; z &lt; 2$</td>
<td>$&gt;10^{10} M_\odot$</td>
<td>$18^{+23}_{-12}$</td>
<td>$1.7^{+2.6}_{-1.2}$</td>
<td>$47^{+48}_{-29}$</td>
<td>$130^{+131}_{-81}$</td>
<td>$7.2^{+6.5}_{-1.3}$</td>
<td>$1.0^{+0.1}_{-0.0}$</td>
</tr>
<tr>
<td></td>
<td>$10^{9-10} M_\odot$</td>
<td>$2.5^{+19}_{-0.6}$</td>
<td>$0.6^{+5.5}_{-1.5}$</td>
<td>$7.8^{+46}_{-32}$</td>
<td>$250^{+1500}_{-2}$</td>
<td>$1.1^{+0.9}_{-0.2}$</td>
<td>$0.8^{+0.0}_{-0.0}$</td>
</tr>
<tr>
<td>$2 &lt; z &lt; 4$</td>
<td>$&gt;10^{10} M_\odot$</td>
<td>$20^{+14}_{-9}$</td>
<td>$2.8^{+3.6}_{-1.7}$</td>
<td>$39^{+22}_{-17}$</td>
<td>$100^{+57}_{-42}$</td>
<td>$16^{+25}_{-7}$</td>
<td>$1.1^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td></td>
<td>$10^{9-10} M_\odot$</td>
<td>$1.8^{+4.6}_{-1.5}$</td>
<td>$0.5^{+1.7}_{-0.4}$</td>
<td>$4.4^{+9.6}_{-3.8}$</td>
<td>$110^{+240}_{-95}$</td>
<td>$1.1^{+1.8}_{-0.4}$</td>
<td>$0.8^{+0.1}_{-0.0}$</td>
</tr>
</tbody>
</table>

* median mass and 68% lower and upper confidence intervals.
* the errors correspond to the 68% confidence intervals of $M_{\text{DH}}^{\text{min}}$.
* including $M_{\text{DH}}$ error and $M_{\text{DH}}^{\text{min}}$ confidence levels.
* not available due to large errors.

where $D(z)$ is the growth factor and $b_0$ is the bias at $z = 0$ (Fry 1996). We calculated the growth factor following Carroll, Press, and Turner (1992). This galaxy-conserving model provides an upper limit of the bias evolution, as shown in figure 13.

On the other hand, if galaxies continue to merge with the same merger rate of their hosting halos, the model gives a lower limit to the bias evolution. In order to compute theoretical predictions for the bias evolution in a hierarchical structure formation model, we adopted the extended Press-Shechter formalism within the framework of the CDM cosmology with the power spectrum normalized so as to reproduce the local cluster abundance ($\sigma_8 = 0.9$) (e.g., see Hamana et al. 2006 for more details). Since the probability distribution functions...
Fig. 13. Bias evolution along with the redshift for the sample galaxies compared with previous observations at high-$z$, the results in the local Universe, and CDM model predictions. The data in the relevant literature, which are represented in figures 6 and 8, are shown with the same symbols. In addition, optically selected samples for LBGs are referred to Lee et al. (2006) (L06) and Ouchi et al. (2004) (O04). The sBzK data were taken from Hayashi et al. (2007) (H07) and Kong et al. (2006) (K06) cited in H07. The spectroscopic samples of DEEP2 are depicted at $z \sim 1$ (Coil et al. 2006). For the optical samples, the larger biases are for more luminous galaxies. The bias ranges for the samples at the local Universe ($z < 0$) are cited from Bahcall et al. (2003) for clusters of galaxies, Padilla et al. (2004) and Girardi et al. (2000) for groups of galaxies, Zehavi et al. (2005) for SDSS sample with the value for typical luminosity ($M_\ast < -20.5$) in $r$ band. The dotted lines show the bias evolution predicted by the galaxy-conserving model [equation (15)]. The merging evolution paths of the hosting halos within the framework of the CDM cosmology based on the extended Press–Shechter model are depicted by solid and dash lines for our samples. The error budgets of the bias evolution, which include the variety history of mass assembly from the observed epoch and the observational error of the bias, are depicted at the left lower corner with solid lines.

5. Discussion

We measured the clustering properties of galaxies in a 24.4 arcmin$^2$ area of GOODS-N region in redshift bins of $1 < z < 2$ and $2 < z < 4$, using our $K$-selected catalog with a limiting magnitude of $K \sim 25$ at the 90% completeness. Our results conclude that DRGs show a conspicuously large clustering amplitude at $2 < z < 4$, and more luminous galaxies in the $K$-band are more strongly clustered. Small-scale excesses ($\theta < 10''$, $< 0.3$ Mpc at $z \sim 3$) of the clustering amplitudes are discernible for those subsamples with $0.5 < J - K < 1.3$, in which most of the LBGs populate. Since the flux in the
various masses, from those of normal galaxies to clusters of galaxies. In galaxy evolution in the context of CDM models, the distribution of galaxies is strongly correlated with that of dark-matter halos. The mass of the hosting dark halo could be one of the most fundamental quantities in galaxy evolution. Therefore, the evolution of the stellar mass of galaxies and dark matter should be investigated in a unified way. In this regard, we divided our sample into two subsamples of massive ($M_* > 10^{10} M_\odot$) and less-massive ($M_* = 10^{9-10} M_\odot$) galaxies, and then compared the bias with those of the underlying dark matter and hosting dark halos.

5.1. Descendants of the Galaxies

We now discuss possible present-day descendants of those galaxies observed at $1 < z < 4$ from the viewpoint of mass and the evolution of the hosting dark halos. Comparing the clustering bias with model predictions, we have estimated the characteristic mass of the hosting halos at the observed epoch (table 2). Then, adopting the extended Press-Shechter model, we computed the history of mass assembly of the hosting halos to the present-day in terms of bias evolution (figure 13) to find out which populations in the local Universe are possible descendants. In particular, we will trace the evolutionary track of the predicted halo masses of DRGs, massive galaxies, and low mass galaxies at different epochs. Figure 13 suggests that the descendants of the galaxies possibly coalesce in halos of various masses, from those of normal galaxies to clusters of galaxies.

The evolutional track would reside in the range of the galaxy-conserving model (upper limit) and the merging model (lower limit) in figure 13. Taking account of the large error budget of the evolutionary path of halos, we stress that the present-day descendants of DRGs are likely to be massive ellipticals located in groups of galaxies or clusters of galaxies. This finding is in good agreement with the results obtained in previous clustering studies for DRGs (e.g., Grazian et al. 2006; Quadri et al. 2007). In fact, the biases at various epochs are roughly on a consistent evolutionary path (red-solid line in figure 13) from $z \sim 3$ to $z \sim 1$ within the error, except for the less-massive DRGs sample of Grazian et al. (2006b) at $z \sim 1.5$.

On the other hand, the bias values and the evolution for galaxies with $M_* > 10^{10} M_\odot$ and $M_* = 10^{9-10} M_\odot$ at $1 < z < 2$ and $2 < z < 4$ trace the evolutionary paths of lower mass halos than those hosting DRGs. Although the error budgets on the bias estimate are very large, it is suggested that the galaxies with $M_* > 10^{10} M_\odot$ evolve into luminous galaxies ($\gtrsim 3 L^*$), which correspond to $M_* \lesssim 1.3 \times 10^{11} M_\odot$ with $M_* / L \sim 3.2$ (Kauffmann 2003). LBGs are frequently argued to be the strong candidates for the progenitor of the present-day early-type galaxies (e.g., Ouchi et al. 2004; Hamana et al. 2006; Lee et al. 2006). The massive galaxies in the present sample would be a more general population for progenitors of luminous early-type galaxies. On the other hand, those with $M_* = 10^{9-10} M_\odot$ are suggested to be the progenitors of less-luminous local galaxies with $M_* \sim 2.0 \times 10^{10} M_\odot$ with $M_* / L \sim 2.5$. In other words, the progenitors of the present-day field galaxies were already populous at $z \lesssim 4$ and bright enough to be observable with the limiting magnitude of $K \sim 25$.

It should be noted, however, that only galaxies with $M_* = 10^{9-10} M_\odot$ at $1 < z < 4$ would not become present-day $L^*$ galaxies. The PDF of the present-day descendants has a very broad spread of mass range ($M_\text{DH}^0$ in table 2) due to the wide variety of the mass assembly history since the observed epoch. Some different high-$z$ galaxy populations may have evolved into a similar low-$z$ population if the sample galaxies followed different evolutionary paths. Since the PDFs are skewed towards larger mass (Hamana et al. 2006), a certain fraction of lower mass galaxies ($M_* < 10^{10} M_\odot$), which are expected to be a more numerous population at high-$z$, is likely to have evolved into normal galaxies at the present-day. To learn what fraction of lower mass galaxies contributes to the present-day normal galaxies, deeper observations in NIR will be necessary.

5.2. Environmental Effect on Star Formation Activity

We give the color dependence of the bias values in figure 12. Because the $U - V \sim 0.7$ color corresponds to A0 stars, the bluer color suggests active star formation. The red massive galaxies ($M_* > 10^{10} M_\odot$), which include DRGs, have a higher bias than that of the bluer sample at $2 < z < 4$. (This is not confirmed at $1 < z < 2$, because most massive galaxies are part of $U - V \gtrsim 0.7$ populations.) However, the tendency is reversed for low-mass galaxies at both epochs of $1 < z < 2$ and $2 < z < 4$; the blue low-mass galaxies tend to have larger bias than the red galaxies. The halo mass hosting low-mass blue galaxies and the occupation number ($M_{\text{DH}}$, $N_{\text{oc}}$) are $(\sim 3.5^{+2.9}_{-1.5} \times 10^{12} M_\odot$, $\sim 4.8^{+3.8}_{-2.3}$) at $1 < z < 2$, while those of the red low-mass galaxies are $(\sim 1.1_{-1.1}^{+5.6} \times 10^{11} M_\odot$, $\sim 0.2_{-0.2}^{+0.8}$). Also, at $2 < z < 4$, the bluer samples have larger host dark halo masses and occupation numbers, though the large error does not allow us to evaluate reliable values. The blue low-mass populations are likely to coalesce in more massive halos than red low-mass populations with a higher halo occupation number. In other words, low-mass galaxies in massive halos are more active in star formation than those in lower mass halos; this fact is suggestive of the environment effect due to the dark halo mass. A similar tendency has been observed for LBGs. The occupation number ($N_{\text{oc}} \sim 1$) of LBGs in massive dark host halos $(\sim 10^{13} M_\odot)$ is much larger than that ($N_{\text{oc}} \sim 0.1$) in lower mass dark halos $(\lesssim 10^{12} M_\odot$ (Ouchi et al. 2004; Lee et al. 2006). The star-formation rates of LBGs in massive halos with $> 10^{12} M_\odot$ are several to ten-times larger than that in less-massive halos (Cooray & Ouchi 2006). These facts also support the environment effect of dark-halo mass on star-formation activity.

Note that there is a strong degeneracy between the fraction of halos occupied by galaxies, the volume density, and the bias. The small size of our data would not give in a statistical sense a strong constraint of the halo occupation number. Therefore, further discussion is beyond our scope.

We, the MOIRCS builders, would like to thank the Subaru Telescope staff for their invaluable help and support in the commissioning of MOIRCS. We thank M. Onodera for a careful reading of the manuscript. We would also...
like to thank an anonymous referee for useful suggestions. This study is based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. A part of the data reduction was carried out on the “sb” computer system operated by ADC and Subaru Telescope. The Image Reduction and Analysis Facility (IRAF) used in this paper is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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