SUBARU DEEP SURVEY. IV. DISCOVERY OF A LARGE-SCALE STRUCTURE AT REDSHIFT $\approx$5$^1$

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ABSTRACT

We report the discovery of a large-scale structure of Ly$\alpha$ emitters (LAEs) at $z = 4.86$ based on wide-field imaging with the prime-focus camera (Suprime-Cam) on the Subaru Telescope. We observed a $25' \times 45'$ area of the Subaru Deep Field in a narrow band (NB711, $\lambda_p = 7126$ Å and FWHM = 73 Å) together with $R$ and $i'$. We isolate from these data 43 LAE candidates down to NB711 = 25.5 mag using color criteria. Follow-up spectroscopy of five candidates suggests the contamination by low-$z$ objects to be $\sim$20%. We find that the LAE candidates are clustered in an elongated region on the sky of 20 Mpc in width and 50 Mpc in length at $z = 4.86$, which is comparable in size to present-day large-scale structures (we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\lambda_0 = 0.7$). This elongated region includes a circular region of 12 Mpc radius of higher surface overdensity ($\delta_c = 2$), which may be the progenitor of a cluster of galaxies. Assuming this circular region to be a sphere with a spatial overdensity of 2, we compare our observation with predictions by cold dark matter models. We find that for an $\Omega_0 = 0.3$ flat model with $\sigma_8 = 0.9$ predicts the number of such spheres consistent with the observed number (one sphere in our survey volume) if the bias parameter of LAEs is $b = 6$. This value suggests that the typical mass of dark halos hosting LAEs at $z \approx 5$ is of the order of $10^{12} M_\odot$. Such a large mass poses an interesting question about the nature of LAEs.

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

1. INTRODUCTION

The formation and evolution of the large-scale clustering of galaxies, as seen in the present-day universe, are central issues in cosmology. Observations of galaxy clustering in the distant universe give us great clues to this issue, including how galaxies were formed in the underlying dark matter. To date, many efforts have been made to detect large-scale clustering of galaxies at high redshifts. Probable detections of galaxy clusters on megaparsec scales have been reported (e.g., Giavalisco, Steidel, & Szalay1994; Pascarelle et al. 1996a; Le Fèvre et al. 1996; Malkan, Teplitz, & McLean 1996; Francis et al. 1996; Keel et al. 1999; Campos et al. 1999; Pentericci et al. 2000). The most remarkable observation is the discovery of a high concentration of Lyman break galaxies (LBGs) at $z \approx 3$ with a size of at least $11' \times 8'$ (or $21 \times 15$ Mpc) by Steidel et al. (1998), who argue that LBGs must be very biased tracers of mass if such a structure is consistent with cold dark matter (CDM) models. More recently, Venemans et al. (2002) have discovered a protocluster of $M \sim 10^{15} M_\odot$ with a size of $2.7 \times 1.8$ Mpc around a radio galaxy at $z = 4.1$ through a narrowband survey.

To place stringent constraints on models of structure formation, it is crucial to observe galaxy clustering over a wide range of scales at various epochs. In this Letter, we report on a narrowband survey in a $25' \times 45'$ field for Ly$\alpha$ emitters (LAEs) at $z = 4.86$. Our main goal is to search at high redshifts for the progenitors of present-day large-scale structures like the Great Wall (Geller & Huchra 1989), in order to trace the evolution of structures on scales of tens of megaparsecs. We also aim at detecting (proto) clusters at $z \sim 5$. Unless otherwise noted, we adopt $\Omega_m = 0.3$ and $\lambda_0 = 0.7$, and we express the Hubble constant as $H_0 = 70 h_{70} \text{ km s}^{-1} \text{Mpc}^{-1}$.

2. OBSERVATIONS

2.1. Imaging

We carried out a deep imaging survey in the sky area of the Subaru Deep Field (SDF; centered at R.A. = $13^h24^m21.4^s$, decl. = $+27^\circ29'23''$ [J2000.0]; Maihara et al. 2001) in the $R$ and $i$ bands and in a narrowband filter centered at 7126 Å, NB711, with the prime-focus camera (Suprime-Cam; Miyazaki et al. 2002) on Subaru in 2001 March–June and 2002 May. The FWHM of the NB711 filter is 73 Å, giving a survey...
depth for LAEs along the sight line of $\Delta z = 0.06$ or, equivalently, 33 h$_{70}^{-1}$ Mpc. We observed two fields of view (FOVs) of Suprime-Cam, allowing for a wide overlap: the central FOV and the northern FOV.

The data of the central FOV have already been reduced and used to study the general properties of LAEs (Ouchi et al. 2003). For the northern FOV, individual CCD data were reduced and combined using IRAF and our own data reduction software (Yagi et al. 2002). For the overlapped region, we use the data of the central FOV, and then in the northern part of the FOV, we found a large-scale overdense region of LAE candidates. We then imaged the northern FOV with an overlap of 15′ to check the reliability of this overdense region as well as to trace a northern extension of the overdense region. We consistently found an overdense region in the data of the northern FOV. The match of LAE candidates in the overlapped region between the two FOV data is $\sim$60%, which can be regarded as an estimate of the completeness of our LAE detection.

Object detection and photometry are made using SExtractor version 2.1.6 (Bertin & Arnouts 1996). The NB711-band image is chosen to detect objects. In this Letter, to ensure secure photometry and a low contamination for our LAE sample, we confine ourselves to objects brighter than NB711 = 25.5 (their number is 34,653). We apply the following criteria (Ouchi et al. 2003) to these objects, to isolate LAEs at $z = 4.86$: $R - NB711 > 0.8$, $R - i > 0.5$, and $i - NB711 > 0$, where $R = (R + i)/2$. The second criterion reduces contamination by foreground galaxies whose emission lines other than Lyα happen to enter the NB711 band (see Fig. 1). The number of objects passing the above criteria is 43. Figure 1 plots on the $R - NB711$ versus $R - i$ plane all objects with NB711 $\leq 25.5$ (right) and model galaxies and Galactic stars (left). This figure demonstrates that the second criterion efficiently removes low-z objects but selects LAEs at $z = 4.86$ (Ouchi et al. 2003).

### 2.2. Spectroscopy

We selected a 6′6 field of the highest overdensity (see § 3.1) for multislit spectroscopy, and we made spectroscopic observations for five candidates in this field with the Faint Object Camera and Spectrograph (Kashikawa et al. 2002) on Subaru on 2002 June 6 to check our photometric selection. Table 1 summarizes their properties. The exposure time was 2 hr for each object. The seeing size was $0′′7$–$0′′8$. We used the 300 line mm$^{-1}$ grating with a dispersion of 1.4 Å pixel$^{-1}$ and a wavelength coverage of 4700–9400 Å. We adopted a slit width of $1′′8$, which gave a spectral resolution of 9.8 Å. The continuum flux limit of our spectroscopy was $6.3 \times 10^{-19}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ ($5\sigma$).

Figure 2 shows spectra of the five candidates after 2 pixel smoothing. All the spectra have an emission line near 7100 Å. Possible candidates (other than Lyα) for this emission line are H$_\alpha$, Hβ, [O iii] $\lambda$5007, and [O ii] $\lambda$3727. We find that the lines are not [O ii] $\lambda$5007 at $z = 0.4$ because of the lack of the Hβ line at the corresponding wavelength; for similar reasons, they are neither H$_\alpha$ nor Hβ. Thus, the five objects are either an LAE or an [O ii] emitter.

We conclude from the following that A, B, and D are convincing LAEs, that C is a probable LAE, and that E may be an [O ii] emitter at $z \sim 0.9$. First, the emission line of A and B shows an asymmetric shape with a blueward cutoﬀ; this is a common feature of high-redshift Lyα emission (e.g., Dey et al. 1998). Second, although we cannot rule out the possibility of D being an [O ii] emitter on the basis of its spectrum alone, we have seen in Figure 1 that its $R - i$ color is red enough to match the expectation for LAEs. Moreover, M. Ouchi et al. (2003, in prep.

### Table 1: Five Candidates with Spectroscopic Observations

| Candidate | $R$ | $i$ | NB711 | $z$ | EW | $j$ |
|-----------|-----|-----|-------|----|----|-----|
| A         | 27.18 | 26.32 | 24.24 | 4.850 | 51 | 3.5 |
| B         | 28.25 | 26.82 | 25.33 | 4.834 | 15 | 0.77|
| C         | 27.22 | 26.56 | 24.88 | 4.856 | 14 | 0.93|
| D         | 27.21 | 25.96 | 25.33 | 4.865 | 6  | 0.49|
| E         | 27.62 | 27.05 | 25.26 | 4.825 | 18 | 1.1 |

* AB magnitudes.
* Rest-frame equivalent width (in angstrom units) estimated from the spectrum, assuming the line to be Lyα. Due to very weak continuum emissions and a relatively short exposure of spectroscopy, EW-values should have large errors.
* Line flux in units of $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. We have not examined the profiles of Lyα emissions because of the low signal-to-noise ratios of the spectra, although A and possibly B appear to have wide velocity widths, which may suggest starburst winds.
* Redshift $z = 0.90$ if the line is [O ii].
aration) find that $C$ and $D$ satisfy the selection criteria for LBGs at $z = 4.7 \pm 0.5$ in the $V-i'$ versus $i'-z'$ plane.\(^{16}\) Indeed, the $V-i'$ colors of $A$, $B$, $C$, and $D$ are $\sim 1.7 - 2.5$, being consistent with the color expected for $z \sim 5$ galaxies; on the other hand, the color of $E$ is $\sim 0.5$. From the above discussion, we estimate the contamination of our sample to be $\sim 17\%$.\(^{17}\)

As an independent check, we have examined the distribution of objects with $R-i > 0.8$ but with $R-i < 0.4$, which are probably low-$z$ interlopers, and we have found that their distribution on the sky is almost uniform and does not correlate with that of the LAE candidates.

### 3. RESULTS AND DISCUSSION

#### 3.1. Large-Scale Structure of LAEs

Figure 3 shows the sky distribution of 43 photometrically selected LAE candidates. We find a remarkable large-scale clustering; an overdense region lies in the east-southeast–west-northwest direction, and there are few objects outside this region. To quantify overdensity, we estimate the local surface density of LAEs, $\Sigma(x, y)$, and compute the surface overdensity, $\delta_2(x, y) = \frac{|\Sigma(x, y) - \bar{\Sigma}|}{\bar{\Sigma}}$, where $\bar{\Sigma}$ is the mean surface density of LAEs. We adopt as $\bar{\Sigma}$ the mean surface density in our image, although a larger area is desirable to obtain a more accurate (i.e., global) estimate of $\bar{\Sigma}$.

The overdensity contours are drawn in Figure 3. The projected size of the overdense region ($\delta_2 \geq 0$) is found to be about $20\ h_{70}^{-1}$ Mpc in width and larger than $50\ h_{70}^{-1}$ Mpc in length (comoving units) since the region seems to continue outside the image at either side. This elongated overdense structure may be a cross section of a wall-like structure that extends along the sight line (note that the survey depth is $33\ h_{70}^{-1}$ Mpc).

Another possibility may be that we are seeing a “redder” part of a structure that is centered at a redshift smaller that the corresponding to the center of NB711 ($z = 4.86$), since all five objects with spectroscopy have $z \leq 4.86$. This elongated structure includes a region of $\delta_2 \geq 2$ that is well approximated by a circle of $12\ h_{70}^{-1}$ Mpc radius. Since the minimum mass of this circular region is computed to be $\approx (4\pi/3)p_7(12)^3 \approx 3 \times 10^{14}\ h_{70}^{-2}\ M_\odot$ ($p_7$ is the mean matter density of the universe), later it may become a massive cluster of galaxies after collapsing to a size of a few megaparsecs. In the present-day universe, clusters are often embedded in large-scale structures. From these features, it is very likely that this elongated region is a proto–large-scale structure at $z = 5$.

#### 3.2. Implications on Cold Dark Matter Models

In a simple manner, we examine whether or not CDM models can reproduce the observed structure. We focus on the circular region of $\delta_2 \geq 2$ since properties of circular regions are predicted easily. We make a reasonable assumption that this region is a sphere of $12\ h_{70}^{-1}$ Mpc radius in three-dimensional space with a spatial overdensity of $\delta = 2$. We consider three CDM models: a $\Lambda$-dominated model with $\Omega_0 = 0.3$, $\lambda_0 = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $\sigma_8 = 0.9$; an open model with $\Omega_0 = 0.3$, 

\(^{16}\) The five candidates are located in the central part of the SDF, where we obtained deep $B, V, i'$ images as well in 2001 March–June (M. Ouchi et al. 2003, in preparation).

\(^{17}\) This value is lower than that estimated by Ouchi et al. (2003) for a deeper sample, $\sim 40\%$, on the basis of photometric properties alone. This is probably because the photometric errors in our sample are smaller than those in Ouchi et al.
$\lambda_0 = 0, H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\sigma_8 = 0.9$; and a standard model with $\Omega_0 = 1, \lambda_0 = 0, H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\sigma_8 = 0.5$. We adopt these $\sigma_8$-values from the $\sigma_8$-$\Omega$ relation derived by Eke, Cole, & Frenk (1996) for local X-ray clusters.

Using linear perturbation theory, we calculate the number of spheres within our observed volume above $\delta = 2$ as (see Steidel et al. 1998):

$$N = \frac{V_0}{V_\delta} \int_{d_\delta}^{d_\Delta} \frac{1}{(2\pi\sigma_d)^3} \exp \left( -\frac{x^2}{2\sigma_d^2} \right) dx,$$

where $V_0$ is the volume surveyed by our observation ($1.4 \times 10^7 h_70^{-3} \text{ Mpc}^3$), $V_\delta$ is the volume of an unperturbed sphere whose mass is equal to $(1 + 2/b)(4\pi/3) \rho_d (12 h_70^{-3})^3$, $d_\delta$ is the linearly extrapolated mass overdensity estimated from the observed mass overdensity (we use the fitting formula of Bernardeau 1994), $\sigma$ is the rms fluctuation of mass overdensity at $z = 4.86$ on a top-hat filter on a scale of the unperturbed sphere, and $b$ is the linear bias parameter for LAEs.

Figure 4 plots $N$ against $b$ for the three models. We find that the best-fit value of $b$ that produces the observed number ($=1$) of spheres is $b = 6$ ($\Lambda$-dominated model), $=4$ (open), and $=15$ ($\Omega_0 = 1$). We can also estimate the lower and upper limits of $b$ by imposing $0.05 \leq N \leq 4.7$ (95% confidence level assuming Poisson statistics); we obtain $b \sim 3–16$, $b \sim 2–12$, and $b \sim 8–37$ for the $\Lambda$-dominated, open, and $\Omega_0 = 1$ models, respectively. Thus, LAEs at $z \approx 5$ must be highly biased tracers of dark matter.

The best-fit values of $b$ that we find for our LAE candidates are similar to or possibly higher than those for LGs at $z \approx 3–4$ obtained in the following work. An analysis of a galaxy overdensity of $10^{15} M_\odot$ at $z = 3.09$, Steidel et al. (1998) have estimated $b \approx 4$ for the $\Omega_0 = 0.3$ flat model. Analyses of the two-point correlation function correlation have given $b \sim 2–5$ for LGs at $z \approx 3$ and $b \approx 4$ for the $\Omega_0 = 0.3$ flat model with the same normalization as we adopt (Porciani & Giavalisco 2002; Ouchi et al. 2001). Higher $b$ at $z \approx 5$ would be reasonable if we recall that $b$ for a given halo mass is predicted to increase with $z$. Indeed, M. Ouchi et al. (2003, in preparation) obtain $b \sim 6$ for LGs at $z \approx 5$, comparable to our value.

Steidel et al. (1998) and Porciani & Giavalisco (2002) have inferred the mass of halos hosting LGs to be of the order of $10^{12} M_\odot$. The $b$-value for $z \sim 5$ LGs estimated by M. Ouchi et al. (2003, in preparation) also gives a similar mass. Hence, halos hosting $z \approx 5$ LAEs are roughly as massive as those of LGs at $z \approx 3–5$. Pascarelle et al. (1996b) have argued that LAEs (found at $z = 2.4$) are subgalactic objects from their small sizes. Those LAEs have also been suggested to be very young (Keel et al. 2002). If LAEs at $z \approx 5$ are also subgalactic and if LGs have relatively large stellar masses as suggested by, e.g., Papovich, Dickinson, & Ferguson (2001) and Shapley et al. (2001), then the high mass of halos hosting $z \approx 5$ LAEs found here will imply that dark halos of a given mass host galaxies of a wide range of stellar mass or a wide range of evolutionary stages.

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