LARGE COSMIC VARIANCE IN THE CLUSTERING PROPERTIES OF Ly$\alpha$ EMITTERS AT $z = 5$

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ABSTRACT

We reported in a previous paper the discovery of a large-scale structure of Lyman-$\alpha$ emitters (LAEs) at $z = 4.86 \pm 0.03$ with a projected size of $20 h_{70}^{-1} \text{Mpc} \times 50 h_{70}^{-1} \text{Mpc}$ in narrowband data of a $25' \times 45'$ area of the Subaru Deep Field ($\Omega_c = 0.3$, $\lambda_c = 0.7$, and $H_0 = 70 h_{70} \text{km} \text{s}^{-1} \text{Mpc}^{-1}$). However, the surveyed area, which corresponds to $55 h_{70}^{-1} \text{Mpc} \times 100 h_{70}^{-1} \text{Mpc}$, was not large enough to conclude that what we were seeing was a typical distribution of $z = 5$ LAEs. In this Letter, we report the results of follow-up imaging of the same sky area using a new narrowband filter (NB704, $\lambda_c = 7046 \text{Å}$ and FWHM = 100 $\text{Å}$) to detect LAEs at $z = 4.79$, i.e., LAEs lying closer to us by $39 h_{70}^{-1} \text{Mpc}$ on average than the $z = 4.86$ objects. We detect 51 LAEs at $z = 4.79 \pm 0.04$ down to NB704 = 25.7, and we find that their sky distribution is quite different from the $z = 4.86$ LAEs'. The clustering of $z = 4.79$ LAEs is very weak on any scale, and there is no large-scale high-contrast structure. The shape and the amplitude of the angular correlation function are thus largely different between the two samples. These results demonstrate a large cosmic variance in the clustering properties of LAEs on scales of $\sim 50 h_{70}^{-1} \text{Mpc}$.

Subject headings: cosmology: observations — early universe — galaxies: evolution — galaxies: high-redshift — galaxies: photometry — large-scale structure of universe

1. INTRODUCTION

The search for the Ly$\alpha$ emission of galaxies using a narrowband filter is a powerful tool for detecting high-$z$ faint galaxies. Indeed, many observations have successfully detected such Ly$\alpha$ emitters (LAEs) from $z \sim 2$ up to $z \sim 6.6$ (e.g., Hu, Cowie, & McMahon 1998; Panciarello, Windhorst, & Keel 1998; Campos et al. 1999; Hu, McMahon, & Cowie 1999; Kudritzki et al. 2000; Rhoads et al. 2000; Stiavelli et al. 2001; Ajiki et al. 2002; Hu et al. 2002; Venemans et al. 2002; Fynbo et al. 2003; Kodaira et al. 2003; Ouchi et al. 2003a; Shimasaku et al. 2003; see also Maiier et al. 2003). Narrowband surveys can also effectively map large-scale distributions of LAEs (e.g., Steidel et al. 2000; Venemans et al. 2002; Hu et al. 2004).

We recently made a survey of LAEs at $z = 4.86$ using the narrowband filter NB711 ($\lambda_c = 7126 \text{Å}$, FWHM = 73 $\text{Å}$) in an area of $25' \times 45'$ and found a large-scale structure of LAEs of $20 h_{70}^{-1} \text{Mpc} \times 50 h_{70}^{-1} \text{Mpc}$ size (Shimasaku et al. 2003). This is the first discovery of large-scale structure in young universes, suggesting that the birth of large-scale structure is very early in the history of the universe and that LAEs are strongly biased against dark matter since cold dark matter models predict that the density fluctuations of dark matter are very small on such large scales. However, the size of the large-scale structure is nearly comparable to the size of the survey region ($55 h_{70}^{-1} \text{Mpc} \times 100 h_{70}^{-1} \text{Mpc}$), and thus we cannot safely conclude that we are seeing a typical distribution of LAEs at $z = 5$. To address this issue, it is important that we enlarge the survey volume.

Motivated by this, we made a follow-up imaging survey of LAEs at $z = 4.79$, i.e., LAEs located closer to us by $39 h_{70}^{-1} \text{Mpc}$ than those at $z = 4.86$, in exactly the same sky area. Using these data, we examine differences in the sky distribution of LAEs between the two redshifts. We adopt $\Omega_c = 0.3$, $\lambda_c = 0.7$, and $H_0 = 70 h_{70} \text{km} \text{s}^{-1} \text{Mpc}^{-1}$.

2. DATA

We carried out deep imaging in the sky area of the Subaru Deep Field (centered at $\alpha = 13^h 24^m 21.4^s$, $\delta = +27^\circ 29' 23''$ [J2000.0]; Maihara et al. 2001) in a narrowband filter centered at 7046 $\text{Å}$ (NB704 filter) with the prime-focus camera (Suprime-Cam; Miyazaki et al. 2002) on Subaru on 2003 February 2 and 3. The FWHM of the NB704 filter is 100 $\text{Å}$, giving a survey depth for LAEs along the sight line of $\Delta z = 0.08$ or, equivalently, $45 h_{70}^{-1} \text{Mpc}$. We observed two fields of view (FoVs) of Suprime-Cam with a large overlap, the central FoV and the northern FoV, to obtain data for the same region ($25' \times 45'$) as imaged in the NB711 filter in a search for $z = 4.86$ LAEs. For both filters, the variation in the response profile is small across the FoV even through the fast (f/1.86) prime-focus optics, with a full variation in $\chi$, of 10 $\text{Å}$ (NB704) and 12 $\text{Å}$ (NB711). This ensures a considerably uniform selection of LAEs with respect to redshift over the survey field.

Individual CCD data are reduced and combined using IRAF and our own data reduction software (Yagi et al. 2002). The seeing sizes of the final images are 0''90. To detect LAEs, we combine broadband $R$ and $i'$ data with the NB704 data. These $R$ and $i'$ data, taken in the spring of 2001, have been used to

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7 The original $25' \times 45'$ area was determined as follows. We first observed the central FoV in NB711, finding in a northern part a large-scale overdense region of LAE candidates. We then imaged the northern FoV with an overlap of $15'$ to trace a northern extension of the overdense region.
detect LAEs at $z = 4.86$ combined with the NB711 data (Ouchi et al. 2003a; Shimasaku et al. 2003). The total exposure time and the limiting magnitude (3σ on a 1′ aperture) are 90 minutes and 27.1 mag ($R$), 138 minutes and 26.9 mag ($i'$), and 198 minutes and 26.7 mag (NB704) for the central FoV and 120 minutes and 27.5 mag ($R$), 110 minutes and 27.3 mag ($i'$), and 216 minutes and 26.8 mag (NB704) for the northern FoV. All magnitudes are AB magnitudes.

Object detection and photometry are made using SExtractor version 2.1.6 (Bertin & Arnouts 1996). The NB704-band image is chosen to detect objects. We define the NB704-band limiting magnitude and the selection criteria for $z = 4.79$ LAEs so that the lower limit to the Lyα flux and the lower limit to the observed equivalent width of Lyα emission ($EW_{\text{obs}}$) are nearly equal to those for the $z = 4.86$ LAE sample in Shimasaku et al. (2003). We set the limiting magnitude to be NB704 = 25.7, corresponding to $f(\text{Ly} \alpha) = 1.1 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ when the contribution from the continuum emission is negligible. The total number of objects down to NB704 = 25.7 is 42,440.

We apply the following three criteria to the detected objects to isolate LAEs at $z = 4.79$: $Ri' - \text{NB704} > 0.6$, $R - i' > 0.5$, and $i' - \text{NB704} > 0$, where $Ri' \equiv (R + i')/2$. Since the NB704 band measures fluxes between the $R$ and $i'$ bands, we define the off-band continuum flux of objects as $Ri' \equiv (R + i')/2$. The first criterion, $Ri' - \text{NB704} > 0.6$, is set to select LAEs with $EW_{\text{obs}} \geq 80$ Å. The second and third criteria are the same as those used to construct the $z = 4.86$ LAE sample. The second criterion reduces contamination by foreground galaxies whose emission lines other than Lyα happen to enter the NB704 band. Figure 1 plots all objects with NB704 $\leq 26$ in the $Ri' - \text{NB704}$ versus NB704 plane.

The number of objects passing the above criteria is 51. We have found that the contamination to the $z = 4.86$ LAE sample from low-$z$ interlopers is about 20% on the basis of spectroscopic observations and Monte Carlo simulations (Shimasaku et al. 2003). We expect a similar contamination rate for the $z = 4.79$ LAE sample. We also expect that the completeness of the $z = 4.79$ sample is close to that of the $z = 4.86$ sample.

### 3. RESULTS

#### 3.1. Sky Distribution

Figure 2 shows the sky distribution of 51 photometrically selected LAE candidates at $z = 4.79$, while Figure 3 is a similar plot for 43 $z = 4.86$ LAE candidates. For each sample, we estimate the local surface density of LAEs, $\Sigma(x, y)$, and compare it with the local overdensity.

Although the NB704 data are deeper than the NB711 data, we have adopted considerably bright magnitudes for the limiting magnitudes of our samples. In this case, contamination is determined mainly from the depths of $R$ and $i'$ data, which are common in the two LAE samples.
The large-scale structure of LAEs at $z = 4.79$ is uniform. The ACF of LAEs does not increase like $N$ at $\theta = 8^\circ$, while the amplitude of the ACF for $z = 4.79$ LAEs is $\sim 0$ at any angular separation.

The ACF of galaxies, including Lyman break galaxies (LBGs), is approximated fairly well by a power-law function, $\theta^{-0.8}$ (for LBGs, see, e.g., Foucaud et al. 2003 and Ouchi et al. 2003b). We thus fitted $\omega(\theta) = A_c(\theta^{-0.8} - C)$ to our LAE data to examine whether or not this function is also a good fit to the LAE data and to compare $A_c$ between the two samples, where $C$ is the integral constraint ($C = 0.15$ arcmin$^{-0.8}$). We obtain $A_c = 0.10 \pm 0.21$ arcmin$^{-0.8}$ and $\chi^2/N = 1.1$ for $z = 4.79$ LAEs. For $z = 4.86$ LAEs, we obtain $A_c = 3.7 \pm 0.3$ arcmin$^{-0.8}$, about 40 times higher than that for $z = 4.79$ LAEs and find that the fit to the $z = 4.86$ data is extremely poor ($\chi^2/N = 14$). If we fitted $A_c(\theta^{-0.8} - C)$ to the $z = 4.86$ data, with $\delta$ being another free parameter, then we find a very flat power-law slope, $\delta = 0.2$, although the fit with this slope is still unsatisfactory ($\chi^2/N = 10$). For $z = 4.79$ LAEs, we obtain $\delta = 0.9$.

The ACF of $z = 4.86$ LAEs does not increase like $\theta^{-0.8}$ but remains more or less flat around $\omega \sim 1-2$ at $\theta = 8^\circ$, except for the data point at 0.5. Figure 3 shows that most of the $z = 4.86$ LAEs belong to the large-scale structure that occupies about 30% of the survey area. For such an extreme distribution, it is shown that the ACF has high values, $\omega \sim 1-2$, at $\theta \leq 8^\circ$, even when we artificially redistribute LAEs uniformly in the large-scale structure (crosses in Fig. 4). Thus, the high, relatively constant amplitudes of the observed ACF are largely due to the large-scale structure at $z = 4.86$.

Since the FWHM of the NB704 filter is wider than that of NB711 by about 30%, the ACF will be lower for $z = 4.79$ LAEs even when the intrinsic spatial correlation is the same. However, the difference in $A_c$ due to this effect is only about 15%.
to the presence of the large-scale structure and the large void regions.

3.3. Number Density

We estimate the spatial number density of LAEs to be $(2.7 \pm 0.4) \times 10^{-4} \, h_{\text{70}}^{-3} \, \text{Mpc}^{-3}$ for the $z = 4.79$ sample and $(3.1 \pm 0.5) \times 10^{-4} \, h_{\text{70}}^{-3} \, \text{Mpc}^{-3}$ for the $z = 4.86$ sample. In these calculations, we adopt a survey volume of $1.9 \times 10^{5} \, h_{\text{70}}^{-3} \, \text{Mpc}^{-3}$ ($z = 4.79$ sample) and $1.4 \times 10^{5} \, h_{\text{70}}^{-3} \, \text{Mpc}^{-3}$ ($z = 4.86$). We have not applied a completeness correction here. The difference in the number density between the two samples is found to be within the 1σ levels, although the $z = 4.86$ LAEs might be slightly more numerous.

The rms fluctuation of mass overdensity at $z = 4.8$ on a sphere with a volume equivalent to the average of our two survey volumes is calculated to be $\sim 0.08$ for $\sigma_{8} = 0.9$, where $\sigma_{8}$ is the present-day rms fluctuation of mass overdensity on a sphere of $8 \, h_{\text{100}}^{-1} \, \text{Mpc}$ radius ($H_{0} = 100 \, h_{\text{100}} \, \text{km s}^{-1} \, \text{Mpc}^{-1}$). This implies that the number density of LAEs found in a volume similar to our average survey volume will fluctuate roughly by $\sim 0.08b_{z}$ (if Poisson noise is not included), where $b_{z}$ is the bias parameter. The observed small fluctuation would prefer relatively small $b_{z}$-values.

3.4. Possible Effects of Velocity Structures

In the analyses above, we have not considered the possibility that our LAEs form structures along redshift ("velocity structures"). A recent spectroscopic observation of a wide-field LAE sample at has revealed distinct velocity structures with large-scale structure extending along the line of sight. Velocity structures in this sample have been found to be within the 1σ levels, although the $z = 4.86$ LAEs might be slightly more numerous.

Because of a too strong observation on scales $\gtrsim 2'$, Hamana et al. (2004) found that the observed ACF of $z = 4.86$ LAEs given in Ouchi et al. (2003a) cannot be reproduced by a simple halo model that assumes LAEs to be associated with dark halos. We find that our $z = 4.86$ LAEs have large-scale structure and that their ACF is high and not fitted by a power law, while the clustering of $z = 4.79$ LAEs is very weak. These results may suggest that the clustering of LAEs is typically weak, possibly tracing the dark matter distribution, and that it has been observed in a rare region in the $z = 4.86$ universe where LAEs form a large, coherent structure of size $\sim 50 \, h_{\text{70}}^{-1} \, \text{Mpc}$. Conversely, if it turns out, from a larger survey, that the $z = 4.86$ region we observed is relatively common in high-$z$ universes, this will suggest that LAEs and LBGs are separate populations in terms of clustering properties, since the clustering of LBGs has been found to be approximated well by halo models (Hamana et al. 2004). Detailed modeling of the clustering of LAEs based on an enlarged sample will give important hints on the nature of LAEs.

Although we did not find in our two LAE samples a clear difference in the number density, a large field-to-field variance in the clustering of LAEs, including velocity structures, can influence measurements of the number density of LAEs based on narrowband surveys, especially if the survey volumes are smaller than ours and if $b_{z}$ is much larger than unity; the $b_{z}$-value derived from the clustering of the $z = 4.86$ LAEs is as large as $\sim 10$. Shallower surveys will suffer from larger variations since LAEs with brighter $\text{Ly} \alpha$ luminosities tend to be clustered more strongly (Ouchi et al. 2003a). For instance, Ajiki et al. (2003) found that the number density of $z = 5.7$ LAEs in their sample is $2 \times 10^{3} \, h_{\text{70}}^{-3} \, \text{Mpc}^{-3}$ is 3 times higher than estimated by Rhoads & Malhotra (2001) based on a similar survey volume. To summarize, our observations show that it is necessary to survey a much larger volume than ours in order to derive the average clustering properties of LAEs.

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