

## LYMAN $\alpha$ EMITTERS BEYOND REDSHIFT 5: THE DAWN OF GALAXY FORMATION

YOSHIKI TANIGUCHI, YASUHIRO SHIOYA, MASARU AJIKI, SHINOBU S. FUJITA, TOHRU NAGAO, & TAKASHI MURAYAMA  
Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba, Sendai 980-8578, Japan

*E-mail: tani@terra.astr.tohoku.ac.jp*

*(Received June 1, 2003; Accepted August 17, 2003)*

### ABSTRACT

The 8m class telescopes in the ground-based optical astronomy together with help from the ultra-sharp eye of the Hubble Space Telescope have enabled us to observe forming galaxies beyond redshift  $z = 5$ . In particular, more than twenty Ly $\alpha$ -emitting galaxies have already been found at  $z > 5$ . These findings provide us with useful hints to investigate how galaxies formed and then evolved in the early universe. Further, detailed analysis of Ly $\alpha$  emission line profiles are useful in exploring the nature of the intergalactic medium because the trailing edge of cosmic reionization could be close to  $z \sim 6 - 7$ , at which forming galaxies have been found recently. We also discuss the importance of superwinds from forming galaxies at high redshift, which has an intimate relationship between galaxies and the intergalactic medium. We then give a review of early cosmic star formation history based on recent progress in searching for Ly $\alpha$ -emitting young galaxies beyond redshift 5.

*Key words* : galaxies: starburst — galaxies: formation – Observational Cosmology

### I. INTRODUCTION

Formation and evolution of galaxies have been intensively discussed in this decade. In particular, the great success of the Hubble Deep Field (HDF) project (Williams et al. 1996; 2000) has provided us with very fruitful and firm observational results on faint galaxies at high redshift through systematic analyses of their broad-band optical and near-infrared (NIR) color properties (e.g., Madau et al. 1996; Lanzetta et al. 1996; Yahata et al. 2000). Follow-up optical and NIR spectroscopy of faint galaxies found in the HDFs resulted in the discovery of many galaxies beyond  $z = 3$ ; so-called Lyman break galaxies (LBGs) (Steidel et al. 1996b; Lowenthal et al. 1997; Cohen et al. 2000; Dawson et al. 2001). In addition to these HDF observations, several excellent deep surveys in blank fields also contributed to the understanding of early evolution of galaxies (Cowie et al. 1996; Steidel et al. 1996a, 1999, 2000; Pettini et al. 2001; Shapley et al. 2001, 2003). This progress has also been supported by ground-based 8-10m class telescopes such as Keck 10m telescopes, VLT, and Subaru Telescope.

The first discovery of a galaxy beyond  $z = 5$  was reported by Weymann et al. (1998); HDF 4-470.3 at  $z = 5.60$ . This identification was made by detecting the redshifted Ly $\alpha$  emission line ( $\lambda_{\text{rest}} = 1216 \text{ \AA}$ ). Since the classical paper by Partridge & Peebles (1967), many challenges have been actually made to search for Ly $\alpha$  emission from very young galaxies at high redshift. Although most of those early attempts ended

in negative results before the mid 1990s (e.g., Pritchett 1994; Thompson et al. 1995), recent advance in optical spectroscopic capability with the 8-10m class telescopes has enabled us to identify such very high- $z$  Ly $\alpha$  emitters (LAEs). Following the success of Weymann et al. (1998), more than twenty such very high- $z$  galaxies have been found to date (see section III).

These galaxies are considered to be located at the trailing edge of the cosmic reionization era and thus we are just facing close to the door of the dark age of the universe (Becker et al. 2001; Djorgovski et al. 2001; see for a review, Loeb & Barkana 2001; Barkana & Loeb 2001). Accordingly, we human beings are now capable of investigating the dawn of galaxy formation which occurred at  $z \gtrsim 6 - 7$ . In this review, we focus our attention to the recent success of deep surveys of Ly $\alpha$ -emitting forming galaxies and discuss the cosmic star formation history, and some implications on superwind activities in such forming galaxies. See also the excellent reviews on this research field given by Thommes (1999), Hu, Cowie, & McMahon (1999), and Stern & Spinrad (1999).

We adopt a flat universe with  $\Omega_{\text{matter}} = 0.3$ ,  $\Omega_{\Lambda} = 0.7$ , and  $h = 0.7$  where  $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$  throughout this review.

### II. LYMAN $\alpha$ EMITTERS AT $2 < z < 5$

#### (a) Introduction

It has long been thought that forming galaxies are strong emission-line objects because massive stars formed in the initial phase could ionize the surrounding gas clouds. Since such forming galaxies are located at high redshift, the brightest emission line in the optical win-

TABLE 1  
A SUMMARY OF THE OPTICAL COUNTERPART SEARCHES FOR DLAs

QSO	$z_{em}$	$z_{abs}$	Ref <sup>a</sup> (cm <sup>-2</sup> )
Q0000-2619	4.36	3.3902	1, 2
Q0100+1300 (PHL 957)	2.681	2.309	3
Q0151+048A	1.922	1.9342	4
PKS 0528-250	2.77	2.811	5, 6
Q2059-360	3.097	3.0831	7
Q2139-4434	3.23	2.380	8, 9
Q2233+131	3.295	3.150	10

<sup>a</sup>1. Macchetto et al. 1993, 2. Giavalisco et al. 1994, 3. Lowenthal et al. 1991, 4. Möller et al. 1998, 5. Möller & Warren 1993, 6. Warren & Möller 1996, 7. Leibundgut & Robertson 1999, 8. Francis et al. 1996, 9. Francis et al. 1997, and 10. Djorgovski et al. 1996.

dow could be the hydrogen Ly $\alpha$  line (e.g., Partridge & Peebles 1967; Meier 1976). This prediction led many astronomers to search for high- $z$  LAEs (see for a review Pritchett 1994). Custom narrowband filters (the band pass is  $\simeq 100$  Å) have often been used to search for the Ly $\alpha$  emission line. The central wavelength is of course tuned to the wavelength of the redshifted Ly $\alpha$ .

Prior discussing to the discovery of Ly $\alpha$  emitters (LAEs) beyond  $z = 5$ , we give a brief review of Ly $\alpha$  emitters between  $z = 2$  and  $z = 5$ . In this section, we also give a summary of survey methods that have been used to find LAEs (see also Thommes 1999; Stern & Spinrad 1999).

## (b) Guided Surveys

### i) Optical Counterparts of Quasar Absorption Line Systems

Since the discovery in 1968 (Burbidge et al. 1968; Bahcall et al. 1968), several populations of absorption systems have been found in quasar spectra. Such quasar absorption systems are classified as follows. 1) Damped Ly $\alpha$  absorption systems (DLAs) with  $N(\text{H I}) \gtrsim 2 \times 10^{20}$  cm<sup>-2</sup>, 2) Lyman limit absorption systems (LLS) with  $N(\text{H I}) \gtrsim 1.6 \times 10^{17}$  cm<sup>-2</sup>, 3) Sub Lyman limit absorption systems (LLS) with  $N(\text{H I}) \sim 10^{16}$  cm<sup>-2</sup>, 4) Ly $\alpha$  forests with  $N(\text{H I}) \sim 10^{12-15}$  cm<sup>-2</sup>, and 5) Metal-line absorption systems probed either by low-ionization absorption lines such as Mg II or by high-ionization absorption lines such as C IV; Mg II absorbers have  $N(\text{H I}) \gtrsim 10^{17}$  cm<sup>-2</sup> while C IV absorbers have  $N(\text{H I}) \gtrsim 10^{16}$  cm<sup>-2</sup>. These systems have been utilized to investigate both protogalactic disks/halos and the intergalactic matter at high redshift (e.g., Weymann et al. 1981; Tytler 1982; Wolfe et al. 1995). Among the absorption system population, much attention has been paid to Damped Ly $\alpha$  absorption systems (DLAs) because their observed H I column densities,  $> 2 \times 10^{20}$  cm<sup>-2</sup>, are comparable to those of galactic disks and thus they are often considered to be

progenitors of the present-day disk galaxies. Possible origins of both DLAs and LLSs have been considered as; 1) Protogalactic disks/halos, 2) merging protogalactic gas clumps in CDM cosmologies, 3) gas-rich dwarf galaxies, 4) collapsing halos with merging clouds, and 5) low surface brightness galaxies. Therefore, it is important to identify counterparts of DLAs and LLSs at high redshift.

Although early searches mostly failed, the first discovery of a LAE beyond  $z = 2$  was reported by Hunstead et al. in 1990. They found a Ly $\alpha$  emitting object as an optical counterpart of the Damped Ly $\alpha$  absorption (DLA) system at  $z_{abs} = 2.465$  which was detected toward the line of sight to Q0836+113 at  $z_{em} = 2.67$ . This LAE is small ( $\lesssim 10$  kpc) and has a very narrow line width (FWHM  $< 60$  km s<sup>-1</sup>). The inferred star

formation rate (SFR<sup>\*</sup>) is also modest,  $SFR \sim 1M_{\odot}$  yr<sup>-1</sup>. Therefore, they suggested that this LAE is a gas-rich H II galaxy.

However, this observation was not confirmed by later observations (Wolfe et al. 1992; Lowenthal et al. 1997). Nevertheless, their work encouraged researchers to carry out similar searches for LAE counterparts of DLAs at high redshift because this method provided a new type of guided search for high- $z$  LAEs. As summarized in Table 1, up to now, LAE counterparts of the seven DLA systems have been confirmed (e.g., Djorgovski et al. 1996) in the redshift range between  $z = 1.9$  and  $z = 3.4$ .

The most distant LAE found so far as a counterpart of DLA is DLA0000-2619 at  $z = 3.39$  (Macchetto et al. 1993; Giavalisco et al. 1994). The second most distant known is DLA 2233+131 at  $z = 3.15$  (Djorgovski et al. 1996). The latter object appears to be a massive disk galaxy with  $M \sim 10^{11}M_{\odot}$ . This reinforces the importance of the optical identification of LAE counterparts

<sup>\*</sup>In this review, we use the relation  $SFR = 9.1 \times 10^{-43} L(\text{Ly}\alpha) M_{\odot}\text{yr}^{-1}$  (Kennicutt 1998; Brocklehurst 1971).

of DLAs at high redshift even though the success rate is not so high. We hope that such surveys will be applied to higher- $z$  DLAs found in very high- $z$  SDSS quasars (e.g., Fan et al. 2000, 2001, 2003)

One interesting problem in the optical counterparts is that some of them have large impact parameters; e.g., a few hundreds kpc from the line of sight toward a quasar. If they are really absorbing agents, their halo size is much larger than for typical galaxies [see also section IV (f)].

## ii) Objects Associated with High- $z$ Active Galactic Nuclei

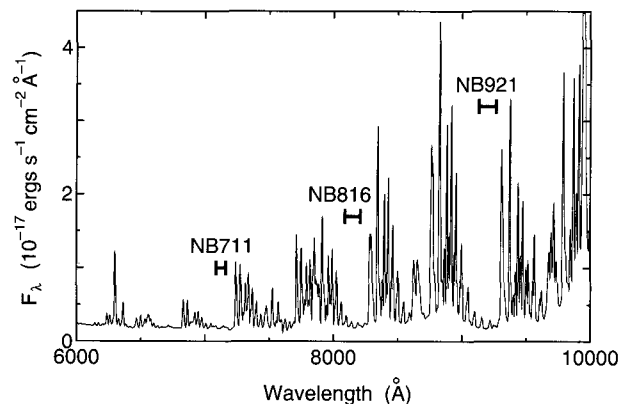
Another type of guided search for high- $z$  LAEs are searches for LAEs at a particular redshift where the presence of a certain high- $z$  source is already known; e.g., active galactic nuclei (AGNs) such as quasars and radio galaxies. Note that the association does not always mean physical companion galaxies. Rather than this, such searches are intended to find galaxies associated with large-scale structure (e.g., a protocluster region) to which the target AGN also belongs.

The first successful result was reported by Djorgovski et al. (1985) who found a Ly $\alpha$ -emitting companion galaxy ( $z = 3.22$ ) associated with a radio-loud quasar PKS 1614+051 at  $z = 3.21$  (see also Djorgovski et al. 1987). Steidel et al. (1991) also found a Ly $\alpha$ -emitting companion ( $z = 2.758$ ) associated with a radio-quiet quasar Q1548+0917 at  $z = 2.749$ .

Hu et al. (1992) conducted a systematic search for Ly $\alpha$  companion galaxies for a sample of 17 quasars. They found companion candidates for three out of 10 radio-loud quasars while found no candidates were found for seven radio-quiet ones. Later, Hu et al. (1996) found a Ly $\alpha$  companion of BR 1202–0725 at  $z = 4.69$ . Its Ly $\alpha$  luminosity leads to the star formation rate of several  $M_{\odot} \text{ yr}^{-1}$  (see also Ohta et al. 2000).

One problem in these surveys is that photoionization sources in such close companion galaxies are relatively uncertain because the intense radiation from the quasar itself affects the ionization of gas clouds in companion galaxies. Indeed, the companion galaxy to PKS 1614+051 shows high-ionization emission lines such as C IV in its UV spectrum.

More recently, Hu & McMahon (1996) searched for LAEs in the field of quasar BR2237–0607 at  $z = 4.55$  using a narrowband filter centered on the quasar’s redshifted Ly $\alpha$  emission using the UH 2.2 m telescope. They found 10 LAE candidates in the narrowband image and confirmed spectroscopically two LAEs at  $z = 4.55$ . Since these two objects are far from the quasar, it is expected that the ionization is attributed to photoionization by massive stars. Keel et al. (1999) made a similar survey in the field of the radio galaxy 53W 002 at  $z = 2.4$  and found  $\approx 20$  LAEs at the same redshift. A summary of the above surveys is given in Table 2.



**Fig. 1.**— Optical spectrum of OH airglow emission lines taken from Stockton (1999). The three narrowband filter bands, NB711, NB816, and NB921, are shown by horizontal bars, all of that are available for the Suprime-Cam on the Subaru Telescope.

## iii) Powerful Radio Galaxies

Powerful radio galaxies at high redshift have been providing nice tools that can be used to investigate observational properties of young galaxies hosting radio sources. However, this issue is out of the scope of this review. We recommend readers to visit the following nice reviews (McCarthy 1993; Stern & Spinrad 1999).

## iv) Systematic Serendipitous Searches for LAEs

Serendipitous discoveries of LAEs at high redshift have sometimes been reported in this decade (e.g., Franx et al. 1997; Dey et al. 1998; Dawson et al. 2001; Lehnert & Bremer 2003). Such objects were really found serendipitously. However, as a survey technique, there is a *systematic* serendipitous search for high- $z$  galaxies. In this technique, a certain spectroscopic database is used. Since most spectroscopic observations could be made to investigate some target objects, we introduce this technique in the category of guided surveys.

Thompson & Djorgovski (1995) reported their “systematic” serendipitous search for LAEs using a database of optical, long-slit spectroscopy obtained with both the Double Spectrograph and 4-shooter instruments on the Hale 5m telescope. The database consists of 421 independent spectra covering 14.97 arcmin<sup>2</sup>; note that  $1\sigma$  limiting flux is  $\sim 1 \times 10^{-17}$  ergs s<sup>-1</sup> cm<sup>-2</sup>. They found 65 emission-line objects among which are two quasars at  $z = 1.67$  and  $z = 1.19$ .

Using much deeper spectroscopic archival data obtained by Keck telescope, Manning et al. (2002) made a similar search for high- $z$  LAEs. They found two LAE candidates at  $z = 3.02$  and  $z = 3.36$ . Since these objects are close to the Lyman break galaxy SSA22-C17 at  $z = 3.30$ , they may be objects associated with the

TABLE 2  
A SUMMARY OF THE GUIDED SURVEYS FOR  $\text{Ly}\alpha$ -EMITTER AT  $2 < z < 5$

Survey <sup>a</sup>	Field <sup>b</sup>	$z_c$ <sup>c</sup>	$(z_{\min}, z_{\max})$ <sup>d</sup>	$V$ <sup>e</sup>	$EW_{\text{lim}}(\text{Ly}\alpha)$ <sup>f</sup>	$N(\text{Ly}\alpha)$ <sup>g</sup>	$n(\text{Ly}\alpha)$ <sup>h</sup>
HM96	BR2237-0607	4.55	(4.52, 4.56)	2304	...	2	$8.7 \times 10^{-4}$
K99	53W002	2.4	(2.32, 2.45)	85338	92	19	$2.2 \times 10^{-4}$
K99	53W002E	2.55	(2.49, 2.61)	78588	291	1	$1.3 \times 10^{-5}$
K99	53W002N	2.55	(2.49, 2.61)	78588	155	1	$1.3 \times 10^{-5}$
K99	53W002NE	2.55	(2.49, 2.61)	78588	184	4	$5.1 \times 10^{-5}$

<sup>a</sup>HM96 = Hu & McMahon (1996), and K99 = Keel et al. (1999).

<sup>b</sup>The name of the targeted field.

<sup>c</sup>The central redshift corresponding to the central wavelength of the narrow-band filter ( $\lambda_c$ ).

<sup>d</sup>The minimum and maximum redshift covered by the narrow-band filter.

<sup>e</sup>The co-moving volume covered by the survey in units of  $h_{0.7}^{-3} \text{Mpc}^3$  with  $\Omega_{\text{matter}} = 0.3$  and  $\Omega_{\Lambda} = 0.7$ .

<sup>f</sup>The smallest equivalent width of the  $\text{Ly}\alpha$  emission detected in the survey in units of  $\text{\AA}$  in the observed frame.

<sup>g</sup>The number of  $\text{Ly}\alpha$  emitters found in the survey.

<sup>h</sup>The number density of  $\text{Ly}\alpha$  emitters found in the survey in units of  $h_{0.7}^3 \text{Mpc}^{-3}$ .

<sup>i</sup>The LBG (Lyman break galaxies) spike region.

<sup>j</sup>La Palma field (Mendez et al. 1997) in the Virgo cluster.

TABLE 3  
A SUMMARY OF THE BLANK-FIELD SURVEYS FOR  $\text{Ly}\alpha$ -EMITTER AT  $2 < z < 5$

Survey <sup>a</sup>	Field <sup>b</sup>	$z_c$ <sup>c</sup>	$(z_{\min}, z_{\max})$ <sup>d</sup>	$V$ <sup>e</sup>	$EW_{\text{lim}}(\text{Ly}\alpha)$ <sup>f</sup>	$N(\text{Ly}\alpha)$ <sup>g</sup>	$n(\text{Ly}\alpha)$ <sup>h</sup>
CH98	HDF	3.4	(3.41, 3.47)	5205	115	5	$9.6 \times 10^{-4}$
CH98	SSA22	3.4	(3.41, 3.47)	5205	90	7	$1.3 \times 10^{-3}$
K99	HU Aqr	2.4	(2.32, 2.45)	85338	241	1	$1.2 \times 10^{-5}$
K99	NGC 6251	2.4	(2.32, 2.45)	85338	...	0	0
S00	LBGS <sup>i</sup>	3.09	(3.07, 3.12)	16741	80	72	$4.3 \times 10^{-3}$
K00	Virgo <sup>j</sup>	3.14	(3.12, 3.15)	6020	...	8	$1.3 \times 10^{-3}$
R00	LALA <sup>k</sup>	4.4	(4.37, 4.43)	212000	80	225	$1.1 \times 10^{-3}$
M02	LALA <sup>l</sup>	4.4	(4.37, 4.57)	740000	80	157	$2.1 \times 10^{-4}$
O03	SDF	4.9	(4.83, 4.89)	89600	82	62 <sup>m</sup>	$6.9 \times 10^{-4}$
F03	Subaru/XMM	3.72	(3.60, 3.83)	93952	254	6	$6.4 \times 10^{-5}$

<sup>a</sup>CH98 = Cowie & Hu (1998), K99 = Keel et al. (1999), S00 = Steidel et al. (2000), K00 = Kudritzki et al. (2000), R00 = Rhoads et al. (2000), M02 = Malhotra & Rhoads (2002), O03 = Ouchi et al. (2003), and F03 = Fujita et al. (2003).

<sup>b</sup>The name of the targeted field.

<sup>c</sup>The central redshift corresponding to the central wavelength of the narrow-band filter ( $\lambda_c$ ).

<sup>d</sup>The minimum and maximum redshift covered by the narrow-band filter.

<sup>e</sup>The co-moving volume covered by the survey in units of  $h_{0.7}^{-3} \text{Mpc}^3$  with  $\Omega_{\text{matter}} = 0.3$  and  $\Omega_{\Lambda} = 0.7$ .

<sup>f</sup>The smallest equivalent width of the  $\text{Ly}\alpha$  emission detected in the survey in units of  $\text{\AA}$  in the observed frame.

<sup>g</sup>The number of  $\text{Ly}\alpha$  emitters found in the survey.

<sup>h</sup>The number density of  $\text{Ly}\alpha$  emitters found in the survey in units of  $h_{0.7}^3 \text{Mpc}^{-3}$ .

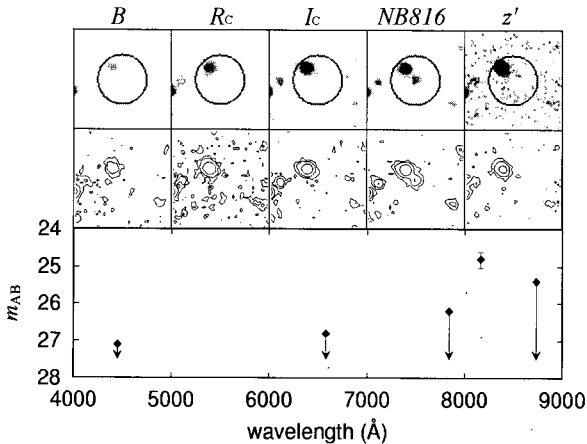
<sup>i</sup>The LBG (Lyman break galaxies) spike region.

<sup>j</sup>La Palma field (Mendez et al. 1997) in the Virgo cluster.

<sup>k</sup>We refer only to their survey results with the NB6599 filter.

<sup>l</sup>Five NB filters centered at 6559  $\text{\AA}$ , 661  $\text{\AA}$ , 6650  $\text{\AA}$ , 6692  $\text{\AA}$ , and 6730  $\text{\AA}$  are used.

<sup>m</sup>They found 87 candidates in total. However, they secured that 62 sources are much more reliable because of their  $R - i'$  colors.



**Fig. 2.**— Thumbnail images of LAE J1044-0130 (upper panel) also displayed as contours (middle panel) taken from Ajiki et al. (2002). The angular size of the circle in each panel corresponds to  $8''$ . The lower panel shows the spectral energy distribution (in magnitudes). From our optical spectroscopy, we find that a galaxy located at  $2''4$  northeast of LAE J1044-0130 shows two emission lines at  $\lambda \simeq 6710 - 6720 \text{ \AA}$ . Since these lines can be identified as the  $[\text{O II}]\lambda 3727$  doublet redshifted to  $z = 0.802 \pm 0.002$  (see Figure 9). This foreground galaxy might enhance the image of LAE J1044-0130 due to gravitational lensing. However, since there is no counter image of the LAE J1044-0130 in our deep NB816 image, the magnification factor might be less than a factor of 2 (Shioya et al. 2002b).

overdensity region identified by Steidel et al. (2000).

Our group actually has the experience of the serendipitous discovery of a high- $z$  object (a BAL quasar at  $z = 3.1$ ) in our long-slit spectrum obtained with ESI on Keck II telescope. Spectroscopic archival data must be checked carefully by anyone who is interested in serendipitous discovery of high- $z$  objects. This may provide an example of the importance of the Virtual Observatory (see for a recent review, Brunner et al. 2002).

### (c) Blank-Field Surveys

One of main purposes of deep surveys is to understand how ordinary galaxies like the Milky Way formed and evolved. For this purpose, it is important to observe typical fields in which there are no known unusual object such as luminous AGNs and massive clusters of galaxies; i.e., blank fields. Famous blank fields are the Hubble Deep Fields (HDFs: Williams et al. 1996, 2000) and the SSA (small selected area) fields selected by the L. L. Cowie team at IfA, UH (Cowie et al. 1996 and references therein).

### i) Spectroscopic Follow-up of Objects Found in Black-Field Surveys

Since the early 1990s, the so-called Lyman break method has often been used to identify high- $z$  galaxies (Steidel & Hamilton 1992, 1993; Steidel et al. 1995, 1998, 1999; Lanzetta et al. 1996; Madau et al. 1996; Yahata et al. 2000; Iwata et al. 2003; Yan et al. 2002). Since such surveys provided nice samples of LBGs at  $z > 3$ , follow-up spectroscopy has been conducted intensively and a large number of high- $z$  LBGs have already been identified (Steidel et al. 1996a, 1996b; Lowenthal et al. 1997; Shapley et al. 2003 and references therein).

Another important discovery came from a spectroscopic survey for galaxies toward a foreground cluster of galaxies at  $z = 0.37$ ; MS 1512-cB58 at  $z = 2.73$  (Yee et al. 1996). This object is apparently bright for such a high- $z$  LBG ( $V = 20.6$ ) and thus it provides a nice laboratory for investigations of young galaxies (Pettini et al. 2000 and references therein).

### ii) Searches with a Narrowband Filter

Deep surveys for LAEs beyond  $z = 2$  with a narrowband filter were already made in the early 1990s. Thompson et al. (1995) used a Fabry-Perot interferometer to search for LAEs with  $z = 2.78 - 4.89$ . Although their  $1\sigma$  limiting flux was down to  $\sim 1.5 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2}$  over  $0.05 \text{ deg}^2$  and  $\sim 8.5 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2}$  over  $0.63 \text{ deg}^2$ , they found no LAE candidates.

The first attempt by Cowie & Hu (1998) with the Keck 10m telescope revealed the presence of five Ly $\alpha$  emitters in HDF-N (N=North) and seven in SSA22 at  $z \approx 3.4$ . The star formation rates of the LAEs are several  $M_{\odot} \text{ yr}^{-1}$  and the star formation rate density is  $\rho_{\text{SFR}} \sim 0.01 M_{\odot} \text{ Mpc}^{-3} \text{ yr}^{-1}$ . Subsequently, Steidel et al. (2000) also succeeded in finding 77 LAE candidates at  $z = 3.1$  in a blank field around SSA22. Furthermore, Kudritzki et al. (2000) found nine LAEs at  $z = 3.1$  during the course of their narrow-band imaging survey aimed at looking for intracluster planetary nebulae in the Virgo cluster (Mendez et al. 1997).

Wide-field deep surveys were conducted by using the Suprime-Cam mounted at the prime focus of the 8.2 m Subaru telescope at Mauna Kea; note that this camera covers a sky area of  $34' \times 27'$ . Using a narrowband filter centered at  $7110 \text{ \AA}$  (NB711), Ouchi et al. (2003) found 87 LAE candidates at  $z = 4.86$  in the Subaru Deep Field (SDF; see for the SDF, Maihara et al. 2001).

Fujita et al. (2003) used an intermediate band filter with a resolution of  $R = 23$  centered at  $5736 \text{ \AA}$  (IA574) on Suprime-Cam in the Subaru XMM Deep Field (SXDF) and found six LAE candidates at  $z \approx 3.7$ . This filter is one of a set of special purpose filters designed for Suprime-Cam (Hayashino et al. 2000; Taniguchi 2001).

Similar wide-field deep surveys were also conducted by using the CCD mosaic camera at the Kitt Peak

National Observatory's 4m Mayall telescope; i.e., the LALA survey [Rhoads et al. 2000; Malhotra & Rhoads 2002; see also section VI (b)]. This camera covers a sky area of  $36' \times 36'$  and thus this is very suitable for all optical surveys. Rhoads et al. (2000) used five narrow-band filters centered at 6559 Å, 6611 Å, 6650 Å, 6682 Å, and 6730 Å, each of which has a passband of  $\approx 80$  Å. This filter set made it possible to search for LAEs with  $4.37 < z < 4.57$ ; as well as for their search for LAEs at  $z \approx 5.7$ , see next section.

We give a summary of the blank-field surveys for Ly $\alpha$ -emitters at  $2 < z < 5$  in Table 3.

#### (d) Gravitationally-Amplified-Field Surveys for Ly $\alpha$ Emitters at $2 < z < 5$

Basically, there is no survey for LAEs at  $2 < z < 5$  in a gravitationally-amplified field although this method has been recently used to search for LAEs beyond  $z = 5$  (Ellis et al. 2001; Hu et al. 2002; see next section). However, it is naturally understood that any help from gravitational lensing is highly useful to find distant LAEs because such LAEs are often very faint. In order to demonstrate this, we introduce an epoch-making serendipitous discovery of LAEs at  $z = 4.92$  by Franx et al. in 1997.

In order to study the observational properties of member galaxies of the cluster Cl 1357+62 at  $z = 0.33$ , they obtained a large mosaic of multi-color WFPC2 images of the cluster using HST. Franx et al. (1997) found a red arc in their image and then they obtained optical spectroscopy of this arc using LRIS at Keck Observatory. Surprisingly, they identified this arc as a LAE at  $z = 4.92$ . They further found that a companion galaxy is also a LAE at nearly the same redshift (the velocity difference is only  $450 \text{ km s}^{-1}$ ). These objects were the most distant ones up to 1997 and their redshifts were very close to  $z = 5$ . Their discovery surely encouraged astronomers who are interested in forming galaxies in the early universe. Indeed, a similar survey made by Frye et al. (2002) resulted in the discovery of eight LAEs at  $3.7 < z < 5.2$  (seven are at  $z < 5$ ) which were selected from their red broad-band colors behind four massive clusters of galaxies, Abell 1689, Abell 2219, Abell 2390, and AC 114.

### III. LYMAN $\alpha$ EMITTERS BEYOND RED-SHIFT 5

#### (a) Introduction

The recent advance provided by the 8-10m class telescopes has also enabled us to carry out deep imaging searches for star-forming galaxies beyond redshift 5. In particular, imaging surveys using narrow-passband filters have proved to be an efficient way to find such galaxies (Hu & McMahan 1996; Cowie & Hu 1998; Steidel et al. 2000; Kudritzki et al. 2000; Rhoads et al. 2000; Rhoads & Malhotra 2001; Hu et al. 2002; Ajiki et al. 2002). Indeed the most distant Ly $\alpha$  emitter known

to date, HCM 6A at  $z = 6.56$  has been discovered by using this technique (Hu et al. 2002; see also Hu et al. 1998, 1999; Ajiki et al. 2002).

Other techniques also led to the discovery of Ly $\alpha$  emitters beyond  $z = 5$  (Dey et al. 1998; Spinrad et al. 1998; Weymann et al. 1998; Dawson et al. 2001, 2002; Ellis et al. 2001). In this section, we give a summary of discoveries of LAEs beyond  $z = 5$  based on various survey techniques.

#### (b) Spectroscopic Follow-up of Objects found in Deep Surveys

The Lyman break method applied to HDF-N brought a number of candidate galaxies beyond  $z = 5$  (e.g., Lanzetta et al. 1996; Madau et al. 1996). Subsequent spectroscopic observations revealed that HDF 4-473.0 is really a LAE at  $z = 5.60$  (Weymann et al. 1998). Spinrad et al. (1998) also found two galaxies (HDF 3-95.1 and HDF 3-95.2) at  $z = 5.34$ . Although these objects do not show strong Ly $\alpha$  emission, they show a continuum break at  $\lambda \simeq 7710$  Å. Two more galaxies beyond  $z = 5$  were found during a spectroscopic survey of faint galaxies in the HDF-N flanking field; F36218-1513 at  $z = 5.767$  and F36246-1511 at  $z = 5.631$  (Dawson et al. 2001). More recently, Lehnert & Bremer (2003) found five LAEs beyond  $z = 5$  ( $5.02 < z < 5.87$ ) from their high- $z$  LBG candidates.

The first galaxy beyond  $z = 5$  was found serendipitously; 0140+326 RD1 at  $z = 5.34$  (Dey et al. 1998). This object was found during their search for LBGs at  $z \sim 4$ . Dawson et al. (2002) also found a LAE at  $z = 5.190$  serendipitously. This object, J123649.2+621539, was found in a long-slit spectrum of Keck/ESI during their spectroscopic search for faint galaxies in the HDF-N NW flanking field. As summarized in Table 4, we know 25 confirmed (or most probable) LAEs beyond  $z = 5$ . Among them, two are serendipitously discovered. This high discovery rate seems to be attributed to the great observational capability in spectroscopy with 8-10m telescopes.

#### (c) Surveys with a Narrowband Filter

Recent surveys with a narrowband filter have been finding a number of LAEs beyond  $z = 5$ . However, such surveys have the following two limitations. The first limitation comes from strong OH airglow emission lines. In Figure 1, we show an optical spectrum of OH airglow emission lines which is kindly supplied by Alan Stockton (see also Stockton 1999). Although there can be seen several gaps at which there is little strong OH emission, OH emission dominates at wavelengths longer than 7000 Å. This prevents us from finding very faint galaxies at high redshift. The well-defined gaps appear around  $\lambda \approx 7110$  Å, 8160 Å, and 9210 Å. These gaps enable us to search for LAEs at  $z \approx 4.8$  (Rhoads et al. 2000; Ouchi et al. 2003), 5.7 (Hu et al. 1998; Ajiki et al. 2002, 2003; Taniguchi et al. 2003), and 6.6 (Hu et al. 2002; Kodaira et al. 2003).

TABLE 4  
A SUMMARY OF GALAXIES BEYOND REDSHIFT 5

No.	Name	Redshift	$f(\text{Ly}\alpha)^a$	$L(\text{Ly}\alpha)^b$	Method <sup>c</sup>	Sp. Mode <sup>d</sup>	Ref. <sup>e</sup>
1	SDF J132418.3+271455	6.578	2.1	10.0	NB	L	1
2	HCM 6A	6.56	2.7	3.3	NB	L	2
3	SDF J132415.7+273058	6.541	1.1	5.6	NB	L	1
4	LAE @ 0226-04 Field	6.17	3.9	17	SF	L	3
5	BDF 1:19	5.8696	0.31	1.2	SF	L	4
6	F36218-1513	5.767	...	...	SF	L	5
7	LALA J142546.76+352036.3	5.746	1.9	6.7	NB	L	6
8	BDF 1:10	5.7441	2.4	8.7	SF	L	4
9	SSA22-HCM1	5.74	1.7	6.1	NB	L	7
10	LALA J142647.16+353612.6	5.700	3.9	14	NB	L	6
11	LAE J1044-0130	5.687	1.5	5.2	NB	H	8
12	LALA J142630.34+354022.5	5.674	2.7	9.3	NB	L	6
13	LAE J1044-0123	5.655	4.1	14	NB	H	9
14	BDF 2:19	5.6488	2.5	8.7	SF	L	4
15	BR1202-0725 LAE	5.64	...	...	NB	L	10
16	F36246-1511	5.631	...	...	SF	L	5
17	HDF 4-473.0	5.60	1.0	3.4	SF	L	11
18	Abell 2218 a <sup>f</sup>	5.576	6.2 <sup>g</sup>	0.64	SF	L/H	12
19	0140+326 RD1	5.348	3.5	11	SD	L	13
20	HDF 3-951.1	5.34	...	...	SF	L	14
21	HDF 3-951.2	5.34	...	...	SF	L	14
22	J123649.2+621539	5.190	3.0	8.5	SD	H	15
23	Abell 1689-3	5.120	...	...	SF	L	16
24	BDF 1:26	5.0558	0.35	0.93	SF	L	4
25	BDF 1:18	5.0175	0.24	0.63	SF	L	4

<sup>a</sup>Observed Ly $\alpha$  flux in units of  $10^{-17}$  ergs s $^{-1}$  cm $^{-2}$ .

<sup>b</sup>Absolute Ly $\alpha$  luminosity in units of  $10^{42}$  ergs s $^{-1}$ . If the source is lensed (i.e., HCM 6A and Abell 2218 a), we give the unlensed luminosity estimated in the reference.

<sup>c</sup>Discovery method. NB = imaging survey with a narrow-passband filter, SF = spectroscopic follow-up in the field of targeted object, and SD = serendipitous discovery.

<sup>d</sup>All the spectroscopic observations were made using either LRIS or ESI or both on the W. M. Keck Observatory. The Echelle mode of ESI provides a high-resolution spectroscopy (denoted as "H"; the spectral resolution is higher than 3000) and the low-resolution mode of ESI and LRIS provide a low-resolution spectroscopy (denoted as "L"; the spectral resolution is lower than 1000).

<sup>e</sup>1. Kodaira et al. 2003, 2. Hu et al. 2002, 3. Cuby et al. 2003, 4. Lehnert & Bremer 2003, 5. Dawson et al. 2001, 6. Rhoads et al. 2003, 7. Hu et al. 1999, 8. Ajiki et al. 2002, 9. Taniguchi et al. 2003, 10. Hu et al. 1998, 11. Weymann et al. 1998, 12. Ellis et al. 2001, 13. Dey et al. 1998, 14. Spinrad et al. 1998, 15. Dawson et al. 2002, and 16. Frye et al. 2002.

<sup>f</sup>Another Ly $\alpha$  emitter Abell 2218 b is found at the same redshift. But this is the counter lensed image of Abell 2218 a.

<sup>g</sup>In Ellis et al. (2001), the Ly $\alpha$  fluxes obtained with both Keck LRIS and ESI are given. The Ly $\alpha$  flux given in this table is their average.

TABLE 5  
CHAIN GALAXIES FOUND BY COWIE ET AL. (1995) AND VAN DEN BERGH ET AL. (1996)

	Cowie et al. (1995)	van den Bergh et al (1996)
Field	SSA 13 & SSA 22	HDF-N
Area	10.7 arcmin $^2$	5.3 arcmin $^2$
$N_{\text{chain}}(I_{814} \leq 25)^a$	24	11
$N_{\text{chain}}(I_{814} > 25)^b$	4	...
$\sigma_{\text{chain}}(I_{814} \leq 25)^c$	2.2 arcmin $^{-2}$	2.1 arcmin $^{-2}$
$\sigma_{\text{chain}}(I_{814} > 25)^d$	0.4 arcmin $^{-2}$	...
$\langle a/b \rangle^e$	$4.8 \pm 2.1$	$3.1 \pm 1.3$

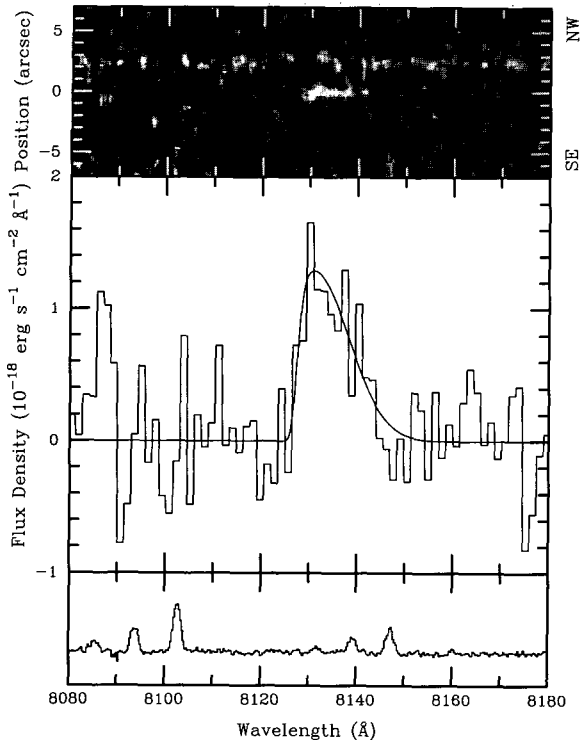
<sup>a</sup>The observed number of chain galaxies with  $I_{814} \leq 25$ .

<sup>b</sup>The observed number of chain galaxies with  $I_{814} > 25$ .

<sup>c</sup>The surface density of chain galaxies with  $I_{814} \leq 25$ .

<sup>d</sup>The surface density of chain galaxies with  $I_{814} > 25$ .

<sup>e</sup>The average value of apparent major-to-minor axial ratio.



**Fig. 3.**— The optical spectrogram (upper panel) and one-dimensional spectrum (middle panel) of LAE J1044-0130 obtained with ESI on Keck II ( $R \sim 3400$ ) taken from Ajiki et al. (2002). The model profile fit is shown by the thick solid curve (see text). Sky (OH airglow) emission lines are shown in the lower panel.

#### (d) Serendipitous Discoveries of LAEs beyond $z = 5$

The second limitation is that survey volumes are so small because of narrower band widths (e.g.,  $\sim 100$  Å). In order to gain survey volumes and to reach faint limiting magnitudes, we need wide-field CCD cameras on 8-10m class telescopes. The Suprime-Cam mounted at the prime focus of the 8.2 m Subaru telescope at Mauna Kea provides a unique opportunity for wide-field (a  $34' \times 27'$  field of view), narrowband imaging surveys for emission-line objects at high redshift. The efficiency of this instrument is higher by a factor of 30 than typical imagers mounted on the other 8-10m class telescopes.

Since the first detection of a galaxy beyond  $z = 5$  (Dey et al. 1998), more than twenty such galaxies have been found (Table 4). The most distant one known to date is HCM 6A whose redshift is 6.56 (Hu et al. 2002), farther than the most distant quasar known, SDSSp J114816.64+525150.3 at  $z = 6.43$  (Fan et al. 2003).

Hu et al. (2002) made imaging surveys of LAEs at  $z \approx 6.6$  for the following six fields using the LAEs on Keck I; three blank fields (HDF-N, SSA 17, and SSA

22) and three cluster fields around Abell 370, Abell 851, and Abell 2390. Then they found several LAE candidates in their surveys (Esther Hu, private communication) and confirmed that HCM-6A found in the Abell 370 field is a LAE at  $z = 6.56$ . This object shows a significant continuum break at wavelengths shorter than the Ly $\alpha$  line peak and the relatively flat UV continuum emission. All these features are expected for a very young, forming galaxy at such a high redshift (e.g., Meier 1976). The unshifted Ly $\alpha$  flux leads to a star formation rate of  $\sim 3M_{\odot} \text{ yr}^{-1}$  with the adopted cosmology.

Recently, some new survey results with narrowband filters with the Suprime-Cam on the 8.2 m Subaru telescope have appeared. First, our group made a deep survey for LAEs at  $z = 5.7$  (Ajiki et al. 2003) guided by one of the very high- $z$  SDSS quasars, SDSSp J104433.04-012502.2 at  $z = 5.74$  (Fan et al. 2000). They found approximately twenty LAE candidates and already confirmed spectroscopically two LAEs at  $z = 5.69$  (Ajiki et al. 2002) and  $z = 5.66$  (Taniguchi et al. 2003). More recently, Kodaira et al. (2003) made a deep imaging survey for LAEs at  $z \approx 6.6$  using the NB921 filter with the Suprime-cam. They succeeded in identifying LAEs at  $z = 6.51$  and  $z = 6.58$  in the SDF [see also section VI (c)]. The latter LAE is more distant than HCM-6A at  $z = 6.56$ . These successful results reinforce that this method is highly useful in searching for high- $z$  LAEs.

#### (e) Summary

To conclude we give a summary in Table 4 of all the galaxies beyond redshift 5 in the literature. New discoveries of LAEs at  $z > 5$  recently reported (Rhoads et al. 2003; Lehnert & Bremer 2003; Kodaira et al. 2003) are also included in this table. However, we do not include a LAE candidate at  $z = 6.5926$  found by Lehnert & Bremer (2003) because it seems necessary to obtain a high-resolution spectrum for the confirmation. We also do not include the object at  $z = 6.68$  reported by Chen et al. (1999) because this redshift is not confirmed by later observations (Stern et al. 2000b; Chen et al. 2000). The radio galaxy, TN J0924-2201 at  $z = 5.19$  (van Breugel et al. 1999) is not included too, because this source is an AGN.

As shown in Table 4, recent optical follow-up spectroscopy has used high-resolution spectrographs like ESI (Sheinis et al. 2000) rather than low-resolution ones like LRIS. The reason for this is that there is a clear advantage in using high-resolution ( $R > 2000 - 3000$ ) spectroscopy to extract Ly $\alpha$  from the forest of OH airglow lines above  $\sim 7000$  Å beyond  $z \sim 5$  (see also Stern & Spinrad 1999). High spectral resolution will be particularly important in future searches for subgalactic Ly $\alpha$  emitters at high redshift if the narrow Ly $\alpha$  profiles found in Abell 2218 (Ellis et al. 2001) and LAE J1044-0123 (Taniguchi et al. 2003) are typical of distant emission-line objects (see section VI).



## IV. SUPERWINDS AT HIGH REDSHIFT

## (a) Introduction

Superwind phenomena are often observed in nearby starburst galaxies such as M82 (e.g., Ohyama et al. 2003a and references therein; see for a review Taniguchi et al. 1988; Heckman et al. 1990). If bursts of massive star formation occurred in a forming galaxy and the kinetic energy released from the collective explosions of supernovae exceeds the gravitational potential energy of the system, a superwind could blow from this young galaxy. The presence of luminous LAEs at high redshift suggests strongly that superwind phenomena are also common for such forming galaxies.

Historically, galactic wind models have been applied to the formation of elliptical galaxies in terms of the monolithic collapse scenario (e.g., Larson 1974; Arimoto & Yoshii 1987). Such monolithic collapse models are now considered to be unlikely because hierarchical clustering models (i.e., cold dark matter models) provide successful explanations of the structure formation in the universe (e.g., Peebles 1993). Nevertheless, it is also known that galactic wind models appear consistent with many observational properties of elliptical galaxies in the local universe. This dilemma may be reconciled if we consider the following situation. It is not necessarily to presume that a pregalactic cloud is a first-generation gigantic gas cloud. If a number of subgalactic gas clouds are assembled into one and then a starburst occurs in its central region, the physical situation seems to be nearly the same as that of the monolithic collapse.

In the galactic wind scenario, the initial starburst occurs at the epoch of galaxy formation in the galaxy center. Subsequently, massive stars die and then a large number of supernovae appear. These supernovae could overlap and then evolve into a so-called superbubble. If the kinetic energy deposited to the surrounding gas overcomes the gravitational potential energy of the galaxy, the gas clouds are blown out into the intergalactic space as a superwind (e.g., Heckman et al. 1990). Galactic superwinds are now considered to be one of the key issues for understanding the interaction and evolution of both galaxies and intergalactic matter (e.g. Heckman 1999; Taniguchi & Shioya 2001). In order to improve our knowledge of galactic superwinds at high redshift, a large sample of superwind candidates at  $z > 3$  is necessary. Recent optical observations have found some possible candidates for superwind galaxies at  $z > 5$  (Dawson et al. 2002; Ajiki et al. 2002; see also Frye et al. 2002). In this section, we give a summary of such observations.

(b) J123649.2+621539 at  $z = 5.19$ 

One interesting object among the LAEs given in Table 1 is J123649.2+621539 at  $z = 5.190$  which was found serendipitously in the HDF-North flanking fields (Dawson et al. 2002). Its Ly $\alpha$  emission-line profile

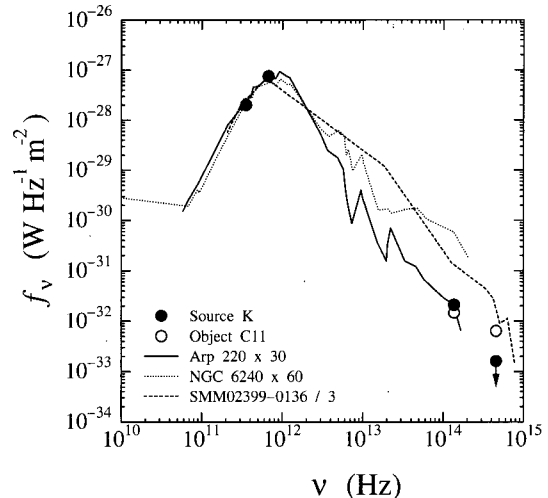


Fig. 4.— Spectral energy distribution of LAB1 taken from Taniguchi et al. (2001). The  $R$ - and  $K$ -band photometric data of the source K are shown by filled circles while those of C11 are shown by open circles (see Steidel et al. 2000). For comparison, we show the SEDs of Arp 220 (solid line), NGC 6240 (dotted line), and SMM 02399–0136 (dashed line).

shows a sharp blue cutoff and broad red wing emission, both of which are often observed in star-forming systems with prominent wind outflows. These features are also expected from radiative transfer in an expanding envelope. Therefore, Dawson et al. (2002) suggested that the Ly $\alpha$  profile of J123649.2+621539 is consistent with a superwind with a velocity of  $\sim 300 \text{ km s}^{-1}$ ; the Ly $\alpha$  line can be decomposed to the following three components, (1) a narrow central emission component with  $FWHM = 280 \text{ km s}^{-1}$ , (2) a broad emission component with  $FWHM = 560 \text{ km s}^{-1}$  redshifted by  $320 \text{ km s}^{-1}$  from the central component, and (3) a broad absorption component with  $FWHM = 800 \text{ km s}^{-1}$  blueshifted by  $360 \text{ km s}^{-1}$  from the central one.

Such superwind activities are expected to be related to the escape of Lyman continuum photons because the velocity gradient in superwinds could increase the escape fraction. However, Dawson et al. (2002) obtained a very small escape fraction,  $f_{\text{esc}} \sim 0.1 \pm 0.3$ . On the other hand, Steidel et al. (2001) obtained  $f_{\text{esc}} \gtrsim 0.5$  for 29 Lyman break galaxies at  $\langle z \rangle = 3.40 \pm 0.09$ . In order to improve the measurement of  $f_{\text{esc}}$  for LAEs at  $z > 5$ , we need a much larger sample of superwind galaxies at  $z > 5$ .

(c) LAE J1044-0130 at  $z = 5.69$ 

During the course of a new search for Ly $\alpha$  emitters at  $z \approx 5.7$  using Subaru Telescope, Ajiki et al. (2002) found a candidate superwind galaxy at  $z = 5.69$ . Its optical thumbnails and optical spectrum are shown in Figures 2 and 3, respectively. Its emission-line shape shows the sharp cutoff at wavelengths shortward of the

line peak and the presence of the excess red-wing emission seems secure (Figure 3). The  $FWHM$  of the  $Ly\alpha$  emission is measured to be  $340\pm 110$  km s $^{-1}$  and the full width at zero intensity (FWZI) is estimated to be  $890\pm 110$  km s $^{-1}$ . These properties are similar to those of the  $Ly\alpha$  emitter at  $z = 5.190$ , J123649.2+621539, found by Dawson et al. (2002).

We note that approximately half of the intrinsic  $Ly\alpha$  emission from LAE J1044-0130 could be absorbed by intergalactic atomic hydrogen (e.g., Dawson et al. 2002). In order to reproduce the observed  $Ly\alpha$  emission-line profile a two-component profile fit was made using the following assumptions: 1) the intrinsic  $Ly\alpha$  emission line profile is Gaussian, and 2) the optical depth of the  $Ly\alpha$  absorption increases with decreasing wavelength shortward of the rest-frame  $Ly\alpha$  peak. The resulting fit is shown in Figure 3 (thick curve), which corresponds to the following emission and absorption line parameters. [1]  $Ly\alpha$  emission: the line center,  $\lambda_{c,em} = 8031$  Å, the line flux,  $f_{em} \simeq 2.4 \times 10^{-17}$  ergs s $^{-1}$  cm $^{-2}$ , and the line width,  $FWHM_{em} \simeq 650$  km s $^{-1}$ ; [2]  $Ly\alpha$  absorption: the line center,  $\lambda_{c,abs} = 8123$  Å, the optical depth at the absorption center,  $\tau_{abs} \simeq 10$ , and the line width,  $FWHM_{abs} \simeq 175$  km s $^{-1}$ . This analysis suggests that the total  $Ly\alpha$  emission-line flux amounts to  $1.7 \times 10^{-17}$  ergs s $^{-1}$  cm $^{-2}$ . Then the absorption corrected, total  $Ly\alpha$  luminosity is estimated as  $L(Ly\alpha) \sim 6.1 \times 10^{42} h_{0.7}^{-2}$  ergs s $^{-1}$ , giving the star formation rate,  $SFR \simeq 6 h_{0.7}^{-2} M_{\odot}$  yr $^{-1}$ .

#### (d) Lyman $\alpha$ Blobs at $z \approx 3.1$

Recent narrow-band imaging surveys have revealed the presence of very extended  $Ly\alpha$  emitters at high redshift,  $z \sim 2 - 3$  (Keel et al. 1999; Steidel et al. 2000). Three sources found by Keel et al. (1999) are all strong C IV emitters (Pascarelle et al. 1996), and thus they are photoionized by the central engine of active galactic nuclei (AGNs). On the other hand, since two sources found by Steidel et al. (2000) have no evidence for the association with AGNs, their origin has been in debate. These two sources are called  $Ly\alpha$  blobs (LABs). The observational properties of the LABs found by Steidel et al. (2000) are summarized as follows; 1) the observed  $Ly\alpha$  luminosities are  $\sim 10^{43}$  ergs s $^{-1}$ , 2) they appear elongated morphologically, 3) their sizes amount to  $\sim 100$  kpc, 4) the observed line widths amount to  $\sim 1000$  km s $^{-1}$ , 5) they are not associated with strong radio-continuum sources such as powerful radio galaxies, and 6) they are strong submm emitters (Chapman et al. 2001).

As for the origin of LABs, two alternative ideas have been proposed. One is that these LABs are superwinds driven by the initial starburst in galaxies because all the above properties as well as the observed frequency of LABs can be explained in terms of the superwind model (Taniguchi & Shioya 2000). More recently, Taniguchi, Shioya, & Kakazu (2001) found that the observed spectral energy distribution of one of them, LAB1, found by

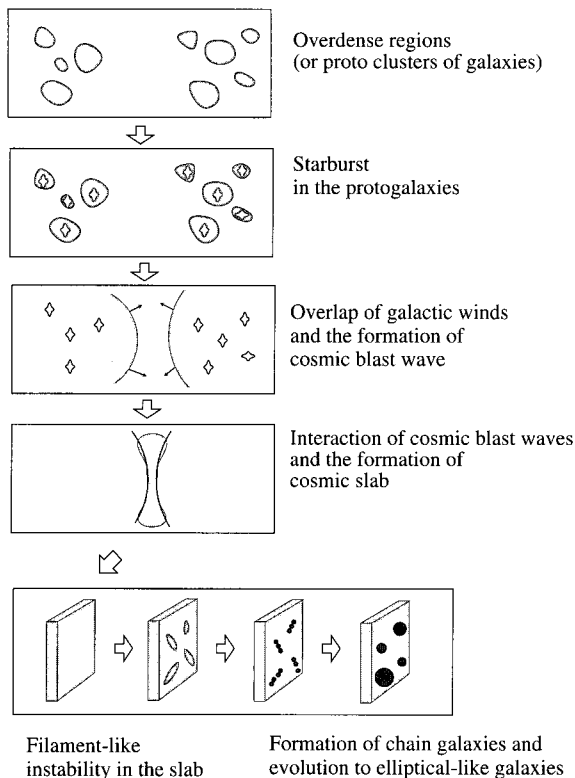
Steidel et al. (2000) is quite similar to that of Arp 220 which is a typical ultraluminous starburst/superwind galaxy in the local universe. This suggests strongly that the superwind model proposed by Taniguchi & Shioya (2000) is applicable to LAB1. It is remarkable that LAB1 is more luminous in the infrared by a factor of 20 than Arp 220, and thus Taniguchi et al. (2001) suggest that LAB1 is an archetypical example of the hyperwind galaxy.

The other idea is that LABs are cooling radiation from protogalaxies in dark matter halos (Haiman, Spaans, & Quataert 2000; Fardal et al. 2001; see also Fabian et al. 1986; Hu 1992). Standard cold dark matter models predict that a large number of dark matter halos collapse at high redshift and they can emit significant  $Ly\alpha$  fluxes through collisional excitation of hydrogen. These  $Ly\alpha$  emitting halos are also consistent with the observed linear sizes, velocity widths, and  $Ly\alpha$  fluxes of the LABs. However, it is uncertain how much far infrared and submillimeter continuum emission can be emitted because little is known about the dust content and its spatial distribution in such dark matter halos. However, this model cannot explain the huge submm luminosity observed in LAB1 (Chapman et al. 2001). Therefore, the superwind model is much preferred. Recent optical spectroscopy of LAB1 using Subaru telescope also suggested that LAB1 is a superwind galaxy (Ohyama et al. 2003b).

In summary, it is likely that LABs are superwinds at  $z \sim 3$ . Another merit of the superwind model is that there seems to be a natural evolutionary link from dust-enshrouded (or dusty) submm sources (hereafter DSSs) to LABs because the central starburst region in a forming elliptical galaxy could be enshrouded by a lot of gas with dust grains (Taniguchi & Shioya 2000). Their scenario is summarized as follows; Step I: The initial starburst occurs in the center of pregalactic gas cloud. Step II: This galaxy may be hidden by surrounding gas clouds for the first several times  $10^8$  years (i.e., the DSS phase). Step III: The superwind blows and thus the DSS phase ceases. The superwind leads to the formation of extended emission-line regions around the galaxy (i.e., the LAB phase). This lasts for a duration of  $\sim 1 \times 10^8$  years. And, Step IV: The galaxy evolves to an ordinary elliptical galaxy  $\sim 10^9$  years after the formation. This superwind model predicts that the LABs are bright at rest-frame far-infrared if they are high-redshift, luminous analogues of nearby superwind galaxies like Arp 220.

#### (e) Chain Galaxies

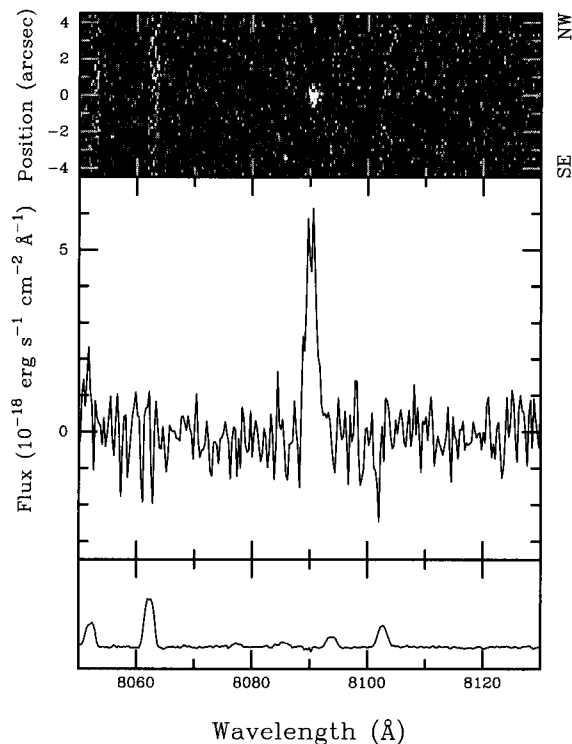
One interesting new population of galaxies at high redshift are chain galaxies (Cowie et al. 1995; van den Bergh et al. 1996; see Table 5). Cowie et al. (1995) found 28 candidates of such chain galaxies in their deep *HST I* band (F814W) images of the two Hawaii deep survey fields, SSA 13 and SSA 22. van den Bergh et al. (1996) also identified such chain galaxies in the



**Fig. 5.**— A schematic illustration of the proposed formation mechanism of chain galaxies taken from Taniguchi & Shioya (2001).

Hubble Deep Field-North (Williams et al. 1996); HDF 2-234 (the tadpole or head-tail galaxy) and HDF 3-531 (the chain galaxy). The chain galaxies tend to be very straight in morphology and their average major-to-minor axial ratio is  $\sim 5$ . Based on these observational properties, Cowie et al. (1995) proposed that the chain galaxies comprise a new population of forming galaxies at high redshift ( $z \sim 0.5 - 3$ ) because they are bluer on average than galaxies with similar  $I$  magnitudes studied by them. In particular, they are very blue in  $B - K$ , suggesting that they are not relatively normal galaxies in the rest ultraviolet band and that the peculiar morphologies are not a consequence of the distribution of the star-forming regions.

As for a possible formation mechanism of chain galaxies, Taniguchi & Shioya (2001) proposed the following scenario. Successive merging of subgalactic gas clumps results in the formation of a galaxy with a mass of  $10^{11-12} M_{\odot}$  at redshift  $z \sim 5$ . Subsequently, supernova explosions occur inside the galaxy and then blow out as a galactic wind (or a superwind). This wind expands into the intergalactic space and then causes a large-scale shell with a radius of several hundreds of kpc. Since this radius may be smaller than the typical separation between galaxies, interactions of shells may



**Fig. 6.**— The optical spectrum of LAE J1044-0123 obtained with the Keck II Echelle Spectrograph and Imager (ESI) taken from Taniguchi et al. (2003). We show the spectrogram in the upper panel and the one-dimensional spectrum extracted with an aperture of 1.2 arcsec.

also occur, resulting in the formation of a large-scale gaseous slab. Since the shell or the slab can be regarded as a gaseous sheet, filament-like gravitational instability is expected to occur. Further gravitational instability occurs in each filament, leading to intense star formation along the filament. This is the chain galaxy phase. The filament collapses gravitationally into one spheroidal system like an elliptical galaxy within one dynamical timescale of the filament ( $\sim 10^8$  yr). Therefore, it seems quite difficult to identify remnants of chain galaxies. Since forming galaxies with massive stars could often experience the superwind phase in their early lives, this idea may remain as a plausible mechanism.

#### (f) Possible Relation to Quasar Absorption Line Systems

Shocked shells driven by superwinds have been often discussed as possible agents of some quasar absorption line systems such as Lyman limit absorption systems (LLSs) and damped Ly $\alpha$  absorption systems (DLAs) (Ostriker & Cowie 1981; Ikeuchi 1981; Chernomordik & Ozerney 1983; Ostriker & Ikeuchi 1983; Voit 1996). Indeed, the H I column densities of shocked shells driven

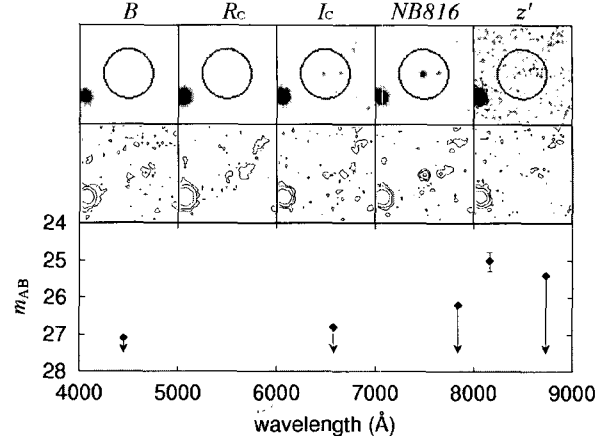
by superwinds are expected to be  $N_{\text{HI}} \gtrsim 10^{19} \text{ cm}^{-2}$  (e.g., Taniguchi & Shioya 2001); note that LLSs have  $N_{\text{HI}} \gtrsim 10^{17} \text{ cm}^{-2}$  (e.g., Steidel 1990). If we see such shells from a highly inclined angle (e.g.,  $\theta_{\text{view}} \gtrsim 80^\circ$ ) or their tangential sections, the H I column density exceeds  $10^{20} \text{ cm}^{-2}$ , causing damped Ly $\alpha$  absorption systems (DLAs, e.g., Peebles 1993; Wolfe et al. 1995). It is also possible that DLAs may arise in the last stages of gravitational collapse of the filaments just as star formation commences. Small cloudlets breaking into the intergalactic medium (IGM) may be observed as Ly $\alpha$  forests with  $N_{\text{HI}} \lesssim 10^{15} \text{ cm}^{-2}$ .

The superwind scenario may have the following merits. One is that the projected distance up to several hundreds kpc is acceptable because the absorbing agents are gas clouds in the shocked shells. The second merit is the metal enrichment in the IGM because the superwind contains a lot of heavy elements. It has been argued that supernova explosions lead to the chemical enrichment of the IGM at high redshift (e.g., Ostriker & Gnedin 1996; Miralda-Escudé & Rees 1997). We estimate the metal enrichment due to the superwind. The mass of metal ejected from a star is  $m_Z = \epsilon_Z m_*$  where  $\epsilon_Z$  is the mass fraction of metal with respect to the stellar mass. Thus the total metal enrichment due to the superwind can be estimated as

$$\Delta Z = \frac{\epsilon_Z m_* N_{\text{SN}}}{M_{\text{shell}}} \simeq 4.2 \times 10^{-3} \epsilon_Z \quad (1)$$

where we adopt  $m_* = 10 M_\odot$  as the typical mass of progenitors of type II supernovae. We then obtain  $\Delta Z \simeq 4.2 \times 10^{-4}$  if  $\epsilon_Z = 0.1$ . Since the metal abundance observed in Ly $\alpha$  forests (e.g., Pettini et al. 1997; Songaila & Cowie 1996; Lu et al. 1998) is of the order of  $0.01 Z_\odot$  where  $Z_\odot$  is the solar metal abundance in mass ( $Z_\odot = 0.02$ ); i.e.,  $Z_{\text{IGM}} \simeq 2 \times 10^{-4}$ . Therefore, the metal ejection as a result of the superwind from a forming massive galaxy may be responsible for the observed metal abundance in the IGM at high redshift.

Spectroscopic evidence for such a shocked-shell absorber was obtained for two Mg II absorbers at  $1 < z < 2$  (Bond et al. 2001). These Mg II absorbers show symmetry-inverted structure; i.e., the absorption profile has a sharp drop in optical depth near the center of the profile and strong black-bottomed absorption on either side. Future searches for such the symmetry-inverted structure in higher redshift absorbers will be recommended. Since it takes  $\sim 1$  Gyr to develop large-scale superwind-driven bubbles (e.g., Arimoto & Yoshii 1987), the presence of superwind activity gives us information on the formation redshift of galaxies; e.g., if the formation redshift is  $z_f \sim 10$ , we may observe superwinds at  $z \sim 3$  preferentially. Therefore, any searches for superwinds beyond  $z = 5$  will provide strong constraints on the formation epoch of massive star formation beyond  $z = 10$ .



**Fig. 7.**— Thumb-nail images of LAE J1044–0123 (upper panel) taken from Taniguchi et al. (2003). The angular size of the circle in each panel corresponds to 8 arcsec. Their contours are shown in the middle panel. The lower panel shows the spectral energy distribution on a magnitude scale.

## V. SUBGALACTIC POPULATIONS AT HIGH REDSHIFT

### (a) Introduction

Hierarchical models of structure formation imply that galaxies were constructed through successive mergers of smaller gaseous clumps (“building blocks”) in the early universe. This assembly process is presumed to have taken place from 0.5 to a few Gyrs after the Big Bang, or over the redshift interval  $z \sim 30 - 1$ . Therefore, in order to elucidate the formation and evolution of galaxies, it is essential to investigate subgalactic objects at high redshifts. Due to the cosmological redshift, the surface brightness of objects decreases with increasing redshift by a factor of  $(1+z)^4$ , the so-called Tolman surface brightness dimming (Tolman 1930). This makes it difficult to estimate the true diameters of any high- $z$  objects and thus it is hard to discover subgalactic small objects solely by direct imaging observations. Hence, it is necessary to find objects with small velocity dispersions, providing firm dynamical evidence for subgalactic masses. In this section, we briefly present recent observations of such subgalactic populations.

### (b) Abell 2218 a at $z = 5.58$

A group led by R. Ellis conducted a blind spectroscopic survey of the appropriate critical lines of several well-constrained lensing clusters, all of which were imaged by HST. During the course of their spectroscopic observations, they found a very promising subgalactic object at  $z = 5.576$  (see also Table 4). This object was found as a pair of emission-line objects, but their careful lensing model analysis showed that this pair arises through a gravitationally lensed source at very high magnification; the magnification factor is as high as  $\simeq$

30. Its  $I$ -band magnitude corrected for this amplification is estimated as  $I \simeq 30$  and the physical size is as small as 150 pc. The star formation rate is estimated as  $\sim 0.5 M_{\odot} \text{ yr}^{-1}$ . It is also remarkable that its dynamical mass is only  $\sim 10^6 M_{\odot}$ , being comparable to those of globular clusters.

(c) **LAE J1044-0123 at  $z = 5.66$**

The author's group has carried out a very deep optical imaging survey for faint Ly $\alpha$  emitters in the field surrounding the quasar SDSSp J104433.04–012502.2 at redshift 5.74 [see section IV (c)]. In addition to LAE J1044–0130 (Ajiki et al. 2002), they also found another single-line emitter which was identified as a LAE at  $z = 5.66$  based on their KeckII/ESI spectrum (Figure 6). Its thumbnails are shown in Figure 7. The most intriguing property of LAE J1044–0123 is that the observed emission-line width (full width at half maximum; FWHM) of redshifted Ly $\alpha$  is only  $2.2 \pm 0.3 \text{ \AA}$ . Since the instrumental spectral resolution is  $1.7 \pm 0.1 \text{ \AA}$ ; the intrinsic width is only  $1.4 \pm 0.5 \text{ \AA}$ , corresponding to  $FWHM_{\text{obs}} \simeq 52 \pm 19 \text{ km s}^{-1}$  or a velocity dispersion  $\sigma_{\text{obs}} = FWHM_{\text{obs}} / (2\sqrt{2\ln 2}) \simeq 22 \text{ km s}^{-1}$ . This value is comparable to those of luminous globular clusters (Djorgovski 1995).

If a source is surrounded by neutral hydrogen, Ly $\alpha$  photons emitted from the source are heavily scattered. Furthermore, the red damping wing of the Gunn-Peterson trough could also suppress the Ly $\alpha$  emission line (Gunn & Peterson 1965; Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Haiman 2002 and references therein). If this is the case for LAE J1044–0123, we may see only a part of the Ly $\alpha$  emission. Haiman (2002) estimated that only 8% of the Ly $\alpha$  emission is detected in the case of HCM-6A at  $z = 6.56$  found by Hu et al. (2002). However, the observed Ly $\alpha$  emission-line profile of LAE J1044–0123 shows the sharp cut-off at wavelengths shortward of the line peak. This property suggests that the H I absorption is dominated by H I gas in the system rather than that in the IGM. Therefore, it seems reasonable to assume that the blue half of the Ly $\alpha$  emission could be absorbed in the case of LAE J1044–0123. Then we estimate a modest velocity dispersion,  $\sigma_0 \sim 2\sigma_{\text{obs}} \sim 44 \text{ km s}^{-1}$ . Given the diameter of this object probed by the Ly $\alpha$  emission,  $D \simeq 7.7 h_{0.7}^{-1} \text{ kpc}$ , we obtain the dynamical timescale of  $\tau_{\text{dyn}} \sim D/\sigma_0 \sim 1.7 \times 10^8 \text{ yr}$ . This would give an upper limit of the star formation timescale in the system; i.e.,  $\tau_{\text{SF}} \lesssim \tau_{\text{dyn}}$ . However, if the observed diameter is determined by the so-called Strömgren sphere photoionized by a central star cluster, it is not necessary to adopt  $\tau_{\text{SF}} \sim \tau_{\text{dyn}}$ . It seems more appropriate to adopt a shorter timescale for such high- $z$  star-forming galaxies, e.g.,  $\tau_{\text{SF}} \sim 10^7 \text{ yr}$ , as adopted for HCM-6A at  $z \approx 6.56$  (Hu et al. 2002) by Haiman (2002). One may also derive a dynamical mass  $M_{\text{dyn}} = (D/2)\sigma_0^2 G^{-1} \sim 2 \times 10^9 M_{\odot}$  (neglecting possible inclination effects).

At the source redshift,  $z = 5.655$ , the mass of a dark matter halo which could collapse is estimated as

$$M_{\text{vir}} \sim 9 \times 10^6 \left( \frac{r_{\text{vir}}}{1 \text{ kpc}} \right)^3 h_{0.7}^{-1} M_{\odot} \quad (2)$$

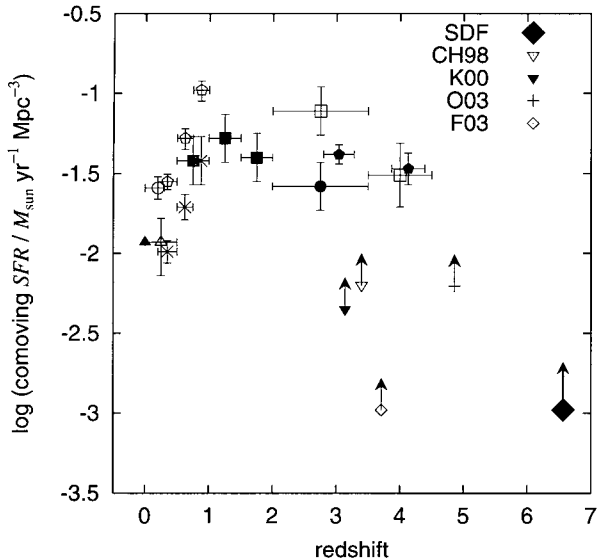
where  $r_{\text{vir}}$  is the Virial radius [see equation (24) in Barkana & Loeb (2001)]. If we adopt  $r_{\text{vir}} = D/2 = 3.85 \text{ kpc}$ , we would obtain  $M_{\text{vir}} \sim 5 \times 10^8 M_{\odot}$ . However, the radius of the dark matter halo could be ten times as large as  $D/2$ . If this is the case, we obtain  $M_{\text{vir}} \sim 5 \times 10^{10} M_{\odot}$  and  $\sigma_0 \sim 75 \text{ km s}^{-1}$ . Comparing this velocity dispersion with the observed one, we estimate that the majority of Ly $\alpha$  emission would be absorbed by neutral hydrogen.

How massive is this source?; i.e.,  $\sim 10^9 M_{\odot}$  or more massive than  $10^{10} M_{\odot}$ . If the star formation timescale is as long as the dynamical one, the stellar mass assembled in LAE J1044–0123 at  $z = 5.655$  exceeds  $10^9 M_{\odot}$ , being comparable to the nominal dynamical mass,  $M_{\text{dyn}} \sim 2 \times 10^9 M_{\odot}$ . Since it is quite unlikely that most mass is assembled to form stars in the system, the dark matter halo around LAE J1044–0123 would be more massive by one order of magnitude at least than the above stellar mass. If this is the case, we could miss the majority of the Ly $\alpha$  emission and the absorption could be attributed to the red damping wing of neutral hydrogen in the IGM. Since the redshift of LAE J1044–0123 ( $z = 5.655$ ) is close to that of SDSSp J104433.04–012502.2 ( $z = 5.74$ ), it is possible that these two objects are located at nearly the same cosmological distance. The angular separation between LAE J1044–0123 and SDSSp J104433.04–012502.2, 113 arcsec, corresponds to the linear separation of  $4.45 h_{0.7}^{-1} \text{ Mpc}$ . The Strömgren radius of SDSSp J104433.04–012502.2 can be estimated to be  $r_S \sim 6.3(t_Q/2 \times 10^7 \text{ yr})^{1/3} \text{ Mpc}$  using equation (1) in Haiman & Cen (2002) where  $t_Q$  is the lifetime of the quasar (see also Cen & Haiman 2000). Even if this quasar is amplified by a factor of 2 by gravitational lensing (Shioya et al. 2002b), we obtain  $r_S \sim 4.9 \text{ Mpc}$ . Therefore, it seems likely that the IGM around LAE J1044–0123 may be ionized completely. If this is the case, we cannot expect that the Ly $\alpha$  emission of LAE J1044–0123 is severely absorbed by the red damping wing emission. In order to examine which is the case,  $L$ -band spectroscopy is recommended because the redshifted [O III] $\lambda 5007$  emission will be detected at  $3.33 \mu\text{m}$ , which can be detected by the James Webb Space Telescope.

## VI. ON-GOING DEEP SURVEY PROGRAMS

### (a) The LALA Survey

The LALA (Large Area Lyman Alpha) Survey has been conducted by using the wide-field camera (a  $36' \times 36'$  field of view) on the Kitt Peak National Observatory's 4m Mayall telescope. Their broad-band images are shared in collaboration with the NOAO Deep



**Fig. 8.**— The star formation rate density ( $\rho_{\text{SFR}}$ ) as a function of redshift  $z$  taken from Kodaira et al. (2003). Their new estimate at  $z \approx 6.6$  (large filled diamond) is shown together with the results of previous Ly $\alpha$  searches at  $z \sim 3 - 5$  (CH98 = Cowie & Hu 1998, K00 = Kudritzki et al. 2000, F03 = Fujita et al. 2003, and O03 = Ouchi et al. 2003). The previous investigations are shown by filled triangle (Gallego et al. 1996), open triangle (Treyer et al. 1998), open circle (Tresse & Maddox 1998), stars (Lilly et al. 1996), open pentagons (Hammer et al. 1999), filled squares (Connolly et al. 1997), filled circles (Madau 1998), and open squares (Pettini et al. 1997). Other results for Lyman break galaxies between  $z = 3 - 4$  are also shown by filled pentagons (Steidel et al. 1999).

Wide-Field Survey (Januzzi & Dey 1999). Together with narrow-band filters, this camera has been used to search for high- $z$  Ly $\alpha$  emitters at  $z \approx 4.5$  (Rhoads et al. 2000; Malhotra & Rhoads 2002) and at  $z \approx 5.7$  (Rhoads & Malhotra 2001; Rhoads et al. 2003); see also section II (b).

Their first search for LAEs at  $z \approx 4.5$  gives a surface density of LAEs at  $z \approx 4.5$ ,  $1.1 \times 10^4 \pm 700 \text{ deg}^{-2}$  (Rhoads et al. 2000). Their follow-up optical spectroscopy led to the identification of an LAE at  $z = 4.52$ . However, they also identified two low- $z$  interlopers, suggesting that the success rate of LAE identification is  $\sim 1/3$ . A similar success rate is also reported by Kodaira et al. (2003) for their LAE search at  $z \approx 6.6$ . They noted that their LAE candidates at  $z \approx 4.5$  tend to have larger emission-line equivalent width with respect to the model prediction (Malhotra & Rhoads 2002). They interpreted this as evidence for massive-star enhanced star formation in young galaxies. Detailed follow-up spectroscopy will be necessary to confirm it.

Rhoads & Malhotra (2001) also made a search for LAEs at  $z \approx 5.7$  using the two narrowband filters cen-

tered at 8150 Å (NB815) and 8230 Å (NB823), each of which has FWHM of 75 Å. They found seven LAE candidates using the NB815 filter and six using the NB823 one. Rhoads et al. (2003) made optical follow-up spectroscopy of four LAE candidates and the found three out of four appear to be LAEs at  $z \approx 5.67, 5.70,$  and  $5.75$ ; the remaining one object is too faint to be detected in their spectroscopy.

## (b) CADIS

Another interesting deep survey program is Calar Alto Deep Imaging Survey (CADIS). This project uses the 2.2 m and 3.5 m telescopes at Calar Alto Observatory in Spain and observe 10 sky fields, each of which has a 120 arcmin<sup>2</sup> area (see for a review, Thommes 1999; see also Hippelein et al. 2003). Although Thommes et al. (1998) found seven candidates for LAE at  $z \sim 5.7$ , their follow-up spectroscopy did not confirm their identification (see Stern & Spinrad 1999).

Recently, Maier et al. (2003) reported their new results on surveys for LAEs with use of their three narrow filter bands centered at 7000 Å, 8200 Å, and 9200 Å; note that they used an imaging Fabry-Perot interferometer. They found 5 bright LAE candidates at  $z \sim 4.8$  and 11 ones at  $z \sim 5.7$ .

One important characteristic of the CADIS survey is that 13 intermediate-band (or medium-band) filters are used in this survey in addition to the usual four broadband filters ( $B, R, K,$  and  $K'$ ). This filter set provides better classifications of stars, galaxies, and quasars at various redshifts (e.g., Wolf et al. 2001, 2003). The use of such an intermediate-band filter system is also planned for the Suprime-Cam on the Subaru Telescope (Taniguchi 2001).

## (c) The Subaru Deep Field

The Subaru telescope team has officially started a large-scale deep survey program in April 2002; the Subaru Deep Field (SDF) project. Several pilot papers related to the SDF project have been already published (Maihara et al. 2000; Ouchi et al. 2003; Kashikawa et al. 2003; see also Totani et al. 2001a, 2001b, 2001c). This project already identified two LAEs at  $z \approx 6.6$  (Kodaira et al. 2003); see also section VII (b). The overall design of the SDF project will be given elsewhere.

## VII. THE EARLY COSMIC STAR FORMATION HISTORY

### (a) Introduction

As already noted before, the Lyman break method allowed us to find a large number of high- $z$  galaxies. Although a small part of LBGs have been confirmed by spectroscopy, photometric redshifts are reasonably available for most LBGs. Therefore, the LBG data are

highly useful to probe cosmic star formation history in the early universe (e.g., Madau et al. 1996; Steidel et al. 1999). In particular, Madau et al. (1996) investigated the cosmic star formation history quantitatively; i.e., the star formation rate density (SFRD) was investigated as a function of redshift (the so-called Madau plot). Strictly speaking, we have to take account of the SFRD contributed by hidden populations such as dusty starburst galaxies (e.g., Hughes et al. 1998; Barger et al. 1998, 1999). Yet, it is shown that the SFRD appears to be constant between  $z \approx 1$  and  $z \approx 4$  (e.g., Madau et al. 1998; Steidel et al. 1999). This constancy appears to extend up to  $z \approx 5$  although the SFRD tends to show a slow decline with  $z$  (Iwata et al. 2003).

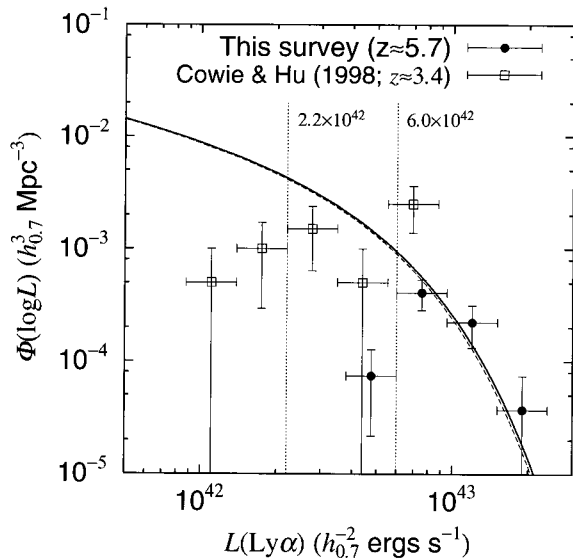
### (b) Viewed from LAEs

Here a question arises as; How is the SFRD beyond  $z = 5$ ? Since it is quite difficult to find LBGs beyond  $z = 5$  because they are basically  $I$  dropouts and thus we cannot estimate their photometric redshifts solely using  $z$  band data. Therefore, LAE survey data are highly useful in investigations of the SFRD beyond  $z = 5$ .

Recently, Kodaira et al. (2003) have found 73 LAE candidates in the Subaru Deep Field (SDF) based on their very deep imaging with the NB921 filter together with  $i'$  and  $z'$  data. They then carried out follow-up optical spectroscopy of nine sources and discovered two LAEs at  $z \approx 6.6$ . Since the SDF is a blank field and the lensing effect is expected to be small in this field, they can perform a simple statistical analysis of star formation activity in the investigated volume. They obtained the average SFR for the two LAEs;  $7.1 \pm 2.0 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$ , being comparable to those of LAEs at  $z \approx 5.1 - 5.8$  (e.g., Ajiki et al. 2002). It should be mentioned that the SFR estimated above is a lower limit because it is quite likely that a blue half or more of the Ly $\alpha$  emission may be absorbed by H I gas and dust grains in the galaxy itself and by the intergalactic H I gas (Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Cen & McDonald 2002). It is also noted that the SFR based on the Ly $\alpha$  luminosity tends to be underestimated by a few times or more than that based on the UV luminosity (see also Hu et al. 2002).

Assuming that approximately 22% ( $=2/9$ ) of 73 LAE candidates are real LAEs at  $z \approx 6.5 - 6.6$ , they obtained a star formation rate density of  $\rho_{\text{SFR}} \approx 5.2 \times 10^{-4} h_{0.7} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$  given the survey volume,  $202,000 h_{0.7}^{-3} \text{ Mpc}^3$ . Their estimate can be regarded as a robust and first meaningful lower limit for the star formation rate density beyond  $z = 6$ . They also compare this value with previous estimates in a so-called Madau plot (Figure 8); note that all the previous estimates are converted to those in the cosmology adopted in this review. As shown in Figure 8, moderate star formation activity already occurred in the early universe beyond  $z = 6$ .

Finally, it is also reminded that we do not integrate the SFRDs of LAE candidates shown in Figure 8, as-



**Fig. 9.**— Ly $\alpha$  luminosity function for the two LAE samples obtained by Ajiki et al. (2003) and Cowie & Hu (1998). The solid curve is from Ajiki et al. (2003) and the dotted one for Cowie & Hu (1998).

suming a certain luminosity function from a lower to an upper limit because there is no reliable luminosity function for high- $z$  LAEs. Recently, Ajiki et al. (2003) estimated the Ly $\alpha$  luminosity function for the LAE samples obtained by both Cowie & Hu (1998) and their own survey. The results are shown in Figure 9. If we integrate the SFRDs for both surveys, we obtain the corrected SFRD shown in Figure 10. The corrected values are quite similar to those estimated from Lyman break galaxies at  $3 < z < 4$  (see also Bouwens et al. 2003). Future careful investigations will be absolutely necessary to estimate a more reliable contribution of LAEs to the cosmic SFRD at high redshift.

## VIII. COMMENTS ON THE REIONIZATION EPOCH OF INTERGALACTIC MEDIUM

### (a) Introduction

It is believed that our universe began approximately 13 billion years ago according to the standard big bang cosmology with the adopted cosmological parameters. Primeval material (hydrogen, helium, and light elements) was completely ionized for the first 300,000 years (its corresponding redshift interval is  $1000 \lesssim z < \infty$ ) and then recombined. Tiny density fluctuations at this stage were thought to evolve to various cosmological objects like galaxies which are observed now in the universe (e.g., Peebles 1993; Fukugita, Hogan, & Peebles 1996; Bahcall et al. 1999). The most distant physical information that we can detect is the so-called cosmic microwave background radiation (CMBR) with

temperature of 2.7 K. This is indeed the redshifted thermal emission from the very young universe at  $z \sim 1000$ . Even though we can detect this information, individual cosmological objects that we can see are distant quasars and galaxies at  $z \sim 6$  (Hu et al. 2002 and see Table 4 in this review; Fan et al. 2003 and references therein). Were there any light sources between  $z \sim 1000$  and  $z \sim 6$ ? Although we human beings have not yet detected any information from the universe between  $z \sim 1000$  and  $z \sim 6$ , what we can say now is that the universe between  $z \sim 1000$  and  $z \sim 6$  appears dark. This era is called the dark age of the universe (Rees 1996, 1999).

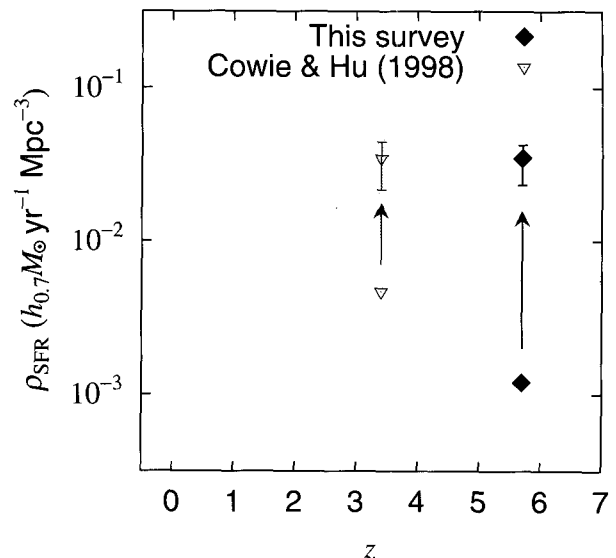
### (b) The Ionization State of Intergalactic Matter

It is evident from the presence of CMBR that the universe once recombined at  $z \sim 1000$ . However, it is also known that the intergalactic space is completely ionized in the universe between  $z \sim 6$  and  $z \sim 0$ . Its observational evidence is obtained from the so-called Gunn-Peterson test (Gunn & Peterson 1965). Since the Gunn-Peterson optical depth at  $z \sim 4$  is much smaller than 1 (Sasaki & Umemura 1996), it is strongly suggested that the intergalactic space at this redshift is really completely ionized (Songaila et al. 1999; see also Songaila & Cowie 2002).

Another interesting absorption feature found in rest-frame UV spectra of high- $z$  quasars are Ly $\alpha$  forests. It has been often considered that these forests are attributed to discrete cloudlets of neutral hydrogen. However, recent cosmological fluid simulations have suggested that they are attributed to density fluctuations in the universe (Cen et al. 1994; Miralda-Escude et al. 1996; Gnedin & Ostriker 1997; Zhang et al. 1997). This means that Ly $\alpha$  forests arise from regions where the fraction of neutral hydrogen is relatively high. If this is the case, it is not necessarily to distinguish between Ly $\alpha$  forests and the Gunn-Peterson optical depth. From this reason, it is now popular to adopt the continuum depression  $D_A$  defined as the integrated continuum absorption between the wavelengths of Ly $\alpha$  and Ly $\beta$ , as a measure of the intergalactic absorption (Oke & Korycansky 1982). For example, the most distant quasar known at  $z = 6.28$  shows  $D_A > 90\%$  (Fan et al. 2001). It is shown that  $D_A$  begins to increase rapidly with redshift beyond  $z = 3$  and exceeds 0.9 at  $z \simeq 5$ . Although it was expected that  $D_A$  reaches approximately 1 at  $z > 5$ , recent observations of high- $z$  quasars at  $z > 5$  have shown that  $D_A$  appears constant; i.e.,  $D_A = 0.9$ . This led Djorgovski et al. (2001) to suggest that we see the trailing edge of the reionization at  $z \approx 6$ , implying that the reionization occurred at  $z > 6$  (Songaila & Cowie 2002).

### (c) The Cosmic Reionization

Recently, Nakamoto, Umemura, & Susa (2001) made numerical simulations of the cosmic reionization process by solving the 3-D radiative transfer equations.



**Fig. 10.**— New star formation rate density corrected for the Ly $\alpha$  luminosity function shown in Figure 9. The filled diamond shows the data point for Ajiki et al. (2003) and the open inverse triangle is for Cowie & Hu (1998).

This simulation shows that neutral regions begin to develop at  $z \simeq 15$  due to effects of both the self-shielding and shadowing and then even such regions are subject to ionization by UV radiation at  $z \simeq 9$ . Although the universe appears completely ionized at  $z \simeq 7$ , the intergalactic medium is still opaque for ionizing photons. It is found that the intergalactic medium finally becomes optically thin for ionizing photons at  $z \simeq 5$ . The most intriguing result of this simulation is that the opacity for ionizing photons keeps a high value even after the completion of reionization of the universe. It is also suggested that Ly $\alpha$  line emission is subject to strong absorption because the total absorption cross section for Ly $\alpha$  is similar to that for photoionization. Accordingly, the condition of  $D_A \approx 1$  does not necessarily mean that the intergalactic space is neutral.

As mentioned before, there are two alternative reionization sources; massive stars in galaxies and AGNs like quasars (e.g., Fukugita & Kawasaki 1994). The number density of quasars has a significant peak at  $z \sim 2$  and then decreases with increasing redshift. Therefore, recently, it has been often considered that massive stars in galaxies are more feasible reionization sources. However, it is still unknown when and how such galaxies formed in the early universe. So-called cold dark matter (CDM) models suggest that the first stars [i.e., Population III (Pop. III) objects] could form at  $z \sim 30$ . Recent theoretical considerations suggest that such stars could be very massive (Abel et al. 1998; Bromm, Coppi, & Larson 1999; Nakamura & Umemura 1999, 2001) although there is an alternative idea that intermediate-mass stars could be pre-



entially formed in zero-metal pregalactic gas clouds (Yoshii & Saio 1986; see also Shioya et al. 2002a).

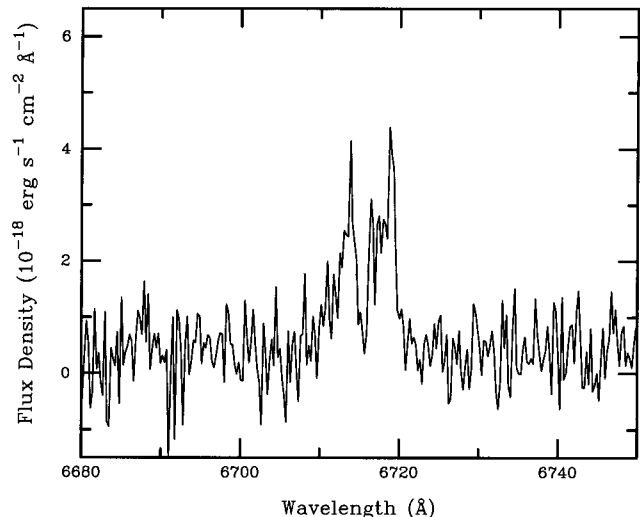
If Pop. III stars are so massive, we have two alternative ionization sources. One is very hot stars with temperature of  $> 10^5$  K and the other is mini AGNs which have hard continuum emission. Hot Pop. III stars may have a softer continuum than mini AGNs. Since the photoionization cross section is proportional approximately to  $\nu^{-3}$ , harder-energy photons can more easily penetrate into gaseous media, giving rise to more smoothed ionization structures in the intergalactic space. On the other hand, the self-shielding effect for softer-energy photons causes highly-contrasted ionization structures. In either case, these sources could reionize the universe up to  $z \simeq 10$  (Loeb & Barkana 2001). This means that the universe was reionized by objects formed in the dark age and then the reionization process ended in the dark age.

It is considered that Pop. III stars formed in subgalactic clumps at  $z \sim 10 - 30$  (Gnedin & Ostriker 1997). If these stars could contribute to the reionization, the star formation density may be  $\sim 0.2 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ , being comparable to that at  $z \simeq 1 - 4$  (Barkana & Loeb 2000; Blain et al. 1999). Although massive stars in these subgalactic clumps at  $z \sim 10 - 30$  could be feasible reionization sources, they are too faint to be detected by using any 8m-class telescopes; if we try to detect  $\sim 0.1 L^*$  galaxies using 8-10m class telescopes (i.e.,  $J$  dropouts), we need more than 100 hours integration for both  $J$  and  $H$  bands (F. Iwamuro, private communication).

It is considered that galaxies with an ordinary mass could form at  $z \sim 10$ . Indeed, very high- $z$  galaxies were already found at  $z = 6.56$  (Hu et al. 2002) and at  $z = 6.58$  (Kodaira et al. 2003). Although new high- $z$  quasars will be found in the existing and future surveys, finding high- $z$  galaxies seems more important because the number density of galaxies would be much higher than that of quasars. In order to understand the reionization process, new systematic searches for Ly $\alpha$  emitting galaxies are very important although the WMAP data suggest that the cosmic reionization epoch may be  $z_{\text{rec}} \approx 17 \pm 4$  (Spergel et al. 2003).

#### (d) Further Comments

Recent discovery of quasars at  $z \sim 6$  by the Sloan Digital Sky Survey (SDSS) made it possible to examine a so-called Gunn-Peterson trough in the UV spectra of such SDSS high- $z$  quasars (e.g., Fan et al. 2001, 2003; Becker et al. 2001). Since such new information can be used to estimate the epoch of the cosmic reionization, deep and wide-field searches for LAEs beyond  $z = 6$  gains high importance (see for a review, Loeb & Barkana 2001). It seems important that there is no continuum emission shortward of the Ly $\alpha$  line of HCM 6A at  $z = 6.56$  (Hu et al. 2002). The two LAEs at  $z = 6.6$  found in Kodaira et al. (2003) also share the same property. It is known that the radiation damp-



**Fig. 11.**— An optical spectrum of the foreground neighbor galaxy ( $z = 0.802$ ) of LAE J1044–0130 (Ajiki et al. 2002) obtained with ESI on Keck II (see Figure 2). The [O II] $\lambda$ 3727 doublet is clearly seen.

ing wing from the neutral H I gas can absorb radiation 20 Å redward of the Ly $\alpha$  wavelength in the observed frame of the object (Miralda-Escudé 1998; Miralda-Escudé & Rees 1998). Therefore, the presence of LAEs beyond  $z = 6$  suggests that the reionization epoch may be earlier than  $z = 6$  (e.g., Hu et al. 2002). However, if a LAE is surrounded by a cosmological H II region that is made by the LAE itself, the Ly $\alpha$  emission line can remain observable even if most intergalactic medium is neutral (Haiman 2002). In order to pursue this issue, we need a larger sample of LAEs between  $z = 6$  and  $z = 7$  scattered in a large sky area.

## IX. NEAR FUTURE PROSPECTS

### (a) Introduction

As demonstrated in this review, more than twenty LAEs beyond  $z = 5$  have been already discovered. It is also expected that a large number of such LAEs will be found soon because there are a number of on-going deep survey programs aiming at finding them. In fact, our group has found more than 20 LAE candidates at  $z \approx 5.7$  (Ajiki et al. 2002). The SDF team has also found  $\sim 70$  LAE candidates at  $z \approx 6.6$ . Therefore, we will be able to investigate the cosmic star formation history probed by a large number of high- $z$  LAEs soon (perhaps, within a couple of years).

### (b) Optical Follow-up Spectroscopy

The progress in LAE searches beyond  $z = 5$  may depend on the efficiency of follow-up optical spectroscopy. Although multi-object spectroscopy mode has been al-

ready ready in most spectrographs on the 8-10m telescopes, high-spectral resolution (e.g.,  $R > 2000 - 3000$ ) is absolutely necessary to confirm the blue-sharp-cutoff profile which is the most important property of the Ly $\alpha$  emission line. The reason for this is that only Ly $\alpha$  can be found in optical spectra of LAEs beyond  $z = 5$ . Indeed, it has been often discussed that a single emission line in optical spectra of faint galaxies can be either Ly $\alpha$  or [O II] $\lambda 3727$  (e.g., Stern et al. 2000a and references therein).

Such a single line with large equivalent width (e.g.,  $> 200 \text{ \AA}$ ) has been considered to be a probable LAE. However, intense star-forming galaxies at intermediate redshift also sometimes have such large equivalent widths of [O II] emission (e.g., Ohya et al. 1999; Stern et al. 2000a). Therefore, single-line objects with a large equivalent width are not always LAEs at high redshift. The continuum break at wavelengths shortward of Ly $\alpha$  also provides firm evidence for a LAE (e.g., Hu et al. 2002). However, the star formation timescale in LAEs beyond  $z = 5$  may not be so long (e.g., less than 1 Gyr). Therefore, LAEs are not always detectable in the continuum when their wavelength is longer than Ly $\alpha$  that can be probed at  $z$  photometric band. Accordingly, the line shape is the best discriminator of LAEs from low- $z$  interlopers. Indeed, if the spectral resolution is high enough to resolve the [O II] doublet line (see Figure 11), it is easily to reject low- $z$  interlopers from high- $z$  LAE candidates.

### (c) New Surveys with Intermediate-Band Filters

New-type filters, intermediate-band filters, have been recently introduced in optical deep surveys such as CADIS [see section VI (b)]. The MAHORоба project planned to be made with use of the Suprime-Cam on the Subaru Telescope also uses such an intermediate-band filter system. This filter system has a spectroscopic resolution of  $R = 23$  covering wavelengths between  $3800 \text{ \AA}$  and  $9900 \text{ \AA}$  (Taniguchi 2001); see Figure 12.

A pilot survey for LAEs at  $z \approx 3.7$  is reported by Fujita et al. (2003), in which one of the intermediate-band filters, IA574 (centered at  $5740 \text{ \AA}$  with FWHM of  $280 \text{ \AA}$ ), is used. Although their survey depth is not so deep, they have found six LAE candidates among 23 strong emission-line sources. Although the use of such an intermediate-band filter is not useful in searching for very faint LAEs, a large number of strong LAEs should be detected, because each filter can probe a volume of  $\sim 10^6 \text{ Mpc}^3$  thanks to the wide-field coverage of the Suprime-Cam.

### (d) NIR Surveys

If we use optical imagers, we cannot find objects beyond  $z = 7$  because the Ly $\alpha$  line passes out of the optical window for such a very high redshift. Therefore,

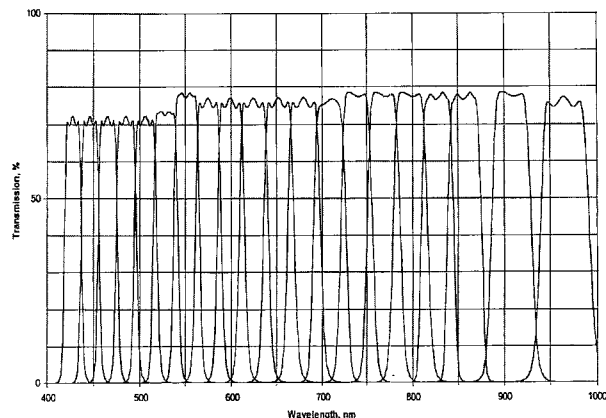


Fig. 12.— Transmission curves for the Subaru intermediate-band filters. Note that the transmission curves of the first two filters are not drawn in this Figure.

it will become much more important to promote near-infrared (NIR) deep surveys (e.g., Pahre & Djorgovski 1995; see also for papers on broad-band NIR surveys, Dickinson et al. 2000; Yahata et al. 2000). One technical problem is that any existing NIR cameras do not have a wide-field coverage. The next-generation NIR camera, MOIRCS, installed on the Subaru telescope may be the widest NIR camera with a field coverage is  $4' \times 7'$ ; note that this may be the widest but its field coverage is almost comparable to typical optical imagers on the 8-10m class telescope like LRIS on Keck I. We need a much wider NIR camera in the future.

We would like to thank the organizers of this exciting and fruitful workshop at Pohang, Korea, in particular, Hyung Mok Lee, and all participants, in particular, Renyue Cen, Paul Shapiro, Dave Sanders, Peter Quinn, and Nick Scoville. We would also like to thank Alan Stockton, Esther Hu, Masayuki Umemura, Zoltan Haiman, Fumihide Iwamuro, Youichi Ohya, Christian Maier, and Satoru Ikeuchi for their kind communications. We also thank all members of the SDF project, in particular, K. Kodaira, H. Karoji, H. Ando, M. Iye, N. Kashikawa, S. Okamura, K. Shimasaku, & M. Ouchi. This work was financially supported in part by the Ministry of Education, Culture, Sports, Science, and Technology (Nos. 10044052, and 10304013).

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