DEEP SPECTROSCOPY OF SYSTEMATICALLY SURVEYED EXTENDED Lyα SOURCES AT z ~ 3–5.1,2

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ABSTRACT

Spatially extended Lyα sources that are faint and/or compact in continuum are candidates for extremely young (<10^7 yr) galaxies at high redshifts. We present medium-resolution (R ~ 2000) VLT/VIMOS spectroscopy of 18 such extended Lyα sources found in our previous study at z ~ 3–5. The deep spectroscopy showed that all 18 objects have large equivalent widths (EWs), exceeding 100 Å in the rest frame. For about 30% of our sample (five objects), we identified conspicuous asymmetry in the profile of the Lyα line. They show broad wing emission components on the red side, and a sharp cutoff on the blue side of the Lyα line. Such asymmetry is often seen in superwind galaxies, and is also consistent with the theoretical prediction of superwinds. In fact, one of them shows systematic velocity structure in the two-dimensional spectrum, suggesting the existence of superwind activity. There are eight objects (8/18 ~ 40%) that have very large EWs, exceeding 200 Å (rest frame), and no clear signature of superwind activities. Such large EWs cannot be explained in terms of photoionization by a moderately old (>10^7 yr) stellar population, even with a top-heavy IMF or an extremely low metallicity. These eight objects clearly show a positive correlation between the Lyα line luminosity and the velocity width. This suggests that these eight objects are good candidates for forming galaxies in a gas-cooling phase (cold accretion).

Subject headings: galaxies: formation — galaxies: high-redshift

1. INTRODUCTION

Galaxies undergoing their initial star formation are predicted to have strong Lyα emission (Partridge & Peebles 1967; Charlot & Fall 1993). Recent imaging surveys using narrowband filters tuned to the restshifted Lyα line have successfully identified a large number of Lyα emitters (LAEs; e.g., Cowie & Hu 1998; Hu et al. 1998; Fynbo et al. 2001, 2003; Rhoads et al. 2000, 2003; Ouchi et al. 2003, 2005, 2007; Shimasaku et al. 2003; Kodaira et al. 2003; Maier et al. 2003; Dawson et al. 2004; Kashikawa et al. 2006; Iye et al. 2006). Some of them are fairly faint in rest-frame UV continuum and have large Lyα equivalent widths, exceeding 240 Å in the rest frame (Malhotra & Rhoads 2002, hereafter MR02). Such large equivalent widths suggest that they are possibly in the initial phases (<<10^7 yr) of star formation. The faintness in UV continuum also suggests that their stellar masses are fairly small, implying that significant star formation has not yet occurred.

In the early phases of galaxy formation (ages of <=10^7 yr), (proto)galaxies are predicted to radiate spatially extended Lyα emission. At least three mechanisms are currently proposed for extended Lyα emission: (1) cooling radiation from gravitationally heated primordial gas infalling into a dark halo potential (Haiman et al. 2000; Fardal et al. 2001; Furlanetto et al. 2005; Birnbom & Dekel 2003; Dekel & Birnboim 2006; Dijkstra et al. 2006a, 2006b), (2) resonant scattering of Lyα photons from the central (hidden) ionizing source (Møller & Warren 1998; Haiman & Rees 2001; Weidinger et al. 2004, 2005; Laursen & Sommer-Larsen 2007), and (3) starburst-driven galactic winds (Taniguchi & Shioya 2000; Taniguchi et al. 2001; Ohyama et al. 2003; Geach et al. 2005).

Recent narrowband imaging surveys for high-z Lyα emitters (LAEs) have found several tens of extended Lyα sources with no significant UV continuum sources sufficient to ionize such a large amount of HI gas (Lyα blobs, or LABs; Keel et al. 1999; Steidel et al. 2000, hereafter S00; Francis et al. 2001; Matsuda et al. 2004, hereafter M04; Palunas et al. 2004; Nilsson et al. 2006; Smith & Jarvis 2007). Two other LABs have also been identified in somewhat different approaches, i.e., mid-IR imaging (Dey et al. 2005) and optical spectroscopy of submillimeter sources (Greve et al. 2007). However, there are still only a small number of extended Lyα sources known to date, as compared to thousands of known normal LAEs. Most of the extended Lyα sources known to date have been identified in narrowband imaging surveys, which cover very narrow redshift ranges. Even the largest sample, made by M04, which is constructed from a narrowband survey targeted on LABs of S00, covers a redshift range of only \( z = 3.09^{+0.04}_{-0.03} \).

Due to the lack of a systematic sample and subsequent follow-up studies, the nature of such extended Lyα sources remains unknown. Even for the most famous objects, two LABs of S00, the origins of the extended Lyα emission are not fully clear. For example, observational studies of the S00 LABs have been made by many astronomers, ranging from radio to X-ray wavelengths (e.g., Chapman et al. 2001, 2004; Basu-Zych & Scharf 2004; Geach...
et al. 2005; Matsuda et al. 2006). These studies suggest that obscured ionizing sources such as starburst regions or AGNs are associated with LABs. Detailed optical spectroscopy of the LABs suggests that outflow from the central sources is responsible for the extended Ly$\alpha$ emission (Ohyama et al. 2003; Wilman et al. 2005), while numerical simulation shows that cooling radiation from infalling gas, combined with a central ionizing source, could also explain the spatial extent, line profiles, and velocity widths of the Ly$\alpha$ emission (Dijkstra et al. 2006b). There is also a detailed observational study by Bower et al. (2004) suggesting that extended Ly$\alpha$ emission of LABs cannot be simply explained with a single mechanism such as a galactic wind or cooling radiation. They are likely to be massive systems harboring galaxy formation sites (Matsuda et al. 2006), although the true nature of the Ly$\alpha$ emission is still unclear.

In order to construct a systematic sample of extended Ly$\alpha$ sources covering a wide range of redshifts, we have carried out a deep, wide-field imaging survey of a blank field, Subaru/XMM-Newton Deep Field, using the Subaru Telescope and seven intermediate-band (IA) filters. This survey enabled us to construct a sample of 41 extended Ly$\alpha$ sources located at $z \sim 3$–5, and to show that this kind of objects commonly exist in the early universe far beyond $z \sim 3$ (Saito et al. 2006, hereafter Paper I). We here present deep follow-up spectroscopy of our photometric sample of Paper I using the high-resolution grism of the Visible Multi-Object Spectrograph (VIMOS) on VLT. This gives a 3 times deeper exposure and a several times higher resolution than our previous spectroscopy presented in Paper I. We construct a spectroscopic sample of 18 spatially extended Ly$\alpha$ sources with large equivalent widths, located at redshifts of $3.3 \leq z \leq 4.7$. This sample allows us to make a quantitative analysis in terms of equivalent width, velocity width, and Ly$\alpha$ line luminosity, as well as the velocity structure traced by the Ly$\alpha$ line profile.

The rest of this paper is organized as follows. We briefly introduce our photometrically selected sample of extended Ly$\alpha$ sources in § 2, based on the previous observations in Paper I. In § 3 we present the details of our spectroscopic observations and data reduction. The results of the spectroscopy thus obtained and a discussion of their implications are presented in § 4. Finally, we summarize the conclusions in § 5.

All magnitudes are in the AB (Oke 1974; Fukugita et al. 1995). We use the standard $\Lambda$-dominated CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 100h = 70$ km s$^{-1}$ Mpc$^{-1}$, unless otherwise noted.

2. OUR SAMPLE OF EXTENDED Ly$\alpha$ SOURCES

The targets of our current work were selected from the photometric sample constructed in Paper I, based on an intermediate-band imaging survey (Subaru proposal ID S02B-163; Kodaira et al.) with the Subaru Prime-focus Camera (Suprime-Cam) mounted on the 8.2 m Subaru Telescope. The field of this survey is the Subaru/XMM-Newton Deep Field South (SXDF-S), located at $\alpha = 02^h 18^m 00^s$, $\delta = -05^\circ 25^\prime 00^\prime\prime$ (J2000). The selection of extended Ly$\alpha$ sources was based on photometry in seven intermediate (IA) bands centered at $\sim 5000$–$7100$ Å (Hayashino et al. 2000), the $B$ band, and a broad band redward of the Ly$\alpha$ line ($R$, $i'$, or $z'$ band). The broadband data were taken in Subaru/XMM-Newton Deep Survey (SXDS; Furusawa et al. 2008). The details of the selection are reported in Paper I. This sample consists of 41 Ly$\alpha$ emitters located at redshifts of $3.24 \leq z \leq 4.95$.

The Ly$\alpha$ sources are spatially extended in the Ly$\alpha$ line, and faint and/or compact in the continuum redward of the Ly$\alpha$. They can be divided into two minor classes, “continuum-compact” and “continuum-faint” objects, based on differences in the selection procedure. About a half of our 41 Ly$\alpha$ emitters, 22 objects, can be regarded as point sources in the redward continuum, and are classified as continuum-compact objects. They show $B$-band dropout, which is consistent with Lyman-break feature of distant galaxies at $z \gtrsim 3$. The remaining 19 objects are continuum-faint objects, which are fainter than the 3$\sigma$ level of sky fluctuation in the redward continuum band. Their continuum break between the redward band and the $B$ band cannot be measured, since they are not detected in the $B$ band. Some of these continuum-faint objects appear to be larger than the PSF size in the redward continuum band, but the sizes measured here are not well constrained due to the low signal-to-noise ratio (S/N). As anticipated from the large excess in the IA band from the redward continuum, objects in the continuum-faint subsample tend to have larger EWs than those in the continuum-compact subsample.

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**Fig. 1.** Luminosity functions (LFs) of our sample (filled squares) and a sample of normal LAEs at $z \approx 3.7$ by Ouchi et al. (open circles). The vertical error bars show the Poisson errors, and the horizontal error bars represent the size of the luminosity bins.

**Fig. 2.** Redshift distribution of extended Ly$\alpha$ sources. The histogram shows the redshift distribution of our photometric sample of 41 extended Ly$\alpha$ sources, based on coarse redshift information obtained from the IA imaging (redshift resolution $\Delta z \sim 0.2$). The open diamonds show the detection limit (2$\sigma$) for each IA band in units of rest-frame surface brightness (right axis).
Since our selection is based on photometry in IA bands, which have several times wider bandwidths than narrow bands, we select objects with large equivalent widths (EWs). Our selection criteria roughly correspond to EW greater than \( \sim 55 \text{ Å} \) in the rest frame, and the largest value of IA-excess corresponds to EW \( \sim 700 \text{ Å} \) in the rest frame. The Ly\( \alpha \) line luminosities are also relatively large, ranging from several \( \times 10^{42} \text{ ergs s}^{-1} \) to \( \times 10^{43} \text{ ergs s}^{-1} \). This roughly corresponds to the bright end of the luminosity function (LF) of normal LAEs at similar redshifts. The comparison between the LF of our 41 objects and that of normal LAEs is shown in Figure 1. The LAE sample shown here is from a narrowband survey of SXDF at \( z \approx 3.7 \) (Ouchi et al. 2007, hereafter O07), with a completeness of \( \sim 70\%–80\% \) at \( \leq 24.2 \text{ mag} \) (\( \geq 3.4 \times 10^{42} \text{ ergs s}^{-1} \)). Note that the brightest bin of the LF of O07’s sample includes only one object. Comparison of the LF in our sample and O07’s sample can put constraints on the relation between our objects and normal LAEs, since O07’s sample can be regarded as consisting of “average” LAEs at \( z \approx 4 \). The comparison shown in Figure 1 may suggest that a significant fraction (\( \sim 30\% \)) of luminous LAEs [\( L(\text{Ly} \alpha) \approx 2.5 \times 10^{43} \text{ ergs s}^{-1} \)] are spatially extended Ly\( \alpha \) sources; the fraction decreases with luminosity down to \( \sim 10\% \) at \( L(\text{Ly} \alpha) \approx 1 \times 10^{43} \text{ ergs s}^{-1} \). However, it should be noted that one object in our sample, IB10–90651, is not included in O07’s sample, despite being located within a field that is covered by their survey. This object has extremely low surface brightness, so that the diffuse outskirt cannot be detected in O07’s relatively shallow narrowband image. Deeper observations (and also a wider redshift coverage) are needed to put further constraints on the fraction of extended Ly\( \alpha \) emitters.

Figure 2 shows the redshift distribution of our objects, based on the IA imaging (two double-counted objects are not eliminated). The rest-frame surface brightness detection limit of each IA band is also plotted in this figure. This shows that extended Ly\( \alpha \) sources commonly exist in the early universe, almost independently of redshift. The size distribution of our objects is shown in Figure 3. We could not find any significant redshift dependence in the spatial extent. Note that the low sensitivity to the line emission also affects the apparent spatial extents of our objects, especially in

![Figure 3](image-url)

**Figure 3.** Size distribution of the photometric sample of 41 extended Ly\( \alpha \) sources. Top: Histogram of the size defined by twice the half-light radius (HLR). Bottom: Size as a function of (roughly estimated) redshift. For both panels, colors correspond to the bands where we detected the Ly\( \alpha \) emission. In the bottom panel, the horizontal error bars indicate the bandwidths of the IA bands, and the vertical error bar shows the minimum and maximum value.

### TABLE 1

**Photometric Properties of the VIMOS Spectroscopic Sample**

| Object ID       | \( \alpha \) (J2000) | \( \delta \) (J2000) | Ly\( \alpha \) Band | Ly\( \alpha \) mag(2") | Ly\( \alpha \) mag(auto) | Continuum Band | Continuum mag(2") |
|-----------------|---------------------|---------------------|---------------------|----------------------|------------------------|-----------------|-------------------|
| IB08–86220      | 2 18 28.34          | -5 18 12.2          | IA527              | 25.76                | 25.40                  | R               | 26.51             |
| IB10–17108      | 2 16 58.05          | -5 34 19.2          | IA574              | 25.07                | 24.83                  | R               | 25.65             |
| IB10–32162      | 2 16 56.90          | -5 30 29.7          | IA574              | 25.22                | 24.90                  | R               | 25.98             |
| IB10–54185      | 2 17 59.49          | -5 25 07.5          | IA574              | 25.61                | 25.13                  | R               | 26.44             |
| IB10–90651      | 2 17 43.35          | -5 16 12.4          | IA574              | 25.84                | 25.50                  | R               | 27.75             |
| IB11–59167      | 2 17 10.21          | -5 23 47.5          | IA598              | 25.80                | 25.54                  | \( ` ` \)         | 27.59             |
| IB11–80344      | 2 17 44.70          | -5 18 15.3          | IA598              | 25.53                | 25.24                  | \( ` ` \)         | 27.03             |
| IB11–89537      | 2 17 45.30          | -5 15 53.6          | IA598              | 25.80                | 25.52                  | \( ` ` \)         | 27.59             |
| IB12–21989      | 2 17 13.35          | -5 32 56.6          | IA624              | 25.71                | 25.06                  | \( ` ` \)         | 25.88             |
| IB12–30834      | 2 17 55.98          | -5 30 53.4          | IA624              | 25.82                | 25.71                  | \( ` ` \)         | 27.09             |
| IB12–48320      | 2 16 55.89          | -5 26 37.1          | IA624              | 25.82                | 25.35                  | \( ` ` \)         | 27.35             |
| IB12–58572      | 2 17 49.10          | -5 24 11.6          | IA624              | 25.97                | 25.32                  | \( ` ` \)         | 26.82             |
| IB12–71781      | 2 17 38.96          | -5 20 58.1          | IA624              | 25.96                | 25.67                  | \( ` ` \)         | 26.77             |
| IB12–81981      | 2 18 14.72          | -5 18 32.5          | IA624              | 25.65                | 25.27                  | \( ` ` \)         | 27.84             |
| IB13–96047      | 2 18 13.33          | -5 15 05.4          | IA651              | 25.80                | 25.16                  | \( ` ` \)         | 25.97             |
| IB13–104299     | 2 18 21.09          | -5 13 25.2          | IA651              | 25.87                | 25.48                  | \( ` ` \)         | 27.45             |
| IB14–47257      | 2 18 1.96           | -5 25 25.3          | IA679              | 25.93                | 25.14                  | \( ` ` \)         | 26.29             |
| IB14–52102      | 2 18 00.12          | -5 24 10.6          | IA679              | 25.39                | 25.15                  | \( ` ` \)         | 26.33             |

\( ^{a} \) Coordinates are based on SXDS version 1 astrometry.

\( ^{c} \) Continuum-compact objects, which can be regarded as point-sources.

\( ^{f} \) Continuum-faint objects, which are fainter than 3 \( \sigma \) in continuum.
higher redshift bands. The diffuse emission at the outskirts becomes more difficult to detect, and the apparent sizes tend to become smaller. This is also suggested from Figure 2, in which the number of objects declines with redshift. True sizes may be larger than our estimation, and the size distribution may resemble that of M04’s LAB sample. Detailed simulations of such effects are presented in Paper I.

From the sample of 41 photometrically selected objects, we selected 21 objects for further follow-up spectroscopy, as described below. About a half of them (11 objects) are continuum-compact objects, and the other half (10 objects) are continuum-faint objects. As noted below, we could not obtain spectra for three objects: IB11−101786 (continuum-faint), IB13−62009 (continuum-faint), and IB14−62116 (continuum-compact). Excluding these three, we obtained a spectroscopic sample of 18 objects (10 continuum-compact and 8 continuum-faint objects). Photometric properties of the 18 objects are briefly summarized in Table 1, and their images are shown in Figure 4. Seven of them...
were spectroscopically confirmed to be high-$z$ Ly$\alpha$ emitters in our previous study (Paper I).

3. VIMOS SPECTROSCOPY

3.1. Observations

We used the VIMOS mounted on the 8.2 m Very Large Telescope (VLT) UT3 “Melipal” to take deep spectra for the objects selected above, under program ID 074.A-0524. The observations were made during three dark nights in the visitor mode run on 2004 November 6 to 9 (UT). Two masks were used in multiobject spectroscopy (MOS) mode of VIMOS, covering the 21 objects. Two of them, IB11–101786 and IB13–62009, were too faint to be detected with the current depth of our spectroscopy. For another object, IB14–62116, the Ly$\alpha$ line was almost completely overlapped with a strong sky emission line that could not be correctly subtracted. We thus obtained spectra for 18 objects. In this run, the HR-orange grism and the GG435 order-cut filter were used. This setting gives a spectral resolution $R = \lambda/\Delta \lambda \approx 2160$ ($\Delta \lambda \approx 2.8 \, \text{Å}$ at $\lambda = 6000 \, \text{Å}$) with a 1.0″ wide slit. This spectral resolution corresponds to a velocity resolution of $\approx 140 \, \text{km s}^{-1}$. The wavelength coverage is typically 5000–6800 Å, above which
there are many sky emission lines, and the correct sky subtraction is quite difficult.

VIMOS has a wide field of view (FoV), consisting of four quadrants of \(\sim 7' \times 8'\) each, which can cover about 1/3 of a single Suprime-Cam FoV. The sky distribution of our objects and the VIMOS FoV are shown in Figure 5. The two MOS masks cover 10 and 8 objects, respectively. The integration time was 9.5 and 8.0 hr, respectively. During this run, the shutter unit for the second (northeastern) quadrant often did not work correctly, and several exposures (30 minutes each) were lost. As a consequence, the integration time for each quadrant ranges from 6.5 to 9.5 hr. The seeing size varied during the three nights from \(\leq 0.5''\) to \(\sim 2.4''\). We excluded from the analysis the frames with seeing worse than \(\sim 1.0''\), so that the effective integration times of objects range from 4.0 to 7.0 hr. We took several standard star frames during the run. Since the accuracy of flux calibration is dependent primarily on the weather condition of the frame, we selected those with the best condition. The frames used for
the calibration were taken at the end of the run. The standard star we used was LTT 3864, an F dwarf located at $\alpha = 10^h32^m13.90^s$, $\delta = -35^\circ37'42.4''$ (J2000).

3.2. Primary Reduction and Flux Calibration

The primary reduction was made with the VIMOS pipeline recipes 1.0 provided by ESO. This software package performs flat-fielding, distortion correction, wavelength calibration, and sky subtraction. The spectral resolution was measured to be $R \approx 2200$ using the sky emission lines. This resolution is sufficient to resolve the Ly$\alpha$ line profiles of our objects, which are known to have velocity widths less than several $\times 10^2$ km s$^{-1}$ (see § 4.2 of Paper I). After primary reduction using the VIMOS pipeline, we performed flux calibration and further analysis using our private software. For the two-dimensional spectra, we smoothed the data with Gaussian kernel with FWHM of $4 \times 5$ pixels, which corresponds to 3.22 Å (wavelength axis) $\times 1.0''$ (spatial axis). To measure the fluxes and the velocity width on the one-dimensional spectra, we used 5 pixel smoothing, roughly corresponding to the current spectral resolution. We then measured the central wavelengths, fluxes, and velocity widths of the Ly$\alpha$ lines. The spectra thus obtained are shown in Figure 6.

3.3. Flux and Velocity Width of the Ly$\alpha$ Line

The Ly$\alpha$ fluxes were calculated by correcting for the fraction of their line fluxes collectible with the 1.0'' wide slitlets (slit-loss correction). Although a similar correction was applied for the previous data presented in Paper I, we here made the correction more carefully than in Paper I, in order to put tight constraints on the Ly$\alpha$ fluxes. The slit-loss correction was made using the following procedure for a combination of photometric and spectroscopic data. We first assumed that (1) the intrinsic continuum spectra are flat within the bandpass of the IA filters, and (2) the continuum levels are equal to that measured with the broad band redward of the Ly$\alpha$ line. Then we calculated the effect of the IGM absorption to the continuum using the redshift information obtained with the spectroscopy by following the formulation of Madau (1995). The pure Ly$\alpha$ line fluxes can be estimated by subtracting the continuum contribution from the IA photometry. We made this estimation of the total flux within an automatic aperture defined by SExtractor 2.1.6 (Bertin & Arnouts 1996) as MAG$_{AUTO}$, $F_{\text{total}}$, and the flux within the slit we used, $F_{\text{slit}}$. The fraction of the collectible flux was then estimated by taking the ratio of the flux values measured with both apertures, i.e., the slit-loss correction was applied by multiplying the line fluxes (from spectra) with $F_{\text{total}}/F_{\text{slit}}$.

The Ly$\alpha$ line fluxes thus obtained, $F(\text{Ly} \alpha)$, are shown in Table 2, together with the values before the slit-loss correction. The errors listed in Table 2 are estimated by integrating the 1 σ noise level of the spectra over the range over which we integrated the flux of the Ly$\alpha$ line.

The Ly$\alpha$ line luminosities were directly calculated from these flux values by using the redshifts obtained spectroscopically. We fitted a Gaussian function to the line profile of each object, and defined the line center as the central wavelength of the Gaussian. Then we determined the redshift from the wavelength of the line center, and calculated the luminosity, $L(\text{Ly} \alpha)$, from the flux and the luminosity distance at the redshift. The velocity widths (FWHM) were measured simultaneously by using the redshifts obtained by the Gaussian fitting. We defined the zero velocity as the line center described above, and calculated the line-of-sight velocities of the wavelengths at which the flux density becomes half of the peak value. The upper and lower limits of the FWHM were estimated by measuring the full velocity widths at (half maximum) $\pm 1$ σ.

3.4. Equivalent Width of the Ly$\alpha$ Line

Since most of our objects do not show any continuum emission, we cannot obtain their EWs solely from the spectral data. Instead, we used the photometric data (broad band redward of the Ly$\alpha$ line) to estimate the continuum flux densities. The continuum flux densities were estimated using a 2'' diameter aperture. Since we measure the EWs using the total flux of the Ly$\alpha$ line, this may cause an underestimate of the UV flux densities. For continuum-compact objects, this does not affect the results, since the spatial extent is small enough. For continuum-faint objects, the spatial extents are generally larger than the PSF size (see Fig. 2 of Paper I), and thus we must keep in mind the underestimation. However, they are fairly faint in continuum (< 3 σ), and the measurement of their size is not so reliable. This implies that using a larger aperture does not always give reasonable results, and makes the measurement more sensitive to the sky fluctuation.

We then divided the Ly$\alpha$ line fluxes obtained spectroscopically (slit-loss corrected) with the continuum fluxes obtained photometrically. Their rest-frame EWs, $\text{EW}_{\text{rest}}$, are also shown in Table 2. All the objects in our sample have fairly large EWs, with a median value of $\text{EW}_{\text{rest}} \approx 210$ Å. For 9 out of 18 objects, the $\text{EW}_{\text{rest}}$ exceeds 200 Å. Eight out of these nine objects are continuum-faint objects, having yet larger EWs, exceeding 240 Å, i.e., all of the continuum-faint objects in our VIMOS sample have large EWs. Another object with $\text{EW}_{\text{rest}} > 200$ Å, IB12–58572, is a continuum-compact object, but its continuum level is the lowest among all the continuum-compact objects in our VIMOS sample ($\sim 3.5$ σ). We plot the EWs as a function of the Ly$\alpha$ line luminosity in Figure 7. The nine objects with $\text{EW}_{\text{rest}} > 200$ Å apparently show a positive correlation between the luminosity and the EW. This is thought to be an artifact caused by the detection limits in the redward continuum bands. For the remaining nine objects, our measurement of the EWs is somewhat more accurate than for objects with large EWs, since the continuum levels exceed 3.7 σ.

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1 The spectrum of this standard star was obtained from the ESO website, http://www.eso.org/sci/observing/tools/standards/spectra/

2 See http://www.eso.org/instruments/vimos/.
Fig. 6.—Spectra taken with VIMOS. For each object, the three panels show the line profile, the residual of the Gaussian fitting, and the two-dimensional spectrum (from top to bottom). In the top panel, the solid curve shows line profile, the dotted curve shows sky spectrum scaled to 1/100, and the vertical dotted lines show central wavelength and ±1 σ of the Gaussian function fitted to the line profile. The Gaussian function is shown with the dashed curve.
Fig. 6—Continued
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**TABLE 2**

**Spectral Properties**

| Object ID     | \( \lambda_c \) \(^{\text{a}} \) (Å) | \( z \) | \( F(\text{Ly}\alpha) \) \( \times 10^{-17} \text{ergs cm}^{-2} \text{s}^{-1} \) | \( L(\text{Ly}\alpha) \) \( \times 10^{32} \text{ergs s}^{-1} \) | \( \Delta V \) (FWHM) \( \text{km s}^{-1} \) | \( EW_{\text{rest}} \) (Å) | Wing |
|---------------|---------------------------------|------|------------------------------------------|----------------------------------------|----------------------------------|-----------------|------|
| IB08–86220    | 5234                            | 3.31 | 3.3(1.9) ± 0.3                          | 3.3 ± 0.5                              | 399.55                          | 121±34          | ...  |
| IB10–17108    | 5824                            | 3.79 | 7.6(4.2) ± 0.7                          | 10 ± 2                                 | 472.20                          | 112±19          | red  |
| IB10–32162    | 5761                            | 3.74 | 7.4(3.6) ± 0.6                          | 9.7 ± 1.7                              | 598.35                          | 149±39          | red  |
| IB10–54185    | 5864                            | 3.82 | 4.2(2.1) ± 0.4                          | 6.5 ± 1.3                              | 260.33                          | 128±25          | red  |
| IB10–90651    | 5691                            | 3.68 | 8.3(4.4) ± 1.9                          | 11 ± 2                                 | 556.34                          | 867±110         | red  |
| IB11–59167    | 6006                            | 3.94 | 2.2(1.2) ± 0.3                          | 3.4 ± 0.8                              | 234.47                          | 265±17          | red  |
| IB11–80344    | 5950                            | 3.89 | 7.9(3.5) ± 0.8                          | 11 ± 3                                 | 723.60                          | 569±39          | red  |
| IB11–89537    | 6115                            | 4.03 | 5.3(2.9) ± 0.5                          | 8.4 ± 1.4                              | 537.59                          | 458±40          | red  |
| IB12–21989    | 6212                            | 4.11 | 7.7(3.7) ± 0.7                          | 13 ± 2                                 | 432.97                          | 184±34          | red  |
| IB12–30834    | 6217                            | 4.11 | 4.9(2.6) ± 0.5                          | 8.0 ± 1.4                              | 411.94                          | 357±35          | red  |
| IB12–48320    | 6124                            | 4.04 | 3.4(1.5) ± 0.4                          | 5.3 ± 1.2                              | 288.50                          | 318±34          | red  |
| IB12–58572    | 6129                            | 4.04 | 3.6(1.3) ± 0.5                          | 5.7 ± 2.0                              | 373.60                          | 208±118         | red  |
| IB12–71781    | 6208                            | 4.11 | 2.5(1.4) ± 0.6                          | 4.1 ± 1.8                              | 255.91                          | 134±35          | red  |
| IB12–81981    | 6224                            | 4.12 | 3.4(1.9) ± 0.4                          | 5.7 ± 1.1                              | 352.32                          | 500±149         | red  |
| IB13–96047    | 6592                            | 4.27 | 5.4(2.0) ± 0.5                          | 10 ± 3                                 | 325.37                          | 135±34          | red  |
| IB13–104299   | 6410                            | 4.42 | 3.2(2.0) ± 0.4                          | 5.7 ± 1.2                              | 218.23                          | 303±36          | red  |
| IB14–47257    | 6878                            | 4.66 | 5.6(2.0) ± 0.8                          | 13 ± 5                                 | 293.84                          | 177±36          | red  |
| IB14–52102    | 6647                            | 4.47 | 4.5(2.5) ± 0.3                          | 9.0 ± 1.2                              | 324.36                          | 152±33          | red  |

\(^{\text{a}}\) Wavelength of the line center.

\(^{\text{b}}\) Values before slit-loss correction are shown in parentheses.
The upper and lower limits for the EWs are estimated as follows. Since the denominators in the calculation of EWs are very small values, the errors in EWs are dominated by the photometric noise level. The errors in EWs are estimated from

\[ \text{EW}_{\text{upper}} = \frac{F(\text{Ly}\alpha) + \text{err}[F(\text{Ly}\alpha)]}{f_z + \text{err}[f_z]}, \]

and

\[ \text{EW}_{\text{lower}} = \frac{F(\text{Ly}\alpha) - \text{err}[F(\text{Ly}\alpha)]}{f_z + \text{err}[f_z]}, \]

where \( F(\text{Ly}\alpha) \) is the \( \text{Ly}\alpha \) line flux, \( f_z \) is the continuum flux density, and \( \text{err}[\cdot] \) denotes the 1 \( \sigma \) noise level.

Note that our measurements of EW are likely to underestimate the intrinsic value, since we did not make any correction for the IGM absorption of the \( \text{Ly}\alpha \) emission.

### 3.5. Wing Component Analysis

Although most of our objects have relatively small velocity widths, some objects have broad wing emission of the \( \text{Ly}\alpha \) line. The \( \text{Ly}\alpha \) line profile of IB10–90651, for example, has broad wing emission on the red side, while the blue side shows a relatively sharp cutoff. Such features of the line profile must reflect the kinematics of \( \text{Ly}\alpha \)-emitting gas, and should act as a diagnostic of inflow/outflow activities in the system. In order to identify such high-velocity wing components in the \( \text{Ly}\alpha \) line profiles, we performed a quantitative analysis for all the objects in our spectroscopic sample. To clearly identify such faint wing components, we needed to have spectra of sufficiently high S/N. We therefore used 8 pixel smoothing, after integrating the spectra along the slit direction. Although the 8 pixel smoothing reduces the spectral resolution to \( \sim 8 \) \( \text{Å} \), this resolution is still high enough to investigate the gas dynamics with the line profile.

The procedure of the analysis is similar to that described in §3.3, except for the smoothing width of 8 pixels. After obtaining improved S/N by smoothing the one-dimensional spectra, we fitted a simple Gaussian function to the \( \text{Ly}\alpha \) line profile of each object. We then plotted the excess of the spectrum from the Gaussian function against the line-of-sight velocity. If the excess of the spectrum greater than 2 \( \sigma \) has a velocity width greater than 250 km s\(^{-1}\) (corresponds to the smoothing width), we here refer to it as the “excess.” If the excess appears from within the 2 \( \sigma \) width of the Gaussian peak and continues beyond \( \pm 500 \) km s\(^{-1}\) from the line center, we define it as “wing emission.” The plots thus obtained are shown in the middle panel of Figure 6, and the results are also summarized in Table 2. For at least five objects, IB10–17108, IB10–32162, IB10–54185, IB10–90651, and IB14–52102, we identified high-velocity wing emission on the red side of the \( \text{Ly}\alpha \) line. On the other hand, none of our objects shows significant wing emission on the blue side. Just two objects, IB12–30834 and IB12–58572, marginally show a blue wing.

### 4. RESULTS AND DISCUSSION

Summarizing the results obtained in the previous section, we categorize our objects according to spectral properties. We can classify our objects in two ways, i.e., in terms of EW and wing emission in the line profile. In terms of EW, we divide our VIMOS sample into two classes. The moderate EW class has 100 < EW < 200 \( \text{Å} \), while the large EW class has EW > 200 \( \text{Å} \) (see Fig. 7). The value of EW = 200 \( \text{Å} \) is fairly large for ordinary starbursts. The large EW class and the small EW class roughly correspond to continuum-compact objects and continuum-faint objects, respectively. In terms of the line profile, we may also classify our objects into two groups, i.e., those with broad asymmetric wing on the red side, and those with no clear signature of such wing emission. For no classes could we find any significant correlation between the spatial extent and the luminosity, the spatial extent and the velocity width, or the spatial extent and the EW.

#### 4.1. Objects with Moderate EWs

The nine objects in the smaller EW group, IB08–86220, IB10–17108, IB10–32162, IB10–54185, IB12–21989, IB12–71781, IB13–96047, IB14–47257, and IB14–52102, have EWs ranging from 100 to 200 \( \text{Å} \). This EW range is the regime of stellar photoionization with a solar metallicity, an upper mass cutoff of 100 \( M_\odot \), and an IMF slope up to 1.5 (Charlot & Fall 1993). The \( \text{Ly}\alpha \) emission of these objects thus can be explained in terms of photoionization by moderately old (\( \sim 10^8 \) yr) stellar populations, not necessarily requiring an extremely top-heavy IMF or a zero metallicity. The most conservative explanation for these objects is thus ordinary starbursts. The large spatial extent of \( \text{Ly}\alpha \) emission can be understood as a result of resonant scattering of \( \text{Ly}\alpha \) photons (e.g., Möller & Warren 1998; Laursen & Sommer-Larsen 2007).

Assuming that the dominant ionizing sources for these objects are ordinary starbursts, we can give rough estimates of the star formation rates (SFRs) of these objects. We here assume Salpeter’s IMF, a stellar mass range of 0.1–100 \( M_\odot \), solar metallicity, no extinction, and case B recombination in the low-density limit (\( N_e < 1.5 \times 10^4 \) cm\(^{-3}\)). We can then use a conversion law of \( L(\text{Ly}\alpha) = 1 \times 10^{37} \text{~(SFR}/M_\odot \text{~yr}^{-1} \text{~ergs s}^{-1}) \) to estimate their SFRs (Osterbrock 1989; Kennicutt 1998). Their SFRs thus estimated are 3.3–13 \( M_\odot \text{~yr}^{-1} \), which is within the SFR range of normal
LAEs known to date (e.g., Fynbo et al. 2003; Rhoads et al. 2003; Dawson et al. 2004).

However, their physical nature, even the SFR, is poorly constrained because of the large uncertainties in dust/IGM absorption, stellar IMF, and the contribution from nonstellar processes. Some of the objects in this class indeed show asymmetric line profiles, suggesting superwind activities (see § 4.2 below). The possible existence of AGNs, although unlikely, also cannot be ruled out completely. Notes for individual objects in this group are summarized in Appendix A.1.

4.2. Objects with Broad Asymmetric Wings

As described in § 3.5, five objects, IB10—17108, IB10—32162, IB10—54185, IB10—90651, and IB14—52102, have asymmetric broad wing emission on the Ly\(\alpha\) line profile. These objects have conspicuous high-velocity wing components on the red side, and a relatively sharp cutoff on the blue side of the Ly\(\alpha\) line. Their wing emission components are extended up to \(\gtrsim 500\) km s\(^{-1}\) from the line centers, and no clear counterparts are found on the blue side. The origin of such asymmetry, which is commonly seen in high-\(z\) Ly\(\alpha\) emission, is thought to be either absorption by intervening neutral hydrogen (Lyman forest absorption), or galactic superwind. Although these two mechanisms cannot be definitely discriminated, the spectra of these five objects show some evidence that favor the existence of superwind activities, as described below.

No significant continuum emission is detected in any of the 18 objects in our sample. Only one object, IB12—21989, shows a marginal signature of continuum emission with \(\sim 2\) \(\sigma\) level of the sky fluctuation, but this object does not have the red wing. This implies that the contribution of the continuum to the wing components we identified is negligible, and there should be a high-velocity Ly\(\alpha\) emission component within the systems. An asymmetric line profile with a broad red wing and a sharp blue cutoff is commonly seen in superwind galaxies (e.g., Ajiki et al. 2002; Dawson et al. 2002), and well agrees with theoretical predictions of the superwind model (Tenorio-Tagle et al. 1999).

In fact, one of these five objects with red wings, IB10—90651, shows a systematic velocity structure in the two-dimensional spectrum (bottom panel of Fig. 6). This object has an extremely extended, diffuse emission component on the red side of the Ly\(\alpha\). It extends up to 5\(\arcsec\) (projected distance of 36 kpc at \(z = 3.68\)) to the south from the center of the object, and the velocity extent is \(\sim 1000\) km s\(^{-1}\) redward from the line center. On the blue side, although fairly faint, we can see a counterimage of the diffuse component extending north to an extent similar to the south component. These velocity structures suggest that this object has a galactic superwind flowing nearly along the slit position angle. The faintness of the blue component can be explained in terms of absorption by the near-side shell of HI gas, while the flux of the red component is enhanced by back-scattering by the far-side shell (Tenorio-Tagle et al. 1999).

Among the five objects with a broad asymmetric wing, IB10—90651 is the only object classified into the continuum-faint subsample. It has the highest EW, the largest velocity width, and the largest spatial extent of the five objects in this group. This may suggest that IB10—90651 is somewhat different from the other four objects. However, all five objects show similar asymmetric line profiles in the one-dimensional spectra. Even for the IB10—90651, which has a diffuse blueshifted component in the two-dimensional spectrum, we cannot see wing emission on the blue side of the Ly\(\alpha\) line. This suggests that all five objects in this group are likely to be superwind galaxies. The fraction of such objects in our whole VIMOS sample, 5/18 \(\sim 30\%\), is quite similar to submillimeter detections in M04’s sample (Geach et al. 2005). Such submillimeter detection suggests the existence of an obscured starburst region responsible for Ly\(\alpha\) emission, and thus suggests the superwind scenario. The difference in the continuum brightness can be attributed to the difference in the dust contents, i.e., IB10—90651 is likely to have the most heavily obscured starburst region.

The lack of diffuse and extended high-velocity components in the four objects other than IB10—90651 may suggest three possibilities. One is that the position angle of the outflow is perpendicular to the slit direction, and our spectroscopic data cannot detect the outflow lobes. This should be examined by further deep spectroscopy with various slit directions or an integral field spectroscopy. If they indeed have superwind activities, the outflow lobes should be detected with sufficiently deep spectroscopy along other position angles. The second possibility is that the Ly\(\alpha\) emission of the four objects other than IB10—90651 is intrinsically faint. This scenario is quite consistent with the relatively small EWs of the four objects compared with IB10—90651. If the superwind activities are weak compared with IB10—90651, the contribution of the outflow to the Ly\(\alpha\) emission must also be weaker, and therefore the EWs are relatively small. The third possibility is observational bias due to the sky emission lines. The wavelengths near 5700 Å are free from strong sky emission lines, and therefore we can detect very diffuse emission components seen in IB10—90651, while the data of other four objects do not have such a high S/N. When we obtained the one-dimensional spectra, we integrated the spectra along the slit direction so as to include all the emission components. This leads to the relatively large velocity width of IB10—90651, for which we detected very extended diffuse components in its two-dimensional spectrum.

Note that there are some other objects that possibly have red side wings, e.g., IB12—81981 (\(\sim 1.5\) \(\sigma\) up to \(\sim 400\) km s\(^{-1}\)). However, the wing components of such objects, if any, are fairly faint, and are affected by neighboring sky emission lines in most cases. If they indeed have wing emission on the red side, they are also likely to have superwind activities within the systems. Other notes for each object are listed in Appendix A.2

4.3. Objects with Large EWs and No Wings

After classifying our objects in two ways, there remains eight objects that have large EWs and no significant wing emission on the red side of the Ly\(\alpha\) line: IB11—59167, IB11—80344, IB11—89537, IB12—30834, IB12—48320, IB12—58572, IB12—81981, and IB13—104299. Except for one, IB12—58572, they are all continuum-faint objects (see § 2) with EW\(_{\text{rest}} > 240\) Å. The EW of 240 Å is predicted for the starbursts with solar metallicity at an age of \(10^6\) yr by Charlot & Fall (1993), and also by MR02 by introducing an extremely top-heavy IMF (slope = 0.5) or zero metallicity, for starbursts with an age of \(\sim 10^7\) yr. As mentioned above in § 3.4, the observed EWs should be smaller than intrinsic values due to the absorption of Ly\(\alpha\) emission by the IGM. Namely, the seven continuum-faint objects have EWs securely exceeding 240 Å.

For these eight sources, the origin of the Ly\(\alpha\) emission is hardly thought to be ordinary starbursts. If their ionizing sources are starbursts, the large EWs would require photoionization by extremely young stellar populations (age \(\ll 10^7\) yr) with an extremely top-heavy IMF and/or very low metallicity. In this case, the stellar components should be dominated by Population III stars. Calculations by MR02 show that a stellar population with zero metallicity and Salpeter’s IMF can achieve an extremely large EW, 1122 Å at an age of \(10^6\) yr. Schaerer (2003) also suggests by treating various IMFs and stellar mass ranges that, under very metal-poor conditions, the EWs of Ly\(\alpha\) emission from very
young starbursts can be highly enhanced, ~1300 Å at an age of 10^6 yr. In this picture, the extended Lyα emission can be attributed to resonant scattering. In addition, it is thought that cooling radiation or supernova explosions also contribute to the Lyα emission, at least in some part.

As for the starbursts, it is also possible that the starburst regions are heavily obscured by dust with a somewhat inhomogeneous distribution. If the dust screen absorbs UV photons traveling along the line of sight, the observed faintness in the UV continuum can be reproduced. Then if UV photons traveling along other directions are not significantly absorbed, they can ionize the H I gas surrounding the starburst region. The Lyα photons from the ionized H I gas can then be resonance scattered, and can lead to spatially extended Lyα emission. Since UV continuum emission cannot be scattered in this manner, these processes can at least qualitatively explain the extended Lyα emission and faint/compact UV continuum emission. This is thought to be a plausible explanation because galaxies at high redshifts are generally surrounded by a larger amount of H I gas than galaxies in the present universe (e.g., Adelberger et al. 2003). The Lyα-emitting gas will be spatially more extended than the starburst region, and thus less sensitive to dust absorption.

If the dust screen covers the whole direction, even Lyα photons cannot escape the system. Instead, the star-forming activities can lead to shock ionization by a superwind (e.g., Taniguchi & Shioya 2000; Taniguchi et al. 2001; Veilleux et al. 2005). However, we could not detect significant high-velocity components in the Lyα line profiles, nor in the two-dimensional spectra. If superwind activities are responsible for the extended Lyα emission for these objects, the shocked region associated with the wind, if any, should be too faint to be detected in our VIMOS spectroscopy. Their relatively small velocity widths of the Lyα line, typically ~300–500 km s^{-1} in FWHM, also suggests that powerful superwinds are unlikely. The exception is two objects, IB11–80344 and IB11–89537, which have relatively large velocity widths, up to ~740 km s^{-1}. These objects might be superwinds, but have smaller velocity widths than the most prominent ones known to date (e.g., ~10^3 km s^{-1}, Heckman et al. 1990). In addition, note that there are some objects that have a marginal signature of wing emission on the red side of the Lyα, e.g., IB12–48320 and IB12–81981. The red-side spectra of these objects are overlapped by relatively strong sky emission lines that cannot be subtracted completely. If a deeper exposure and/or a more sufficient sky subtraction become available, we could possibly detect a high-velocity wing component in the line profile for some objects.

Apart from such uncertainties, the eight objects show a remarkable feature. Figure 8 plots the velocity width as a function of the Lyα line luminosity. If the ionizing mechanism is cold accretion, the velocity width will roughly correspond to the circular velocity of the system, and thus will be scaled to the mass of the system. On the other hand, the Lyα luminosity should be positively correlated with the gravitational energy of the system, and thus scaled to the mass of the system. Therefore, the velocity width and the Lyα line luminosity should have a positive correlation. Among all the objects in our VIMOS sample, the eight objects with large EWs and no wings clearly show a positive correlation. Among the eight objects, the eight objects show a relatively tight correlation between the luminosity and the velocity width. Although not a definite constraint, this result supports the idea of cold accretion. Their relatively small velocity widths also agree well with a theoretical prediction of cooling radiation (Fardal et al. 2001). Even for the two objects with relatively large velocity widths (ΔV > 500 km s^{-1}), these velocity widths can be reproduced by taking into account the effect of resonant scattering, or perhaps an additional ionizing source in the system (Dijkstra et al. 2006a, 2006b).

Furthermore, there is another marginal feature that agrees with the prediction of Dijkstra et al.; at least two objects (e.g., IB12–58572 and IB12–104299) show an odd asymmetry of the line profile, i.e., slightly broader on the blue side than on the red side, unlike typical Lyα emission at high redshifts. Thus, cold accretion...
can be a reasonable explanation for these eight objects. It is also true that other mechanisms contribute to the \( \text{Ly}\alpha \) emission, together with cold accretion. Such additional mechanisms are discussed in § 4.4. Notes for individual objects are described in Appendix A.3.

### 4.4. Constraints from Other Data

We have mentioned about four possibilities for the origins of the spatially extended \( \text{Ly}\alpha \) emission: stellar photoionization, photoionization by AGNs, shock heating by superwinds, and cooling radiation from infalling material (cold accretion). These scenarios predict characteristic emission lines of each ionizing source. Since our VIMOS data do not have sufficiently wide spectral coverages to cover such emission lines, we reanalyzed the low-resolution spectroscopic data taken with FOCAS on Subaru Telescope (Paper I) to check whether the emission lines are detected. Each frame of FOCAS data is not deep enough for this purpose, so that we stacked all seven spectra to improve the S/N. We estimated the 1 \( \sigma \) upper limits for the fluxes of these lines relative to the \( \text{Ly}\alpha \) line from the photon-counting errors. The results are summarized in Table 3. In addition to our optical spectroscopic data, we used the X-ray data taken with \( \text{XMM-Newton} \) for diagnostics of the physical origins.

For starbursts, there are two cases described in § 4.3, i.e., extremely young starbursts dominated by Population III stars, and starbursts heavily obscured by dust. The former case of starbursts has an extremely low metallicity and a top-heavy IMF. Such an extremely young stellar population formed in primordial conditions should have He \( \equiv \lambda 1640 \) emission (Schaerer 2003). The He \( \equiv \) line is also predicted for the case of cooling radiation (Yang et al. 2006). While the \( \text{Ly}\alpha \) line is optically thick in general, this line should be optically thin. This implies that the He \( \equiv \) line is suitable for probing the gas dynamics, and thus a good probe to discriminate stellar photoionization and cooling radiation. However, none of our objects in the FOCAS spectroscopic sample has detectable He \( \equiv \) emission. On the composite spectrum, there is apparently an emission-like feature near the wavelength of rest-frame 1640 Å with an intensity of \( \sim 1/10 \) of the \( \text{Ly}\alpha \) (see Fig. 4 of Paper I). This is, however, just a marginal signature, since the wavelengths near the rest-frame 1640 Å are largely affected by sky emission lines. The emission-like signal is comparable to 1 \( \sigma \) noise level, and is slightly offset from 1640 Å. Therefore, we can only estimate the upper limit of the flux ratio, He \( \equiv /\text{Ly}\alpha \leq 0.2 \).

For the case of obscured starbursts, there should be characteristic metal lines, such as \([\text{O}] \equiv \lambda 3727, [\text{O}] \equiv \lambda 4959, 5007, \) and \( \text{H}\alpha \equiv \lambda 6563 \). These lines are less sensitive to dust absorption than the \( \text{Ly}\alpha \) line, and should be good diagnostics of starbursts, although they are redshifted beyond the wavelength coverage of our FOCAS data. Such metal lines can also be seen in superwind galaxies. The primordial gas surrounding galaxies should be chemically enriched by supernova explosions, resulting in spatially extended metal lines. Namely, superwind galaxies are expected to have spatially extended \( \text{C} \equiv \) line emission with a strength of \( \sim 1/10 \) of the \( \text{Ly}\alpha \) line (Heckman et al. 1991b). We showed in Paper I that there are no such metal emission lines either in the individual spectra or in the stacked spectrum, down to our current detection limits. This suggests that at least the majority of the FOCAS sample (seven objects) are unlikely to be superwinds. These pieces of evidence from the observations are, however, just weak constraints on the superwind scenario. In fact, IB10—90651 was proved to have extended diffuse emission components with an outflow-like velocity structure (see § 4.2) in our VIMOS spectroscopy. Further deep follow-up observations may also find diffuse emission components suggesting the superwind scenario for objects other than IB10—90651.

The \( \text{C} \equiv \) emission line, as well as \([\text{O}] \equiv \) or He \( \equiv \) lines, can also be diagnostics of AGN activities. Similarly to superwinds, the AGN scenario is likely to be ruled out by the absence of \( \text{C} \equiv \) or \([\text{O}] \equiv \) lines on the FOCAS spectra, although they are just weak constraints. The upper limits of the fluxes of \( \text{C} \equiv \) and \([\text{O}] \equiv \) lines are estimated to be 17% and 13% of the \( \text{Ly}\alpha \), respectively. Our IA images show that, although they are more extended than point sources, the sizes of \( \text{Ly}\alpha \) emission components are typically \( \sim 10–15 \) kpc, and are smaller than those of \( \text{Ly}\alpha \) nebulae associated with AGNs (e.g., Heckman et al. 1991a; Weidinger et al. 2004, 2005). The velocity widths of our objects are also shown by VIMOS data to be smaller than those of \( \text{Ly}\alpha \) nebulae associated with AGNs known to date (e.g., van Ojik et al. 1997; Reuland et al. 2003; Weidinger et al. 2004, 2005). Together with the faintness in the UV continuum, these facts suggest that if complex ionizing sources are AGNs, they must be obscured (type II) AGNs. In order to examine such AGN activities, it is important to compare them with type II AGNs known to date. Type II AGNs are, however, suggested to be quite rare by photometric studies of LAE samples (Malhotra et al. 2003; Wang et al. 2004). We will then just show the results of our analysis of X-ray data taken with \( \text{XMM-Newton} \).

Most of our field is covered by X-ray data with two pointings of \( \text{XMM-Newton} \) (Ueda et al. 2008), and the X-ray flux limits can be estimated by using these data. The sensitivity is sufficient to detect bright quasars at \( z \sim 4 \). In order to set the strongest constraints, we here used the data of 0.5–4.5 keV band, the most sensitive band of \( \text{XMM-Newton} \). We estimated the 1 \( \sigma \) flux limits in the rest-frame 2–10 keV from the count rate limits, by assuming X-ray spectra of \( F_{\gamma} \propto e^{-\gamma} \) and absorption with a hydrogen column density of \( N_{\gamma} = 1 \times 10^{23} \) cm\(^{-2} \) and \( N_{\gamma} = 1 \times 10^{24} \) cm\(^{-2} \). The flux limits thus estimated are listed in Table 4. The typical values of their flux limits in the case of \( N_{\gamma} = 1 \times 10^{23} \) cm\(^{-2} \) are a few \( \times 10^{-18} \) erg s\(^{-1} \) at \( z \sim 4 \). These are comparable to the X-ray luminosities of Type II QSOs known to date (Norman et al. 2002; Stern et al. 2002; Dawson et al. 2003). Our analysis ignores the reflection components of X-ray emission, so that the upper limits listed in Table 4 are thought to be the most conservative values, i.e., the X-ray luminosities are likely to be significantly smaller than those of type II QSOs. Note that we cannot set any constraints if our objects are Compton-thick, \( N_{\gamma} \gg 10^{24} \) cm\(^{-2} \). These imply that our objects are unlikely to be harboring Type II QSOs, although the possibility of AGNs is not completely ruled out due to the relatively shallow exposure of the X-ray data.

### 5. CONCLUSIONS

We have carried out deep, medium-resolution (\( R \sim 2000 \)) follow-up spectroscopy of 18 extended \( \text{Ly}\alpha \) sources at \( z \sim 3–5 \) that are faint and/or compact in the UV continuum, using VLT/VIMOS.

| Line     | \( X/\text{Ly}\alpha \) \(^a\) | Noise \(^b\) |
|----------|-------------------------------|-------------|
| \( \text{N} \equiv \lambda 1240 \) | 0.09 | 0.05 |
| \( \text{C} \equiv \lambda 1549 \) | 0.10 | 0.07 |
| \( \text{He} \equiv \lambda 15640 \) | 0.09 | 0.08 |

\(^a\) Line flux relative to the \( \text{Ly}\alpha \), measured by integrating the stacked spectrum.  
\(^b\) 1 \( \sigma \) noise of the relative flux estimated from the photon counting error.
and S/N of our data enabled us to make a quantitative analysis of the
components is
lactic superwind model. We found diffuse high-velocity emission
features agree quite well with theoretical predictions of the ga-
no significant wing emission was found on the blue side. Such
/C25
8
/C11
/C0
IB08-86220

—z = 3.31, SFR ≳ 3.3 M⊙ yr⁻¹, EW_rest ≳ 120 Å. Even the upper limit of EW does not exceed 200 Å. Our analysis
may suffer from relatively large residuals of the sky emission at ≳ 5225 s and ≳ 5240 Å.
IB10—17108. —z = 3.79, SFR ≳ 10 M⊙ yr⁻¹, EW_rest ≳ 110 Å. The EW is the smallest in our sample, and the uncertainty in the
EW is relatively small. Wing emission can be seen on the red side (see Appendix A.2).
IB10—32162.—z = 3.74, SFR ≳ 9.7 M⊙ yr⁻¹, EW_rest ≳ 150 Å. The upper limit of the EW is relatively large for this group of
objects, ≳ 180 Å. The velocity width is relatively large, ΔV ≳ 610 km s⁻¹ (FWHM). Wing emission can be seen on the red side (see Appendix A.2).

APPENDIX A

NOTES FOR INDIVIDUAL OBJECTS

A1. OBJECTS WITH MODERATE EWs

IB08—86220. —z = 3.31, SFR ≳ 3.3 M⊙ yr⁻¹, EW_rest ≳ 120 Å. Even the upper limit of EW does not exceed 200 Å. Our analysis
may suffer from relatively large residuals of the sky emission at ≳ 5225 s and ≳ 5240 Å.
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objects, ≳ 180 Å. The velocity width is relatively large, ΔV ≳ 610 km s⁻¹ (FWHM). Wing emission can be seen on the red side (see Appendix A.2).

We found that all 18 objects in our VIMOS sample have fairly large
equivalent widths (EWs) of the Lyα emission, with a median value of ≳ 210 Å in the rest frame. Half of our sample (nine objects) have
moderately large EWs of ≳ 100–200 Å, and can be accounted for
by ordinary starbursts with a solar metallicity. The high resolution
and S/N of our data enabled us to make a quantitative analysis of the
Lyα line profiles. The velocity widths we found are relatively
small, typically ≳ 300–500 km s⁻¹.

For five objects (≈ 30%), we identified conspicuous broad
wing emission components on the red side of the Lyα line, while
no significant wing emission was found on the blue side. Such features agree quite well with theoretical predictions of the gal-
actic superwind model. We found diffuse high-velocity emission
components extending up to ≳ 70 kpc in the two-dimensional
spectrum of one of these five objects. The velocity extent of these components is ≳ 2000 km s⁻¹ with systematic velocity structure,
i.e., the southern part is redshifted and the northern part is blue-
shifted. These features suggest the existence of galactic super-
wind activities.

Excluding the objects above, there remain eight objects that have large EWs exceeding 200 Å (seven have EWs exceeding
240 Å), and no clear signature of high-velocity wing emission on the either side of the Lyα line. These objects are hardly accounted for by ordinary starbursts, and our IA images and FOCAS spectra show no clear signature of AGN activities. Non-detection in X-ray data taken with XMM-Newton also suggests they are unlikely to be of AGN origin, like Type II QSOs. Their relatively small spatial extents and velocity widths agree well with theo-
retical predictions of cooling radiation. Furthermore, their velo-
city widths clearly show a positive correlation with the Lyα line luminosities. These facts suggest that they are candidates for
forming galaxies in gas-cooling phase, i.e., the very first stage of
galaxy formation.

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SPECTROSCOPY OF EXTENDED Lyα SOURCES

IB10−54185.—$z = 3.82$, SFR $\geq 6.5 \, M_\odot \, yr^{-1}$, $\Delta V \approx 130 \, km \, s^{-1}$. The velocity width is quite small, $\Delta V \approx 300 \, km \, s^{-1}$. Wing emission can be seen on the red side (see Appendix A.2).

IB12−21989.—$z = 4.11$, SFR $\approx 13 \, M_\odot \, yr^{-1}$, $\Delta V \approx 180 \, A$. Continuum emission can be seen at the $\approx 1.5 \, \sigma$ level, and the EW calculated directly from the spectrum is $\approx 35 \, A$. Our photometry may suffer from neighboring continuum sources.

IB12−71781.—$z = 4.11$, SFR $\approx 4.1 \, M_\odot \, yr^{-1}$, $\Delta V \approx 130 \, A$. The upper limit of the EW is fairly large, $\approx 230 \, A$, so that this object is possibly not categorized as an ordinary starburst. Our analysis may suffer from the several sky emission lines on the red side of the Lyα (e.g., $\approx 6235 \, A$).

IB13−96047.—$z = 4.27$, SFR $\approx 10 \, M_\odot \, yr^{-1}$, $\Delta V \approx 140 \, A$. Even the upper limit of the EW does not exceed 200 $\, A$. Our spectral analysis may suffer from several neighboring sky emission lines on both sides of the Lyα. Neighboring continuum sources may affect our photometric analysis.

IB14−47257.—$z = 4.66$, SFR $\approx 13 \, M_\odot \, yr^{-1}$, $\Delta V \approx 180 \, A$. With an upper limit of EW $\approx 240 \, A$, this object not be an ordinary starburst. The spectrum suffers from relatively strong residuals of the sky emission at $\approx 6865, 6900,$ and $6910 \, A$ near the Lyα line. The Lyα line itself is overlapped with weak sky emissions.

IB14−52102.—$z = 4.47$, SFR $\approx 9.0 \, M_\odot \, yr^{-1}$, $\Delta V \approx 150 \, A$. With an upper limit of EW $\approx 200 \, A$, this object may not be an ordinary starburst. The line profile has wing emission on the red side (see Appendix A.2).

A2. OBJECTS WITH BROAD ASYMMETRIC WINGS

IB10−17108.—$z = 4.11$, $\Delta V \approx 490 \, km \, s^{-1}$. Also listed in Appendix A.1. The wing component is very clear, and extended up to $\approx 700 \, km \, s^{-1}$ from the line center.

IB10−32162.—$z = 3.74$, $\Delta V \approx 150 \, A$, $\Delta V \approx 610 \, km \, s^{-1}$. Also listed in Appendix A.1. The velocity width of the main component is fairly large, $\approx 610 \, km \, s^{-1}$. The wing component is not very clear, but the line profile shows a significant asymmetry.

IB10−54185.—$z = 3.82$, $\Delta V \approx 130 \, A$, $\Delta V \approx 300 \, km \, s^{-1}$. Also listed in Appendix A.1. The spectrum may suffer from sky emission lines on the red side ($\approx 5890 \, A$ and a weak one at $\approx 5870 \, A$), but the red side wing exceeds the $3 \, \sigma$ noise level at $\approx 450 \, km \, s^{-1}$ from the line center. The wing component can be seen up to $\approx 600−1000 \, km \, s^{-1}$.

IB10−90651.—$z = 3.68$, $\Delta V \approx 860 \, A$, $\Delta V \approx 570$. The EW is the largest in our sample. The wing emission is extended up to $\approx 500 \, km \, s^{-1}$. A systematic velocity structure of diffuse emission can be seen in the two-dimensional spectrum.

IB14−52102.—$z = 4.47$, $\Delta V \approx 150 \, A$, $\Delta V \approx 350 \, km \, s^{-1}$. Also listed in Appendix A.1. The wing component exceeds the $3 \, \sigma$ noise level, and is extended up to $\approx 500 \, km \, s^{-1}$.

A3. OBJECTS WITH LARGE EW AND NO WINGS

IB11−59167.—$z = 3.94$, $\Delta V \approx 270 \, km \, s^{-1}$. A systematic (outflow-like) velocity structure may exist, but the spectrum may suffer from incomplete sky subtraction at $\approx 6000 \, A$.

IB11−80344.—$z = 3.89$, $\Delta V \approx 569 \, A$, $\Delta V \approx 740 \, km \, s^{-1}$. The lower limit of the EW is $\approx 380 \, A$. The velocity width is large, and the line profile has a double-peaked shape. This fairly symmetric double-peaked profile with a peak separation of $\approx 5 \, A$ may suggest that this object is an [O II] emitter at $z \approx 0.6$. However, the EW would be $\approx 1700 \, A$ in the rest frame, which is far greater than known [O II] emitters. Thus, we conclude that this object is a Lyα emitter.

IB11−89537.—$z = 4.03$, $\Delta V \approx 460 \, A$, $\Delta V \approx 560 \, km \, s^{-1}$. The lower limit of the EW is $\approx 300 \, A$. Wing emission on the red side may exist. The spectrum may suffer from a neighboring continuum source.

IB12−30834.—$z = 4.11$, $\Delta V \approx 360 \, A$, $\Delta V \approx 430 \, km \, s^{-1}$. The lower limit of EW is $\approx 240 \, A$. The line profile is quite similar (nearly Gaussian), and the velocity width is relatively small.

IB12−48320.—$z = 4.04$, $\Delta V \approx 320$, $\Delta V \approx 320 \, km \, s^{-1}$. The lower limit of the EW is $\approx 200 \, A$. A relatively strong residual of sky subtraction remains on the red side at $\approx 6145 \, A$. The line profile may suffer from a weak sky emission line here.

IB12−58572.—$z = 4.04$, $\Delta V \approx 210 \, A$, $\Delta V \approx 400 \, km \, s^{-1}$. The lower limit of the EW does not exceed 200 $\, A$. This object was categorized as a continuum-compact source in Appendix A.2.

IB12−81981.—$z = 4.12$, $\Delta V \approx 500 \, A$, $\Delta V \approx 380 \, km \, s^{-1}$. The lower limit of the EW is $\approx 260 \, A$. The profile shows asymmetry, but with no significant wing emission can be seen. The red side suffers from relatively strong sky emission lines at $\approx 6235$ and $6260 \, A$, and several weak ones.

IB13−104299.—$z = 4.42$, $\Delta V \approx 300 \, A$, $\Delta V \approx 260 \, km \, s^{-1}$. The lower limit of EW does not exceed 200 $\, A$. The spectrum may suffer from several sky emission lines at $\approx 6560, 6580,$ and $6600 \, A$. The photometry may suffer from a neighboring continuum source.

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