Clustering Properties of Low-Luminosity Star-Forming Galaxies at $z = 0.24$ and $0.40$ in the Subaru Deep Field*

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Abstract

We present our analysis on the clustering properties of star-forming galaxies selected by narrow-band excesses in the Subaru Deep Field. Specifically, we focus on Hα emitting galaxies at $z = 0.24$ and $z = 0.40$ in the same field, to investigate possible evolutionary signatures of clustering properties of star-forming galaxies. Based on an analysis on 228 Hα emitting galaxies with $39.8 < \log L(\text{H}α) < 40.8$ at $z = 0.40$, we find that their two-point correlation function can be estimated as $\xi = (r/1.62^{+0.64}_{-0.50}\text{Mpc})^{-1.84\pm0.08}$. This is similar to that of Hα emitting galaxies in the same Hα luminosity range at $z = 0.24$, $\xi = (r/1.88^{+0.60}_{-0.49}\text{Mpc})^{-1.89\pm0.07}$. These correlation lengths are smaller than those for a brighter galaxy sample studied by Meneux et al. (2006) in the same redshift range. The evolution of the correlation length between $z = 0.24$ and $z = 0.40$ is interpreted by the gravitational growth of the dark-matter halos.

Key words: galaxies: distances and redshifts — galaxies: evolution — cosmology: large-scale structure of universe

1. Introduction

The formation and evolution of galaxies as well as dependence on the environment, e.g., the formation of large-scale structure, are fundamental problems of modern cosmology. Studying the evolution of the clustering of galaxies is useful to understand the evolution of galaxies and that of large-scale structures. Galaxies are considered to form within dark-matter halos. Owing to WMAP observations (Spergel et al. 2007), the cosmological parameters have been well determined, and the evolution of the clustering of dark-matter halos is now well understood both analytically (Mo & White 1996; Sheth & Tormen 1999) and from N-body simulations (Jenkins et al. 1998; Kauffmann et al. 1999; Springel et al. 2005). However, the physical relationship between galaxy populations and the dark-matter halos is not clear, since galaxy formation processes include gas cooling, star formation, and feedback.

In the present universe, galaxies selected from optical observations are considered to trace the distribution of underlying dark-matter halos (Verde et al. 2002). However, the strength of the clustering depends on the properties of galaxy populations: e.g., luminosity (Zehavi et al. 2005), color or spectral type (Zehavi et al. 2002), and stellar mass (Li et al. 2006). The dependence of clustering on the properties of galaxies gives a constraint on theories of galaxy formation. To constrain the model of galaxy formation, it is useful to investigate such dependences in detail. In this paper, we concentrate on the dependence of clustering on the luminosity of galaxies.

Norberg et al. (2001) fit the relative bias, $b/b^*$, as a function of $L/L^*$, $b/b^* = 0.85 + 0.15 L/L^*$, where $b^*$ is the bias for $L^*$ galaxies and the bias is defined as the square root of the ratio of the galaxy and dark-matter correlation functions, $b = (\xi_g/\xi_{DM})^{1/2}$. Using the SDSS data, Tegmark et al. (2004) gave another fitting function, $b/b^* = 0.85 + 0.15L/L^* - 0.04(M - M^*)$. The relative bias at the low-luminosity end is less than Tegmark’s relation in Zehavi et al. (2005). Therefore, the relative bias of low-luminosity galaxies is still controversial.

Recently, the dependence of clustering on the luminosity has been studied up to $z \sim 1.5$ from the VIMOS-VLT Deep Survey (Marinoni et al. 2005; Meneux et al. 2006; Pollo et al. 2006), the DEEP2 Galaxy Redshift Survey (Coil et al. 2006), and the Canada-France Legacy Survey (CFHTLS: McCracken et al. 2008). Brighter galaxies are more strongly clustered than low-luminosity galaxies, and the dependence of the relative bias on the luminosity at $z \sim 0.8$ is in agreement with that in the local Universe (Marinoni et al. 2005). The observed decreasing of the clustering strength is consistent with a simple gravitational growth picture (Meneux et al. 2006). However, the evolution of the clustering of low-luminosity galaxies has not been clear until now, since those objects are too faint for spectroscopic surveys.

In this paper, we present the clustering properties of Hα emitters at $z = 0.24$ and $z = 0.40$, which are low-luminosity active star-forming galaxies in the Subaru Deep Field. Their mean absolute magnitude is $<M_B> \sim -17.0$, which is 1 mag fainter than the previous observations (Pollo et al. 2006; Meneux et al. 2006). We have therefore studied the evolution of galaxies with low luminosities. Using the narrowband

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imaging survey, we have selected star-forming galaxies within the restricted redshift to fainter magnitudes. Throughout this paper, magnitudes are given in the AB system. We adopted a flat universe with $\Omega_{\text{matter}} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$.

2. Photometric Catalog

In this paper, we use official photometric catalogs of the Subaru Deep Field (SDF) project, which is a very deep optical imaging survey using the Suprime-Cam (Miyazaki et al. 2002) on the 8.2 m Subaru Telescope (Kaifu et al. 2000; Iye et al. 2004) at Mauna Kea Observatories. The SDF is located near to the North Galactic Pole, centered at $\alpha (J2000.0) = 13^h 24^m 38^s 9$ and $\delta (J2000.0) = +27^\circ 29^\prime 25^\prime\prime 9$. Details of the SDF project are given in Kashikawa et al. (2004). The SDF official photometric catalogs can be obtained from the SDF web site. These official catalogs contain 5 broadband ($B$, $V$, $R_c$, $i'$, and $z'$) and 2 narrowband (NB816 and NB921) photometric data. In this work, we used the $i'$-selected catalog with 2$\arcsec$ diameter aperture photometry. The PSF size in this catalog is $0.3^\prime$ (Kashikawa et al. 2004). Since the Galactic extinction is not corrected in the magnitudes in the official catalog, we applied a Galactic extinction correction of $E(B - V) = 0.017$ (Schlegel et al. 1998). The photometric correction for each band was $A_B = 0.067$, $A_V = 0.052$, $A_{R_c} = 0.043$, $A_{i'} = 0.033$, $A_{z'} = 0.025$, $A_{NB816} = 0.030$, and $A_{NB921} = 0.024$.

The narrowband filters used in SDF were NB816 [$\lambda_c = 8150\AA$, $\Delta \lambda (\text{FWHM}) = 120\AA$] and NB921 [$\lambda_c = 9196\AA$, $\Delta \lambda (\text{FWHM}) = 132\AA$]. These narrowband filter data were used to search for H$\alpha$ emitters at $z = 0.24$ and $z = 0.40$; note that the H$\alpha$ luminosity function and the angular correlation function of H$\alpha$ emitters at $z = 0.24$ in the SDF have already been studied by our group (Morioka et al. 2008). The limiting magnitudes for $3\sigma$ detection on a 2$\arcsec$ diameter aperture are $B_{\text{lim},3\sigma} = 28.45$, $V_{\text{lim},3\sigma} = 27.74$, $R_c_{\text{lim},3\sigma} = 27.80$, $i'_{\text{lim},3\sigma} = 27.43$, $z'_{\text{lim},3\sigma} = 26.62$, $NB816_{\text{lim},3\sigma} = 26.63$, and $NB921_{\text{lim},3\sigma} = 26.54$.

3. Results

3.1. Selection of H$\alpha$ Emitters

First, we describe the selection method of H$\alpha$ emitters at $z = 0.40$, which are basically similar to that of Fujita et al. (2003), Ly et al. (2007) and Shioya et al. (2008). For emission-line galaxies at $z = 0.40$, redshifted H$\alpha$ emissions enter the NB921 band. We therefore selected emission-line galaxies as NB921-excess objects. In order to select NB921-excess objects, we used the $z'$ band as the off-band continuum. Taking account of the photometric error, we selected NB921-excess objects using the following criteria:

$$z' - \text{NB921} \geq \max [0.1, 3\sigma (z' - \text{NB921})],$$

where

$$3\sigma (z' - \text{NB921}) = -2.5\log(1 - (f_{3\sigma, \text{NB921}})^2 + (f_{3\sigma, z'})^2/f_{\text{NB921}}).$$

We show these criteria in figure 1. In order to avoid the influence of saturation of brighter objects, we adopted another criterion of NB921 $> 20$. For galaxies with $z' > z'_{\text{lim},3\sigma}$, we used the lower-limit value ($z' - \text{NB921})_{\text{low,limit}} = z'_{\text{lim},3\sigma} - \text{NB921}$ for our sample selection. We then select the NB921-excess objects to the NB921$_{\text{faintest}} = 25.63$, which is determined by $\text{NB921}_{\text{faintest}} + 3\sigma (z' - \text{NB921})_{\text{NB921}} = \text{NB921}_{\text{faintest}} = \text{NB921}_{\text{faintest}} + 3\sigma (z' - \text{NB921})_{\text{lim,3\sigma}}$. Although the median of the $z' - \text{NB921}$ is slightly different from 0 ($\sim -0.05$, see Ly et al. 2007, for this offset), we did not apply any correction for the NB921 and $z'$ magnitudes. We then found 2039 sources that satisfied the above criteria. A narrowband survey of emission-line galaxies potentially detected galaxies with different emission lines at different redshifts. The emission lines that could be detected in the NB921 passband were H$\alpha$, H$\beta$, [O III] $\lambda\lambda 4959,5007$, [O II] $\lambda 3727$, Ly$\alpha$, and so on. In order to distinguish H$\alpha$ emitters at $z = 0.40$ from such emission-line objects, we investigated their broad-band colors by comparing 2039 observed emitters with model spectral energy distributions (Coleman et al. 1980). In figure 2, we show a $B - R_c$ vs. $R_c - z'$ color–color diagram of 2039 sources and the loci of the model galaxies. We selected H$\alpha$ emitters by using the following criteria:

$$B - R_c \geq 1.08 (R_c - z') + 0.55,$$

and

$$B - R_c \geq 2.80 (R_c - z') - 0.84.$$

To investigate how our selection criteria suffered from contamination of galaxies at different redshifts, we plotted the colors of galaxies with a spectroscopic redshift [specifically, 28 H$\alpha$ emitters, 60 [O III] emitters, 24 H$\beta$ emitters and 2 [O II] emitters presented in Cowie et al. (2004), and 2 H$\alpha$ emitters,
22 [O III] emitters and 4 [O II] emitters presented in Ly et al. (2007) in figure 2. The contamination of [O III], Hβ and [O II] emitters is 3/30 (10%). These results are considered to justify our selection criteria. Finally, we selected 356 Hα emitter candidates.

We have already studied Hα emitters at z = 0.24 in the SDF (Morioka et al. 2008). Using the SDF official photometric catalog, we selected Hα emitters at z = 0.24. Our selection criteria were as follows: (1) 20 ≤ NB816 ≤ 26.1, (2) iz − NB816 > max[0.1, 3.5(iz − NB816)], (3) (B − V) > 1.6(V − Rc) − 0.1 & (B − V) > 3.1(V − Rc) − 0.9, and (4) (B − V) > 0.8(Rc − z’) + 0.2 & (B − V) > 2.5(Rc − z’) − 1.2, where iz continuum is defined as iz = 0.57 f_i + 0.43 f_z.. In total, 258 Hα emitters were selected.

3.2. Hα Luminosity of Hα Emitters

Since the clustering properties depend on the luminosity of galaxies, we have to know the luminosity range of our sample. In order to obtain the Hα luminosity for each source, we corrected for the presence of [N II] lines. Further, we also applied a mean internal extinction correction to each object. For these two corrections, we adopted a flux ratio of f(Hα)/f([N II] λ 6548,6584) = 2.3 obtained by Kennicutt 1992; Gallego et al. 1997; used by Tresse & Maddox 1998; Yan et al. 1999; Iwamuro et al. 2000) and A_Hα = 1 (Gallego et al. 1995). We also applied a statistical correction (28% for NB921 and 21% for NB816; the average value of flux decrease due to the filter transmission) to the measured flux of each object, because the filter transmission function is not square in shape (Fujita et al. 2003). The Hα flux is given from the observed flux, f_observable(Hα + [N II]), by

\[ f_{\text{cor}}(H\alpha) = f_{\text{obs}}(H\alpha + [N\ II]) \times \frac{f(H\alpha)}{f(H\alpha + [N\ II])} \times 10^{0.4A_{H\alpha}} \times C, \]

where C = 1.28 for NB921 and 1.21 for NB816. Finally, the Hα luminosity is given by \( L(H\alpha) = 4\pi d_L^2 f_{\text{cor}}(H\alpha) \), where \( d_L \) is the luminosity distance at the redshift corresponding to the center of the filter passband: \( d_L = 2.17 \text{ Gpc for } z = 0.40 \) and 1.22 Gpc for \( z = 0.24 \).

Figure 3 shows the Hα luminosity functions of our samples. The Hα luminosity function at \( z = 0.24 \) is considered to be complete between log \( L(H\alpha) = 39.4 \) and log \( L(H\alpha) = 40.8 \). On the other hand, that at \( z = 0.40 \) is incomplete for log \( L(H\alpha) = 39.8 \). To compare the clustering properties of Hα emitters without the luminosity effect, we made a subsample with the same luminosity range [39.8 ≤ log \( L(H\alpha) ≤ 40.8 \)].

The numbers of Hα emitters whose luminosity range from log \( L(H\alpha) = 39.8 \) to log \( L(H\alpha) = 40.8 \) are 139 at \( z = 0.24 \) and 228 at \( z = 0.40 \). We also made another subsample with log \( L(H\alpha) > 40.8 \) for Hα emitters at \( z = 0.40 \) which contains 126 Hα emitters.

3.3. Spatial Distribution and Angular Two-Point Correlation Function

Figure 4 shows the spatial distribution of our Hα emitters in the SDF. The left panel shows that at \( z = 0.24 \), and right panel shows that at \( z = 0.40 \). Objects in the range of 39.8 ≤ log \( L(H\alpha) ≤ 40.8 \) are shown with larger filled circles.

To discuss the clustering properties quantitatively, we derived the angular two-point correlation function (ACF), \( w(\theta) \), using
Hα emitters in the SDF. The ACF was well fit by a power law, $w(\theta) = 0.0047^{+0.0010}_{-0.0009} \theta^{-0.94 \pm 0.04}$. We used data points between $0^\circ.001$ and $0^\circ.1$ for a power-law fit.

It is useful to evaluate the correlation length, $r_0$, of the two-point correlation function, $\xi(r) = (r/r_0)^{-\gamma}$. The correlation length is derived from the ACF through Limber’s equation (e.g., Peebles 1980). Assuming that the redshift distribution of Hα emitters has a top-hat shape of $z = 0.40 \pm 0.010$, we obtained a correlation length of $r_0 = 1.51$ Mpc. The two-point correlation function for all Hα emitters is written as $\xi(r) = (r/1.51$ Mpc$)^{-1.94}$. We also evaluated the ACF and the correlation function for both subsamples of Hα emitters at $z = 0.40$. The ACF of luminous Hα emitters [$\log L(\text{H} \alpha) > 40.8$] was fit by a power law, $w(\theta) = 0.0080^{+0.0033}_{-0.0023} \theta^{-0.64 \pm 0.04}$, and the correlation function is $\xi(r) = (1/1.86^{+1.42}_{-0.88}$ Mpc$)^{-1.86 \pm 0.08}$. The ACF of low-luminosity Hα emitters [$39.8 < \log L(\text{H} \alpha) < 40.8$] was fit by a power law, $w(\theta) = 0.0078^{+0.0033}_{-0.0023} \theta^{-0.84 \pm 0.08}$, and the correlation function is $\xi(r) = (1/1.62^{+0.64}_{-0.60}$ Mpc$)^{-1.84 \pm 0.08}$. For Hα emitters at $z = 0.24$ [$39.8 < \log L(\text{H} \alpha) < 40.8$], the ACF is $w(\theta) = 0.013^{+0.005}_{-0.004} \theta^{-0.89 \pm 0.07}$, and the correlation function is $\xi(r) = (1/1.88^{+0.60}_{-0.49}$ Mpc$)^{-1.89 \pm 0.07}$. For Hα emitters at $z = 0.24$, we assumed that their redshift distribution has a top-hat shape of $z = 0.242 \pm 0.009$. We show these ACFs in figure 6. We summarize these best-fit parameters in table 1.

### 4. Discussion

Figure 7 shows the correlation length, $r_0$, as a function of the redshift. For a comparison, we also show those at $z < 0.15$ in the 2dFGRS (Norberg et al. 2001) and at $0.2 < z < 1.5$ in the VIMOS-VLT Deep Survey (VVDS) (Meneux et al. 2006) together with our results of Hα emitters at $z = 0.40$ and 0.24. We also show the correlation length of Hα emitters at $z = 0.24$ in the COSMOS field (Shioya et al. 2008). The two-point correlation function of Hα emitters at $z = 0.24$ in the COSMOS field, $\xi = (r/1.87^{+0.21}_{-0.20}$ Mpc$)^{-1.88 \pm 0.03}$, is very similar to that for our sample at $z = 0.24$, although we note that their average $B$-band absolute magnitude, $\langle M_B \rangle = -18.5$, is 1.5 mag brighter than our sample.

First, the correlation lengths of our Hα emitters [$39.8 < \log L(\text{H} \alpha) < 40.8$] at $z = 0.24$ and 0.40 are smaller than those of early- and late-type galaxies at $0.2 < z < 0.5$, derived by Meneux et al. (2006) from VVDS. Since the correlation length depends on the luminosity of galaxies, we need to make a fair comparison using absolute magnitudes in the same rest-frame wavelength. The mean $B$-band absolute magnitudes, $\langle M_B \rangle$, of our sample with $39.8 < \log L(\text{H} \alpha) < 40.8$ are $\langle M_B \rangle = -16.9$ and $\langle M_B \rangle = -17.0$ for $z = 0.40$ and $z = 0.24$, respectively.

### Table 1. Best-fit parameters of angular correlation functions.

| Sample | $A_w$                | $\beta$       | $r_0$      |
|--------|----------------------|---------------|------------|
| $z = 0.40$ (all) | $0.0047^{+0.0010}_{-0.0009}$ | $0.94 \pm 0.04$ | $1.5^{+0.28}_{-0.28}$ |
| $z = 0.40$ [$\log L(\text{H} \alpha) > 40.8$] | $0.0080^{+0.0033}_{-0.0023}$ | $0.84 \pm 0.08$ | $1.65^{+0.64}_{-0.50}$ |
| $z = 0.40$ [$39.8 < \log L(\text{H} \alpha) < 40.8$] | $0.0078^{+0.0033}_{-0.0023}$ | $0.84 \pm 0.08$ | $1.65^{+0.64}_{-0.50}$ |
| $z = 0.24$ [$39.8 < \log L(\text{H} \alpha) < 40.8$] | $0.013^{+0.005}_{-0.004}$ | $0.89 \pm 0.07$ | $1.88^{+0.60}_{-0.49}$ |

Fig. 3. Hα luminosity functions at $z = 0.24$ (open squares) and at $z = 0.40$ (filled circles). Since the Hα luminosity function at $z = 0.24$ is considered to be complete at $39.8 < \log L(\text{H} \alpha) < 40.8$, we make subsamples of Hα emitters both at $z = 0.24$ and $z = 0.40$ within the range of $39.8 < \log L(\text{H} \alpha) < 40.8$.

The estimator defined by Landy and Szalay (1993),

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

(6)

where $DD(\theta)$, $DR(\theta)$, and $RR(\theta)$ are normalized numbers of galaxy–galaxy, galaxy–random, random–random pairs, respectively. The random sample consists of 100000 sources with the same geometrical constraints as the galaxy sample. The formal error in $w(\theta)$ is described by

$$\sigma_w = \sqrt{[1 + w(\theta)]/DD}$$

(Hewett 1982). Because of the finite size of the survey, this estimate will be a negative offset from the true $w(\theta)$, which is called the integral constant. We calculated the integral constant, $C = 0.02$ using the following definition (Roche et al. 2002; see also Kovac et al. 2007):

$$C = \frac{\sum RR A_\theta \theta^{-\beta}}{\sum RR}.$$
Fig. 4. (Left) Spatial distribution of H\(\alpha\) emitters at \(z = 0.24\). Large filled circles show objects in \(39.8 < \log L(\text{H}\alpha) < 40.8\). (Right) Spatial distribution of H\(\alpha\) emitters at \(z = 0.40\). Large filled circles show objects in \(39.8 < \log L(\text{H}\alpha) < 40.8\) and small ones show objects in \(\log L(\text{H}\alpha) > 40.8\). Shadowed regions show the areas masked out for detection. The field size of the SDF is \(37^\circ \times 27^\circ\).

Fig. 5. Angular two-point correlation function of all H\(\alpha\) emitter candidates (crosses), the luminous subsample (open boxes), and the faint subsample (open circles) at \(z = 0.40\). The solid line, dashed line, and dotted line show the best-fit single power law for all H\(\alpha\) emitters, the luminous subsample, and the low-luminosity subsample, respectively.

Fig. 6. Angular two-point correlation function of H\(\alpha\) emitter candidates of \(39.8 < \log L(\text{H}\alpha) < 40.8\) (filled circles). The solid line shows the best-fit single power law: \(w(\theta) = 0.0078 \theta^{-0.84}\). For a comparison, we also plot the angular two-point correlation function of H\(\alpha\) emitters at \(z = 0.24\) of the same luminosity range (open circles). The dotted line shows the best-fit single power law, \(w(\theta) = 0.013 \theta^{-0.89}\).

On the other hand, the mean \(B\)-band absolute magnitudes of Meneux’s sample are \(\langle M_B \rangle = -19.1\) and \(-18.1\) for early-type and late-type galaxies, respectively. The smaller correlation length of our H\(\alpha\) emitters is interpreted by their small luminosity.

We note that the clustering amplitude of our luminous H\(\alpha\) emitter sample at \(z = 0.40\) is weaker than those of the samples of Meneux et al. (2006). This may imply that the small clustering amplitude of our H\(\alpha\) emitter sample depends not only on the low luminosity, but also on the spectral type, e.g., the clustering amplitude of red galaxies is larger than that of blue galaxies. As shown in figure 2, the color of most of our sample...
is consistent with the Scd-Irr type in Coleman et al. (1980), which is the same as types 3 and 4 in Meneux et al. (2006). The clustering amplitude may depend on the equivalent widths of the emission lines, rather than the global SED. Our sample is biased toward galaxies with a large emission-line equivalent width, which are considered to be in a very active phase of star formation (e.g., Leitherer et al. 1999). We note that there is no significant difference in the correlation length between our two samples, although it would be expected that the brighter sample could have a larger correlation length than that for a sample with $39.8 < \log L(\text{H} \alpha) < 40.8$. One possibility is that our brighter sample galaxies are due to brightening by the current star-formation activity.

Next, we compare the correlation length of the H\&alph emitters at $z = 0.40$ with that of the H\&alph emitters at $z = 0.24$. Although these are consistent within the error, the ratio of $r_0$ at $z = 0.40$ to that at $z = 0.24$ (0.86) is also consistent with the expected value from the gravitational growth of dark-matter halos. This fact implies that the H\&alph emitters at $z = 0.40$ exist in the same environment where the H\&alph emitters at $z = 0.24$ exist. If we assume the gravitational growth of dark-matter halos to $z \sim 0$, the correlation length of this kind of galaxy evolve to $r_0 \sim 2.3$ Mpc. The ratio of the correlation length to that of the $L^*$ galaxies ($M^* = -20.5$) is 0.36. This ratio is smaller than the prediction of Norberg’s law. It is suggested that the clustering amplitude of low-luminosity galaxies becomes smaller for lower luminosity galaxies.
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