A CLOSE COMPARISON BETWEEN OBSERVED AND MODELED Lyα LINES FOR \( z \approx 2.2 \) Lyα EMITTERS*†‡

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ABSTRACT

We present the results of an Lyα profile analysis of 12 Lyα emitters (LAEs) at \( z \approx 2.2 \) with high-resolution Lyα spectra. We find that all 12 objects have an Lyα profile with the main peak redward of the systemic redshift defined by nebular lines, and five have a weak, secondary peak blueward of the systemic redshift (blue bump). The average velocity offset of the red main peak (the blue bump, if any) with respect to the systemic redshift is \( \Delta v_{\text{Ly},r} = 174 \pm 19 \text{ km s}^{-1} \) (\( \Delta v_{\text{Ly},b} = -316 \pm 45 \text{ km s}^{-1} \)), which is smaller than (comparable to) that of Lyman break galaxies (LBGs). The outflow velocities inferred from metal absorption lines in three individual and one stacked profiles are comparable to those of LBGs. The uniform expanding shell model constructed by Verhamme et al. reproduces not only the Lyα profiles but also other observed quantities, including the outflow velocity and the FWHM of nebular lines for the non-blue-bump objects. On the other hand, the model predicts too high FWHMs of nebular lines for the blue bump objects, although this discrepancy may disappear if we introduce additional Lyα photons produced by gravitational cooling. We show that the small \( \Delta v_{\text{Ly},r} \) values of our sample can be explained by low neutral hydrogen column densities of \( N_{\text{H}_1} = 18.9 \text{ cm}^{-2} \) on average. This value is more than one order of magnitude lower than those of LBGs but is consistent with recent findings that LAEs have high ionization parameters and low H I gas masses. This result suggests that low \( N_{\text{H}_1} \) values, giving reduced numbers of resonant scattering of Lyα photons, are the key to the strong Lyα emission of LAEs.

Key words: galaxies: high-redshift – galaxies: ISM – line: profiles – radiative transfer

1. INTRODUCTION

Lyα emitters (LAEs) are objects commonly seen in both the local and high-\( z \) universes with large Lyα equivalent widths, EW(Lyα) \( \gtrsim 20–30 \text{ Å} \) (local: Deharveng et al. 2008; Cowie et al. 2011; high-\( z \): Hu & McMahon 1996; Rhoads & Malhotra 2001; Ouchi et al. 2008, 2010). Previous studies based on spectral energy distributions (SEDs) have revealed that typical LAEs are young, low-mass galaxies with a small dust content (e.g., Gawiser et al. 2007; Nilsson et al. 2007; Guaita et al. 2011; Nakajima et al. 2012; Kusakabe et al. 2015), although there are some evolved LAEs with a moderate mass and dust (Ono et al. 2010b; Hagen et al. 2014). Morphological studies of their UV continuum have shown that the galactic counterparts of LAEs are typically compact (e.g., Bond et al. 2009) and their typical size does not evolve with redshift (Malhotra et al. 2012). Furthermore, clustering analyses have revealed that LAEs have the lowest dark matter halo masses at every redshift (Guaita et al. 2010; Ouchi et al. 2010). These properties suggest that LAEs are an important galaxy population as the building block candidates in the ΛCDM model (Rauch et al. 2008).

Given their importance in galaxy evolution, the Lyα escape mechanism in LAEs is still poorly understood. Resonant scattering strongly extends the path length of Lyα photons through galactic gas and renders them prone to absorption by dust grains. On one hand, some observational studies at the local universe have proposed that outflows facilitate the escape of Lyα photons from galaxies (e.g., Kunth et al. 1998) as they reduce the number of scattering. Likewise, others (e.g., Kornei et al. 2010; Atek et al. 2014) have shown that the dust content correlates with Lyα emissivity. While these effects would certainly be at work, there has been no decisive conclusion (see Cassata et al. 2015). On the other hand, theoretical studies have computed the Lyα radiation transfer (RT) through idealized spherically symmetric shells of homogeneous and isothermal neutral hydrogen gas, especially in the form of an expanding shell (e.g., Zheng & Miralda-Escudé 2002; Verhamme et al. 2006; Dijkstra & Loeb 2009; Kollmeier et al. 2010). They have investigated how properties of the interstellar medium (ISM) affect the Lyα escape and emergent Lyα profiles. The result is that the Lyα RT is a complicated process altered by galactic outflows/inflows, the neutral hydrogen column density and dust content of the ISM, and the inclination of the galaxy disk (e.g., Verhamme et al. 2012; Behrens & Braun 2014; Zheng & Wallace 2014). One of the goals in these theoretical studies is to aid in understanding of the galaxy properties from observed Lyα lines and to identify the key factor for the Lyα escape.

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† Based in part on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
‡ This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

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To study the Lyα RT and escape through close comparisons of observed and modeled Lyα lines, it is important to obtain spectral lines other than the Lyα line. The central wavelength and the width of nebular lines (e.g., Hα and [O III]) tell us the galaxy’s systemic redshift and internal velocity. The blueshift of interstellar (IS) absorption lines with respect to the systemic redshift gives the galactic outflow velocity, and the width of the IS lines can be interpreted as the sum of thermal and macroscopic (rotation and turbulence) velocities of the outflowing gas. These lines can help us to disentangle the complicated Lyα RT and understand the Lyα escape.

However, owing to the typical faintness of LAEs, it is only recently that these additional lines have been successfully detected in narrowband-selected LAEs (nebular lines: e.g., Finkelstein et al. 2011; McLinden et al. 2011; Hashimoto et al. 2013; IS absorption lines: Hashimoto et al. 2013; Shibuya et al. 2014b). Thus, in contrast to LBGs whose Lyα profiles have been closely compared with Lyα RT models (e.g., Verhamme et al. 2008; Christensen et al. 2012; Kulas et al. 2012), there are only a few studies that have performed Lyα profile comparisons of LAEs (e.g., Chonis et al. 2013). Recent simultaneous detections of Lyα and nebular emission lines have statistically confirmed that the Lyα profiles of LAEs are asymmetric with a red main peak redshifted with respect to the systemic $\Delta v_{Ly\alpha, r} > 0$ km s$^{-1}$ (e.g., Erb et al. 2014; Shibuya et al. 2014b; Song et al. 2014). Likewise, IS absorption studies in LAEs have shown that they are blueshifted with respect to the systemic by $|\Delta v_{Ly\alpha}| \sim 100-200$ km s$^{-1}$ (Hashimoto et al. 2013; Shibuya et al. 2014b), which is comparable to those of LBGs (e.g., Pettini et al. 2001; Shapley et al. 2003; Steidel et al. 2010; Kulas et al. 2012). These results suggest that LAEs do have outflows and motivate us to apply expanding shell models to LAEs.

To examine Lyα escape mechanisms in LAEs through detailed Lyα modeling, we focus on the small $\Delta v_{Ly\alpha, r}$ of LAEs, $\Delta v_{Ly\alpha, r} \simeq 200$ km s$^{-1}$, compared to those of LBGs, $\Delta v_{Ly\alpha, r} \simeq 400$ km s$^{-1}$ (e.g., Steidel et al. 2010; Kulas et al. 2012), with similar physical quantities such as stellar mass, star formation rate (SFR), and velocity dispersion (Hashimoto et al. 2013; Erb et al. 2014; Shibuya et al. 2014b; Song et al. 2014). Hashimoto et al. (2013) and Shibuya et al. (2014b) have also shown that LAEs have comparable outflow velocities, measured from IS absorption lines, to those of LBGs. These results imply that a definitive difference between LAEs and LBGs in velocity properties is $\Delta v_{Ly\alpha, r}$. In addition, Hashimoto et al. (2013) have demonstrated that EW(Lyα) anticorrelates with $\Delta v_{Ly\alpha, r}$ using a large sample of LAEs and LBGs (see also Erb et al. 2014; Shibuya et al. 2014b). Therefore, understanding the reason why LAEs have small $\Delta v_{Ly\alpha, r}$ through detailed Lyα modeling, should shed light on the Lyα RT and Lyα escape mechanisms in LAEs.

According to the theoretical studies, there are several possible explanations for a small $\Delta v_{Ly\alpha, r}$: a high outflow velocity (e.g., Verhamme et al. 2006); a very low neutral hydrogen column density ($N_{HI}$) of the ISM (e.g., Verhamme et al. 2006, 2015); an inhomogeneous ISM with a covering fraction (CF) below unity, where CF is defined as the fraction of sightlines that are optically thick to the Lyα radiation, i.e., gas with holes (e.g., Behrens et al. 2014; Verhamme et al. 2015); and a clumpy ISM with a low covering factor, $f_c$, which is defined as the average number of clouds intersected by a random line of sight (e.g., Hansen & Oh 2006; Dijkstra & Kramer 2012; Laursen et al. 2013).

In this work, we focus on applying the uniform expanding shell model based on a 3D Lyα RT constructed by Verhamme et al. (2006) and Schaerer et al. (2011) to 12 LAEs whose Lyα and nebular emission lines (e.g., Hα, O iii) have been observed at a high spectral resolution (Hashimoto et al. 2013; Nakajima et al. 2013; Shibuya et al. 2014b). With the systemic redshifts and the FWHMs determined from nebular emission lines, the stellar dust extinction derived from SED fitting, and the galactic outflow velocities inferred from low ionization state (LIS) absorption lines, we first statistically examine how well the model can reproduce the Lyα profiles and other observables (see Verhamme et al. 2008; Kulas et al. 2012; Chonis et al. 2013). After demonstrating the validity of the model, we securely derive physical quantities such as $N_{HI}$ and discuss the origin of the small $\Delta v_{Ly\alpha, r}$ and implications for the Lyα escape in LAEs. Possible other scenarios mentioned above for the small $\Delta v_{Ly\alpha, r}$ are also qualitatively discussed.

This paper is organized as follows. We describe our spectroscopy observations in Section 2 and discuss profiles of Lyα and nebular emission lines in Section 3. We apply the uniform expanding shell model to our data and show comparisons with observables in Section 4. Discussion on the blue bumps and the origin of the small Lyα velocity offsets is given in Section 5, followed by conclusions in Section 6.

Throughout this paper, magnitudes are given in the AB system (Oke & Gunn 1983), and we assume a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA AND OBSERVATIONS

Our initial sample of objects is taken from large $z \sim 2.2$ LAE samples in the COSMOS field, the Chandra Deep Field South (CDFS), and the Subaru/XMM-Newton Deep Survey (SXDS) (Nakajima et al. 2012; Nakajima et al. 2013; K. Nakajima et al. 2015, in preparation). These LAE samples are all based on Subaru/Suprime-Cam imaging observations with our custom-made narrowband filter, NB387 ($\lambda_c = 3870$ Å and FWHM = 94 Å). The LAEs have been selected by color criteria of $B - NB387$ and $u' - NB387$, satisfying the condition that the rest-frame photometric Lyα EW (EW(Lyα photo)) be larger than 30 Å. From these, we only use 12 LAEs whose Lyα and nebular emission lines (e.g., Hα and [O iii]) are both spectroscopically confirmed. Among the 12 objects, 11 have been presented in Hashimoto et al. (2013) and Shibuya et al. (2014b). We add one new LAE with EW(Lyα photo) $\sim$ 280 Å, whose detailed properties will be discussed in T. Hashimoto et al. (2015, in preparation).

In this section, we briefly summarize our near-infrared spectroscopy (Section 2.1), optical spectroscopy (Section 2.2), and the contamination of AGNs in the sample (Section 2.3).

2.1. Near-infrared Spectroscopy

In order to detect nebular emission lines, we performed three near-infrared observations with Magellan/MMIRS (PI: M. Ouchi); Keck/NIRSPEC (PI: K. Nakajima); and Subaru/FMOS (PI: K. Nakajima). Canonical spectral resolutions for our observation settings are $R \sim 1120, 1500$, and 2200 for MMIRS, NIRSPEC, and FMOS, respectively.
Details of the observation and data reduction procedures for MMIRS and NIRSPEC have been presented in Hashimoto et al. (2013) and Nakajima et al. (2013), respectively. Briefly, two CDFS objects, CDFS-3865 and CDFS-6482, were observed with MMIRS using the HK grism covering 2.254–2.45 μm, resulting in successful Hα and [O III] λλ 4959, 5007 detections. A follow-up observation was carried out for CDFS-3865 with NIRSPEC. The [O III] λ3727 line was additionally detected with the J band (1.15–1.36 μm). Four COSMOS objects, COSMOS-08501, COSMOS-13636, COSMOS-30679, and COSMOS-43982, were observed with NIRSPEC and its K band (2.2–2.43 μm), resulting in Hα line detections. The [O II] λ5007 line was also detected from COSMOS-30679 using the H band (1.48–1.76 μm).

The data from FMOS will be presented in K. Nakajima et al. (2015, in preparation). Its spectral coverage is 0.9–1.8 μm. We detected [O III] line(s) in eight objects: COSMOS-08357, COSMOS-12805, COSMOS-13138, COSMOS-13636, COSMOS-38380, COSMOS-43982, SXDS-10600, and SXDS-10942.

2.2. Optical Spectroscopy

In order to detect Lyα and metal absorption lines, we carried out several observations with Magellan/MagE (PI: M. Rauch) and Keck/LRIS (PI: M. Ouchi). The spectral resolutions for our observations were R ~ 4100 and ~1100 for MagE and LRIS, respectively. The slit was positioned on the Lyα centroids in the NB387 images.

Details of the observation and data reduction procedures for MagE and LRIS have been presented in Hashimoto et al. (2013) and Shibuya et al. (2014b), respectively, except for COSMOS-08501. First, we describe this new object in detail (Section 2.2.1), and then we give a brief summary for the rest of the sample (Section 2.2.2).

2.2.1. Optical Spectroscopy for COSMOS-08501

The MagE observations were carried out for COSMOS-08501 in 2012 February and 2013 December. We obtained 3 × 3000 s and 1 × 3000 s exposure times during each run, resulting in a 12,000 s total integration time. Spectroscopic standard stars, dome flats, and Xenon flash lamp flats were obtained on each night for calibrations. On these nights, the typical seeing sizes were 1′′. The slit width was 1′′ for both runs, corresponding to R ~ 4100. The spectra were reduced with an IDL-based pipeline, MagE_REDUCE, constructed by G. Becker (see also Kelson et al. 2003). This pipeline processes raw frames, performing wavelength calibration and optimal sky subtraction, and extracts 1D spectra. Each of these reduced frames was then combined to form our final calibrated spectrum. From this, the Lyα line was identified above the 3σ noise of the local continuum.

2.2.2. Optical Spectroscopy for the Rest of the Sample

CDFS-3865, CDFS-6482, and COSMOS-30679 were observed with MagE; COSMOS-08357, COSMOS-12085, COSMOS-13138, COSMOS-38380, SXDS-10600, and SXDS-10942 were observed with LRIS; and finally, COSMOS-13636 and COSMOS-43982 were observed with both spectrographs. We identified the Lyα line in all objects. In addition, we detected several metal absorption lines (e.g., Si II λ1260 and C IV λ1548 lines) in a stacked MagE spectrum of CDFS-3865, CDFS-6482, COSMOS-13636, and COSMOS-30679 (Hashimoto et al. 2013), as well as in individual LRIS spectra of COSMOS-12805, COSMOS-13636, and SXDS-10600 (Shibuya et al. 2014b).

A summary of our observations is listed in Table 1, and our Lyα and nebular emission line profiles are shown in Figure 1.

2.3. AGNs in the Sample

The presence of AGNs in the MagE objects has been examined in Hashimoto et al. (2013) and Nakajima et al. (2013), and those of the LRIS objects in Shibuya et al. (2014b).

In short, for the MagE objects, we inspected it in three ways. We first compared the sky coordinates of the objects with those in very deep archival X-ray and radio catalogs. Then we checked for the presence of high ionization state lines such as C IV λ1549 and He II λ1640 lines in the spectra. Finally, we applied the BPT diagnostic diagram (Baldwin et al. 1981) to the objects. No AGN activity is seen except for COSMOS-43982, whose high [N II]/Hα line ratio is consistent with that of an AGN.

On the other hand, owing to the lack of Hα or [N II] λ6568 data, we were only able to use the two forms of investigation for the LRIS objects. Of these, only COSMOS-43982 showed clear detection of the C IV λ1549 line in its optical spectrum.

In summary, we have ruled out AGN activity in all but COSMOS-43982.

3. OBSERVATIONAL RESULTS

3.1. Line Center and FWHM Measurements for Nebular Emission Lines

Line center (i.e., redshift) and FWHM measurements of nebular emission lines are crucial for a detailed modeling of the Lyα line, since they encode information on the intrinsic (i.e., before being affected by radiative transfer) Lyα redshift and FWHM. In order to obtain these parameters and their uncertainties, we apply a Monte Carlo technique as follows. First, for each line of each object, we measure the 1σ noise of the local continuum. Then we create 10⁵ fake spectra by perturbing the flux at each wavelength of the true spectrum by the measured 1σ error (Kulas et al. 2012; Chonis et al. 2013). For each fake spectrum, the wavelength at the highest flux peak is adopted as the line center, and the wavelength range encompassing half the maximum flux is adopted as the FWHM. The standard deviation of the distribution of measurements from the 10⁵ artificial spectra is adopted as the error on the line center and FWHM. When multiple lines are detected, we adopt a weighted mean value of them. A summary of the measurements is listed in columns (2) and (3) of Table 2. All redshift (FWHM) values are corrected for the LSR motion (instrumental resolution). When the line is unresolved, the instrumental resolution is given as an upper limit. The mean FWHM value for a sample of eight objects with a measurable velocity dispersion is FWHM(neb) = 129 ± 55 km s⁻¹, which is smaller than that of LBGs, FWHM(neb) = 200–250 km s⁻¹ (Pettini et al. 2001; Erb et al. 2006a; Kulas et al. 2012). This is consistent with the recent results by Erb et al. (2014), who have found that the median FWHM(neb) of 36 z ~ 2 LAEs is 127 km s⁻¹. These results indicate that LAEs have smaller dynamical masses than LBGs.
Table 1
Summary of the Observations

| Object         | α(J2000)   | δ(J2000)   | EW(Lyα)$_{\text{ratio}}$ (Å) | $\lambda$ (Lyα) \(10^{42}\) erg s$^{-1}$ | NIR Obs. | Opt. Obs. | Source$^a$ |
|----------------|------------|------------|-------------------------------|-----------------------------------------|----------|-----------|------------|
| (1)            | (2)        | (3)        | (4)                          | (5)                                     | (6)      | (7)       | (8)        |
| CDFS-3865      | 03:32:32.31| ~28:00:52.20| 64 ± 29                      | 29.8 ± 4.9                              | NIRSPEC (J) | MagE     | H13, N13   |
|                |            |            |                              |                                         | MMIRS (HK) | MagE     | H13, N13   |
| CDFS-6482      | 03:32:49.34| ~27:59:52.35| 76 ± 52                      | 15.4 ± 8.1                              | NIRSPEC (K) | MagE     | N13        |
| COSMOS-08501   | 10:01:16.80| +02:05:36.26| 280 ± 30                     | 8.8 ± 1.1                               | NIRSPEC (H) | MagE     | N13        |
| COSMOS-30679   | 10:00:29.81| +02:18:49.00| 87 ± 7                       | 8.5 ± 0.7                               | NIRSPEC (H and K) | MagE | H13, N13   |
| COSMOS-13636   | 09:59:59.38| +02:08:38.36| 73 ± 5                       | 11.3 ± 0.5                              | FMOS (H)  | N13, S14  |
|                |            |            |                              |                                         | NIRSPEC (K) | MagE and LRIS | H13, N13, S14 |
| COSMOS-43982$^b$ | 09:59:54.39| +02:26:29.96| 130 ± 12                     | 11.0 ± 0.5                              | MMIRS (HK) | MagE and LRIS | H13, N13, S14 |
| COSMOS-08357   | 09:59:59.07| +02:05:31.60| 47 ± 8                       | 0.5 ± 0.1                               | FMOS (H)  | S14, N15  |
| COSMOS-12805   | 10:00:15.29| +02:08:07.50| 34 ± 6                       | 2.6 ± 0.3                               | FMOS (H)  | S14, N15  |
| COSMOS-13138   | 10:00:02.61| +02:08:24.50| 40 ± 10                      | 0.4 ± 0.1                               | FMOS (H)  | S14, N15  |
| COSMOS-38380   | 09:59:40.94| +02:23:04.20| 137 ± 15                     | 2.6 ± 0.3                               | FMOS (H)  | S14, N15  |
| SXDS-10600     | 02:17:46.09| ~06:57:05.00| 58 ± 3                       | 1.9 ± 0.1                               | FMOS (H)  | S14, N15  |
| SXDS-10942     | 02:17:59.54| ~06:57:25.60| 135 ± 10                     | 0.3 ± 0.0                               | FMOS (H)  | S14, N15  |

Notes. (1) Object ID; (2), (3) R.A. and decl.; (4), (5) rest-frame Lyα EW and luminosity derived from narrow- and broadband photometry; (6) instruments and filters used for the NIR observations; (7) instruments used for the optical observations; and (8) source of the information.

$^a$ H13: Hashimoto et al. (2013); N13: Nakajima et al. (2013); S14: Shibuya et al. (2014b); N15: K. Nakajima et al. (2015, in preparation).

$^b$ AGN-like object.

### 3.2. Two-component [O iii] Profiles

Among the nebular emission lines we have obtained, while most objects show normal symmetric Gaussian profiles, COSMOS-13138 and SXDS-10600 show an asymmetric [O iii] profile with a secondary blueshifted and redshifted component, respectively (see Figure 2). Such a profile has been reported in various objects: both local and high-z star-forming galaxies and ULIRGs (e.g., Shapiro et al. 2009; Genzel et al. 2011; Newman et al. 2012; Soto et al. 2012), a high-z oxygen-two blob ([O iii] blob; Harikane et al. 2014), and a few Lyα blobs (LABs; Yang et al. 2014). However, in LAEs, there has been no study that reports its presence.

Aforementioned studies apply a two-Gaussian-component fit with a narrow and broad component to the line. To examine the presence of two components, we also perform a fit with two Gaussians. We have six parameters: fluxes, line centers, and FWHMs for both components. We require that the widths of both components are larger than the spectral resolution, and that the broad component has a larger FWHM than the narrow component. Best-fit parameters are determined through minimum $\chi^2$ realizations, and the parameter range satisfying $\chi^2 < \chi^2_{\text{min}} + 1$ is adopted as the error, where $\chi^2_{\text{min}}$ denotes the minimum $\chi^2$ value. The results are listed in Table 3. For each object, both components are significantly detected with $\gtrsim 4\sigma$, demonstrating that some fraction of LAEs have two-component line profiles.

The velocity offsets of the two components are 104 ± 11 km s$^{-1}$ (COSMOS-13138) and 115 ± 8 km s$^{-1}$ (SXDS-10600), respectively.

The FWHM values of the broad component after correction for instrumental resolution are 70 ± 50 km s$^{-1}$ and 80 ± 30 km s$^{-1}$. These are much smaller than those of the star-forming galaxies at $z \sim 2$ (FWHM = 300–1000 km s$^{-1}$; Genzel et al. 2011) and slightly smaller than those of the [O iii] blob (FWHM = 120–130 km s$^{-1}$) of Harkane et al. (2014) and the LABs (FWHM = 100–280 km s$^{-1}$) of Yang et al. (2014). Our small values exclude the possibility of the broad component originating from an AGN activity (see Osterbrock & Ferland 2006) or a powerful outflow driven by a starburst (e.g., Shapiro et al. 2009; Genzel et al. 2011; Newman et al. 2012) because in these cases, the FWHM of the broad component should be as large as ~300–1000 km s$^{-1}$. It is possible that the two-component lines originate from two large star-forming regions (e.g., Harikane et al. 2014) or mergers. As discussed in Harikane et al. (2014), the velocity offset of the two components, ~100 km s$^{-1}$, may be due to a rotation of the objects.

### 3.3. Lyα Profile with a Blue Bump

While the majority of Lyα profiles are single peaked (e.g., Shapley et al. 2003; Steidel et al. 2010), a fraction of Lyα profiles are known to be multiple peaked (e.g., Rauch et al. 2008; Kulas et al. 2012; Yamada et al. 2012). In particular, we shall refer to a secondary small peak blueward of the systemic redshift as “the blue bump” (see the case 2 profile in Figure 12 in Verhamme et al. 2006). Theoretical studies have shown that the blue bump is a natural outcome of the radiative transfer in a low-speed galactic outflow (e.g., Zheng & Miralda-Escudé 2002).
We consider a blue bump to be detected if there exists an excess emission blueward of the systemic redshift above the $3\sigma$ noise of the local continuum. We detect a blue bump of five objects: the MagE ones of CDFS-3865 and COSMOS-43982, and the LRIS ones of COSMOS-12805, COSMOS-13138, COSMOS-43982, and SXDS-10942 (column (4) of Table 2). The position of the blue bump is designated by a blue arrow in Figure 1.

The frequency of blue bump objects in the sample is $40\%$ ($5/12$). There are four LAEs in the literature that have a blue bump: one of the two LAEs studied in McLinden et al. (2011) and all three LAEs studied in Chonis et al. (2013). For the total sample of 17 LAEs, the frequency is calculated to be $\sim 50\%$ ($9/17$). Note that this is a lower limit owing to the limited spectral resolution. On the other hand, Kulas et al. (2012) have studied 18 $z \sim 2$–3 LBGs with $z_{\text{sys}}$ measurements that are preselected to have multiple-peaked $\text{Ly}\alpha$ profiles. They have argued that $\sim 30\%$ of the parent sample is multiply peaked and that 11 out of the 18 objects have a blue bump, indicating that the blue bump frequency in LBGs is $\sim 20\%$ ($\sim 30\% \times 11/18$). These results imply that the blue bump feature is slightly more common in LAEs than in LBGs, although a larger sample observed at higher spectral resolution is needed for a definite conclusion.

![Figure 1](image-url)
Table 2

Summary of the Observed Spectroscopic Properties of the Sample

| Object     | \( z_{\text{sys}} \) | FWHM(neb) (km s\(^{-1}\)) | Blue Bump \( \Delta v_{\text{Ly,}\alpha, r} \) (km s\(^{-1}\)) | \( \Delta v_{\text{Ly,}\alpha, b} \) (km s\(^{-1}\)) | \( \Delta v_{\text{peak}} \) (km s\(^{-1}\)) | EW(Ly\(\alpha\))spec (\(\AA\)) | \( S_{\text{w}} \) |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------------|--------------|
| CDFS-3865  | 2.17242 ± 0.00016 | 242 ± 31        | Yes             | 245 ± 36        | −352 ± 59       | 597 ± 67             | 40 ± 2      | 8.8 ± 0.3    |
| CDFS-6482  | 2.20490 ± 0.00042 | 99_{-56}^{+56}  | No              | 118 ± 48        | ...             | ...                  | 26 ± 2      | 6.6 ± 1.7    |
| COSMOS-08501 | 2.16161 ± 0.00042 | <200            | No              | 82 ± 40         | ...             | ...                  | 10 ± 1      | 2.2 ± 2.7    |
| COSMOS-30679 | 2.19725 ± 0.00020 | 92 ± 45         | No              | 290 ± 33        | ...             | ...                  | 10 ± 1      | 3.1 ± 1.0    |
| COSMOS-13636 (MagE) | 2.16075 ± 0.00019 | 73 ± 5          | No              | 146 ± 25        | ...             | ...                  | 23 ± 5      | 5.3 ± 1.0    |
| COSMOS-13636 (LRIS) | 2.16075 ± 0.00019 | 73 ± 5          | No              | 161 ± 18        | ...             | ...                  | 26 ± 1      | 6.2 ± 0.5    |
| COSMOS-43982 (MagE) | 2.19267 ± 0.00036 | 325 ± 36        | Yes             | 117 ± 53        | −297 ± 57       | 414 ± 78             | 24 ± 17     | 7.9 ± 1.3    |
| COSMOS-43982 (LRIS) | 2.19267 ± 0.00036 | 325 ± 36        | Yes             | 155 ± 40        | −165 ± 90       | 320 ± 98             | 42 ± 3      | −4.2 ± 0.6   |
| COSMOS-08357 | 2.18053 ± 0.00031 | <136            | No              | 106 ± 71        | ...             | ...                  | 19 ± 3      | −4.2 ± 7.9   |
| COSMOS-12805 | 2.15887 ± 0.00024 | 110 ± 16        | Yes             | 171 ± 25        | −605 ± 114      | 776 ± 117            | 24 ± 1      | 8.9 ± 0.7    |
| COSMOS-13138 | 2.17914 ± 0.00012 | 63 ± 6          | Yes             | 191 ± 59        | −214 ± 87       | 405 ± 105            | 46 ± 11     | −1.6 ± 4.8   |
| COSMOS-38380 | 2.21245 ± 0.00015 | 99 ± 9          | No              | 338 ± 21        | ...             | ...                  | 73 ± 7      | 2.5 ± 0.8    |
| SXDS-10600 | 2.20922 ± 0.00014 | 55 ± 28         | No              | 186 ± 13        | ...             | ...                  | 44 ± 1      | 11.7 ± 0.2   |
| SXDS-10942 | 2.19574 ± 0.00025 | <136            | Yes             | 135 ± 10        | −374 ± 41       | 556 ± 66             | 94 ± 10     | 1.3 ± 0.3    |

Note. The symbol "..." indicates that we have no measurement. (1) Object ID; (2) systemic redshift derived from the weighted mean of the nebular emission redshifts; (3) weighted mean FWHM of nebular emission line; (4) presence of a blue bump emission in the Ly\(\alpha\) profile; (5) velocity offset of the Ly\(\alpha\) main red peak with respect to \( z_{\text{sys}} \); (6) velocity offset of the Ly\(\alpha\) blue bump with respect to \( z_{\text{sys}} \); (7) separation between \( \Delta v_{\text{Ly,}\alpha, r} \) and \( \Delta v_{\text{Ly,}\alpha, b} \); (8) rest-frame Ly\(\alpha\) EW derived from spectroscopy; and (9) weighted skewness of the Ly\(\alpha\) line.

3.4. Ly\(\alpha\) Velocity Properties

We derive three velocity offsets related to the Ly\(\alpha\) line: the velocity offset of the main red peak of the Ly\(\alpha\) line with respect to the systemic redshift,

\[
\Delta v_{\text{Ly,}\alpha, r} = c \frac{z_{\text{Ly,}\alpha, r} - z_{\text{sys}}}{1 + z_{\text{sys}}},
\]

that of the blue bump of the Ly\(\alpha\) line with respect to the systemic redshift, if any,

\[
\Delta v_{\text{Ly,}\alpha, b} = c \frac{z_{\text{Ly,}\alpha, b} - z_{\text{sys}}}{1 + z_{\text{sys}}},
\]

and that of the two peaks,

\[
\Delta v_{\text{peak}} = \Delta v_{\text{Ly,}\alpha, r} - \Delta v_{\text{Ly,}\alpha, b},
\]

where \( z_{\text{sys}}, z_{\text{Ly,}\alpha, r}, \) and \( z_{\text{Ly,}\alpha, b} \) represent the systemic redshift, the Ly\(\alpha\) redshift of the main red peak, and that of the blue bump, respectively.

3.4.1. Ly\(\alpha\) Main Red Peak Velocity Offsets, \( \Delta v_{\text{Ly,}\alpha, r} \)

We estimate \( \Delta v_{\text{Ly,}\alpha, r} \) value using a Monte Carlo technique in a similar manner to that in Section 3.1. First, for each object, we measure the \( \sigma \) error in the Ly\(\alpha\) spectrum set by the continuum level at the wavelength longer than 1216 Å. Then we create 10\(^3\) fake spectra converted to velocity space by simultaneously perturbing the flux at each wavelength and the systemic redshift listed in Table 2 by their \( \sigma \) errors. Finally, we measure the velocity at the highest flux peak. The mean and the standard deviation value of the distribution of 10\(^3\) measurements are adopted as the \( \Delta v_{\text{Ly,}\alpha, r} \) and its error, respectively. The derived \( \Delta v_{\text{Ly,}\alpha, r} \) values are listed in column (5) of Table 2, ranging from 82 km s\(^{-1}\) to 338 km s\(^{-1}\) with a mean value of 174 ± 19 km s\(^{-1}\). In most cases, these values are consistent with those measured in Hashimoto et al. (2013) and Shibuya et al. (2014b) within 1\(\sigma\); however, they are not for COSMOS-08357 and COSMOS-12805. This is due to the fact that these studies have applied a symmetric/asymmetric profile fit to the Ly\(\alpha\) line. In Figure 1, we show the two \( \Delta v_{\text{Ly,}\alpha, r} \) values derived from the Monte Carlo and the profile fit technique as the orange and green line segments, respectively. For the sake of consistency in the definition of the \( \Delta v_{\text{Ly,}\alpha, r} \) in the shell model (Verhamme et al. 2006; Schaerer et al. 2011), we adopt here the new measurements. We note that our discussion is unchanged even if we adopt the previous \( \Delta v_{\text{Ly,}\alpha, r} \) values.

The \( \Delta v_{\text{Ly,}\alpha, r} \) value has been measured in more than 60 LAEs (Finkelstein et al. 2011; McLinden et al. 2011; Chonis et al. 2013; Guitaia et al. 2013; Hashimoto et al. 2013; Erb et al. 2014; Shibuya et al. 2014b; Song et al. 2014). These studies have shown that LAEs at \( z \approx 2–3 \) have a mean \( \Delta v_{\text{Ly,}\alpha, r} \) of \( \approx 200 \) km s\(^{-1}\), which is significantly smaller than that of LBGs at a similar redshift, \( \Delta v_{\text{Ly,}\alpha, r} \approx 400 \) km s\(^{-1}\) (e.g., Steidel et al. 2010; Rakic et al. 2011; Kulas et al. 2012). The left panel of Figure 3 represents the histogram of \( \Delta v_{\text{Ly,}\alpha, r} \) for the 12 LAEs (14 spectra) studied in this study and 18 LBGs given by Kulas et al. (2012). We carry out the Kolmogorov–Smirnov (K-S) test for the two populations. The resultant probability is \( 10^{-6} \), indicating that \( \Delta v_{\text{Ly,}\alpha, r} \) is definitively different between LAEs and LBGs.
For each detected blue bump in Section 3.3, we measure the $\Delta v_{\text{Ly},b}$ value in the same manner as for $\Delta v_{\text{Ly},r}$. We obtain $\Delta v_{\text{Ly},b} = -352 \pm 59$ km s$^{-1}$ (CDFS-3865), $-297 \pm 57$ km s$^{-1}$ (MagE-COSMOS-43982), $-605 \pm 114$ km s$^{-1}$ (COSMOS-12805), $214 \pm 87$ km s$^{-1}$ (COSMOS-13138), $-165 \pm 90$ km s$^{-1}$ (LRIS-COSMOS-43982), and $-374 \pm 41$ km s$^{-1}$ (SXDS-10942) as listed in column (6) of Table 2. We have obtained two different measurements for COSMOS-3865 owing to the spectral resolution effect; however, they are consistent with each other within 1σ (see also Section 4.3.3). We combine our $\Delta v_{\text{Ly},b}$ measurements with those in the four aforementioned LAEs with a blue bump to construct a large sample of LAEs with a blue bump consisting of nine objects (10 spectra): one from McLinden et al. (2011) with $\Delta v_{\text{Ly},b} = -454$ km s$^{-1}$ and three from Chonis et al. (2013) with $\Delta v_{\text{Ly},b} = -127$, $-250$, and $-236$ km s$^{-1}$. The mean $\Delta v_{\text{Ly},b}$ value of the large sample is $\Delta v_{\text{Ly},b} = -316 \pm 45$ km s$^{-1}$, which is consistent with that of 11 LGBs with a blue bump, $\Delta v_{\text{Ly},b} = -367 \pm 46$ km s$^{-1}$ (Kulas et al. 2012). We calculate the K-S probability to be 0.3901, indicating that LAEs’ $\Delta v_{\text{Ly},b}$ values are comparable to LGBs’. The middle panel of Figure 3 shows the $\Delta v_{\text{Ly},b}$ distribution for the LAE and LBG samples.

We check whether our conclusion remains unchanged even if the spectral resolution effect is taken into account. The sample by Kulas et al. (2012) has been obtained with three settings: 300-line grating and 400- and 600-line grisms, corresponding to a spectral resolution of $R \sim 600$, 800, and 1300, respectively. We compare the mean $\Delta v_{\text{Ly},b}$ value of our four LAEs taken by LRIS ($R \sim 1100$) with that of six LGBs with a blue bump obtained at a similar resolution ($R \sim 1300$). The resultant mean $\Delta v_{\text{Ly},b}$ values for LAEs and LGBs are $-340 \pm 99$ and $-356 \pm 70$ km s$^{-1}$, respectively, and the K-S probability is 0.9238. Thus, we obtain the same conclusion.

### 3.4.3. Velocity Offsets between the Main Red Peak and the Blue Bump, $\Delta v_{\text{peak}}$

Finally, for each of the spectra with a blue bump, we measure the velocity offset between the red and blue peaks: $\Delta v_{\text{peak}} = 597 \pm 67$ km s$^{-1}$ (CDFS-3865), $414 \pm 78$ km s$^{-1}$ (MagE-COSMOS-43982), $776 \pm 117$ km s$^{-1}$ (COSMOS-12805), $405 \pm 105$ km s$^{-1}$ (COSMOS-13138), $320 \pm 98$ km s$^{-1}$ (LRIS-COSMOS-43982), and $556 \pm 66$ km s$^{-1}$ (SXDS-10942), as listed in column (7) of Table 2. In order to make a large sample with $\Delta v_{\text{peak}}$ measured, we utilize again the four LAEs with the blue bump from the literature: one LAE studied in McLinden et al. (2011) with $\Delta v_{\text{peak}} = 796$ km s$^{-1}$ and three LAEs studied in Chonis et al. (2013) with $\Delta v_{\text{peak}} = 300$, 425, and 415 km s$^{-1}$. The mean value of the nine objects (10 spectra) is $\Delta v_{\text{peak}} = 500 \pm 56$ km s$^{-1}$, which is significantly smaller than the value derived for 11 LGBs with a blue bump, $\Delta v_{\text{peak}} = 801 \pm 41$ km s$^{-1}$ (Group I in Kulas et al. 2012). The K-S probability is calculated to be 0.00636, indicating that LAEs and LGBs have distinctive $\Delta v_{\text{peak}}$ values. See the right panel of Figure 3 for their distributions.

We examine the spectral resolution effect in exactly the same manner as in Section 3.4.2. The mean $\Delta v_{\text{peak}}$ value of the four LAEs taken by LRIS ($R \sim 1100$) and that of the six LGBs with a blue bump obtained at a similar spectral resolution ($R \sim 1300$) are $\Delta v_{\text{peak}} = 514 \pm 100$ and 778 $\pm 59$ km s$^{-1}$, respectively. In conjunction with the K-S probability, 0.09524, we conclude that LAEs have a significantly smaller $\Delta v_{\text{peak}}$ value than that of LBG even at the same spectral resolution. Our finding is recently supported by Henry et al. (2015) and Yang et al. (2014), who have examined Lyα velocity properties
and their relations to the Lyα escape fraction for local galaxies called “Green Pea” galaxies (Cardamone et al. 2009). They have found that the Lyα escape fraction is higher for objects with smaller $\Delta V_{\text{peak}}$.

In summary, we have derived three Lyα velocity offsets, $\Delta V_{1216,\alpha}$, $\Delta V_{1244,\alpha}$, and $\Delta V_{\text{peak}}$. While we need a larger sample of objects with a blue bump for a definite conclusion, we find that LAEs have a smaller (comparable) $\Delta V_{1216,\alpha}$ ($\Delta V_{1244,\alpha}$) value relative to LBGs, which makes their $\Delta V_{\text{peak}}$ value also smaller than that of LBGs.

3.5. Other Physical Quantities

In this section, we describe other physical quantities related to this work. We describe metal absorption line properties in Section 3.5.1, SED fitting properties in Section 3.5.2, and morphological properties in Section 3.5.3.

3.5.1. Metal Absorption Line Properties

LIS metal absorption lines encode information on cold neutral gas in galaxies. The mean blueshift of LIS absorption lines with respect to the systemic velocity, $\Delta V_{\text{abs}}$, gives the average speed of the galactic outflow (e.g., Pettini et al. 2001; Shapley et al. 2003; Martin 2005). In the following sections, we compare the $\Delta V_{\text{abs}}$ values of our LAE sample with the results from Lyα RT fitting.

Shibuya et al. (2014b) have detected several LIS absorption lines in a few narrowband-selected LAEs on an individual basis. The derived mean blueshifts are $\Delta V_{\text{abs}} = -130 \pm 70$ km s$^{-1}$ (COSMOS-13636), $-170 \pm 50$ km s$^{-1}$ (COSMOS-12805), and $-260 \pm 60$ km s$^{-1}$ (SXDS-10600). Additionally, Hashimoto et al. (2013) have detected several LIS absorption lines in a stacked spectrum of four LAEs: CDFS-3865, CDFS-6482, COSMOS-13636, and COSMOS-30679. The mean blueshift of the LIS metal absorption lines is $\Delta V_{\text{abs}} = -102 \pm 65$ km s$^{-1}$. These values are listed in column (2) of Table 4.

3.5.2. SED Fitting Properties

In this study, we utilize SED fitting results of the sample, in particular, stellar dust extinction, $E(B - V)_a$, and stellar mass, $M_\ast$. In the following sections, we compare the $E(B - V)_a$ values with the results from Lyα RT fitting and investigate the correlation between the Lyα profile trends and $M_\ast$.

SED fitting results for the MagE (LRIS) objects have been presented in Hashimoto et al. (2013) and Nakajima et al. (2013) (Shibuya et al. 2014b). For the detailed procedure of the fitting, we refer the reader to Ono et al. (2010a, 2010b). The derived $E(B - V)_a$ and $M_\ast$ values are listed in columns (3) and (4) of Table 4. The former range from $E(B - V)_a = 0.04$ to 0.40 with a mean value of $E(B - V)_a = 0.16$, and the latter from $\log M_\ast/M_\odot = 7.7$ to 10.8 with a mean of $\log M_\ast/M_\odot = 9.3$, respectively.

3.5.3. Morphological Properties

In the following sections, we use three morphological properties studied for $z \sim 2.2$ LAEs in Shibuya et al. (2014a); the presence of a merger, the spatial offset between Lyα and stellar continuum emission peaks, $\delta_{\text{Lyα}}$, and the ellipticity. Shibuya et al. (2014a) have utilized $H_\beta$ and $H_\alpha$ data taken with ACS and WFC3 on HST to examine rest-frame UV and optical morphologies, respectively. Among the objects presented in this study, the rest-frame UV images of the eight COSMOS objects have been investigated in Shibuya et al. (2014a).

The presence of a merger has been examined with two methods: the close-pair method (e.g., Le Fèvre et al. 2000; Law et al. 2012) and the morphological index method, especially the CAS system (Abraham et al. 1996; Conselice et al. 2000). In Shibuya et al. (2014a), the former method has been applied to objects with $H_\beta < 26.5$, which is the case for all the COSMOS objects presented in this study except for COSMOS-13138. The result is that two objects, COSMOS-13636 and COSMOS-12805, are mergers, while the remaining seven are not. On the other hand, the latter method has been done for objects with $H_\beta < 25.0$ and a half-light radius, $r_e$, larger than 0.5. The reason why Shibuya et al. (2014a) have limited the sample for the latter method is to obtain reliable values of the indices. This is the case for three COSMOS objects presented in this study, COSMOS-13636, COSMOS-43982, and COSMOS-38380. The result is that none of the three are mergers. The two results for COSMOS-13636 are not consistent with each other because we have used two different methods. Thus, among the eight COSMOS objects, COSMOS-13636 and COSMOS-12805 may be mergers (column (5) of Table 4).

The Lyα spatial offset, $\delta_{\text{Lyα}}$, has been examined by performing source detections with SExtractor for Subaru NB387 and HST $i_{\text{814}}$ images. While compact objects with a symmetric UV light profile tend to have a small $\delta_{\text{Lyα}}$ value, objects with an asymmetric, disturbed UV light profile are likely to have a large $\delta_{\text{Lyα}}$ value (e.g., Jiang et al. 2013; Shibuya et al. 2014a). Thus, this quantity could be a useful tracer of the H1 gas stability around the galaxy. The value is reliably obtained for the objects with $H_\beta < 26.5$ and NB387 < 24.5, where the typical positional error in $H_\beta$ (NB387) is less than 0.05 (0.2). For the eight COSMOS objects in this
study, none have a significant Lyα spatial offset larger than the typical error of the \( b_{\text{Ly} \alpha} \sim 0.36 \).

The ellipticity, \( \epsilon = 1 - a/b \), where \( a \) and \( b \) are the major and minor axes, is a useful indicator of the galactic disk inclination. In Shibuya et al. (2014a), this has been measured using GALFIT software (Peng et al. 2002) for the objects with \( b_{\text{Ly} \alpha} < 25.0 \) and \( \epsilon \) larger than the typical PSF size. The former criterion, corresponding to SNR = 30 detection, is needed for the reliable ellipticity measurements (e.g., Mosleh et al. 2012; Ono et al. 2013). Only three objects, COSMOS-30679, COSMOS-38380, and COSMOS-43982, satisfy these criteria. The resultant ellipticity values are \( \epsilon = 0.24 \) (COSMOS-30679), 0.34 (COSMOS-38380), and 0.49 (AGN-COSMOS-43982), respectively (column (6) of Table 4).

4. Lyα RADIATIVE TRANSFER MODEL AND FITTING PROCEDURE

4.1. A Library of Synthetic Spectra

The library of synthetic Lyα spectra used in this study has been described in Schaerer et al. (2011). Lyα RT has been computed with McLya (Verhamme et al. 2006) through spherically symmetric expanding shells of homogeneous and isothermal neutral hydrogen gas. The shell is described by four parameters:

1. the radial expansion velocity, \( V_{\text{sys}} \);
2. the neutral hydrogen column density along the line of sight, \( N_{\text{HI}} \);
3. the Doppler parameter, \( b \), describing the thermal and turbulent motion in the shell;
4. and the dust absorption optical depth at the Lyα wavelength, \( \tau_d \), related to the gas dust extinction by \( E(B - V)_{\text{gas}} \approx (0.06 \ldots 0.11)\tau_d \), where the lower and higher values in the parentheses correspond to the attenuation law for starbursts (Calzetti et al. 2000) and the Galactic extinction law (Seaton 1979), respectively.

The Lyα source is located at the center of the shell. The intrinsic (i.e., before being affected by the radiative transfer effect) spectrum is a Gaussian Lyα line plus a flat continuum and is characterized by two parameters:

1. the Lyα equivalent width, \( \text{EW}_{\text{eq}}(\text{Ly} \alpha) \); and
2. \( \text{FWHM}_{\text{eq}}(\text{Ly} \alpha) \).

For a comparison with the observed data, each rest-frame model has been shifted using the systemic redshift \( z_{\text{sys}} \) values listed in Table 2. To reflect the \( z_{\text{sys}} \) uncertainty, we have allowed the observed Lyα spectra to shift relative to the velocity zero point within the error. Thus, combinations of seven free parameters are fitted to the data.

This library of Lyα spectra has been successfully used to reproduce various observed Lyα line profiles of \( z > 3 \) LBGs, from strong emission to broad absorption (Schaerer & Verhamme 2008; Verhamme et al. 2008; Dessauges-Zavadsky et al. 2010; Vanzella et al. 2010; Lidman et al. 2012).

4.2. Fitting of Observed Spectra

To perform a statistical comparison between the observed and modeled Lyα line profiles, we calculate the \( \chi^2 \) values for each of the possible combinations of the parameters for each galaxy (see Chonis et al. 2013). Since model spectra are...
normalized and at an infinite spectral resolution, two steps are needed before the $\chi^2$ calculation. First, we normalize the observed spectra using the continuum level estimated at wavelengths longer than 1216 Å. Second, each model Ly$\alpha$ spectrum has been convolved with a Gaussian whose FWHM corresponds to spectral resolutions:

$$\text{FWHM} = c/R,$$

where $c$ is the speed of light.

We note that our fitting technique gives exactly the same statistical weight to all data points of the continuum and the Ly$\alpha$ line. Finally, for the sake of consistency, for each object we calculate $\chi^2$ in the wavelength range from $-3 \times \text{FWHM}_{\text{obs}}(\text{Ly} \alpha)$ to $+3 \times \text{FWHM}_{\text{obs}}(\text{Ly} \alpha)$ around the Ly$\alpha$ line center.

In Figure 4, we demonstrate how the best fit and its associated errors are found using $\chi^2$ values. To do this, examples of the fit to $V_{\text{exp}}$ are shown for well and poorly constrained objects. In the left panels of this figure, one can see a broad range of $V_{\text{exp}}$ values with low reduced $\chi^2$ for COSMOS-08357, whose Ly$\alpha$ S/N is $\sim$11, in comparison to CDFS-3865 with an Ly$\alpha$ S/N of $\sim$98. To measure median and 1$\sigma$ values, we convert $\chi^2$ values into probabilities using the formula $p \propto \exp(-\chi^2/2)$ for each set of five 2D parameters ($V_{\text{exp}}$ versus $N_{\text{H}_1}$, $V_{\text{exp}}$ versus $\tau_a$, $V_{\text{exp}}$ versus $b$, $V_{\text{exp}}$ versus FWHM$_m$(Ly$\alpha$), and $V_{\text{exp}}$ versus EW$_{\text{int}}$(Ly$\alpha$)). After normalizing them so that the total probability is unity, we draw a probability density function (PDF) and a cumulative density function (CDF) as shown in the middle and the right panels, respectively. Finally, we adopt the values where CDF = 0.50, 0.16, and 0.84 as the median and $\pm 1\sigma$, respectively. Performing this for each five-2D-parameter set results in five median and $\pm 1\sigma$ values. As can be seen, all five median and $\pm 1\sigma$ values are consistent with each other for CDFS-3865, whereas they are not for COSMOS-08357. In the latter case, we adopt the average of the five median and $\pm 1\sigma$ values.

4.3. Results

We show the reproduced Ly$\alpha$ profiles (Section 4.3.1), describe the derived parameters (Section 4.3.2), and examine the influence of spectral resolution on the results (Section 4.3.3).

4.3.1. Fitted Profiles

Figure 5 shows the best-fit model spectra with the observed ones. All the Ly$\alpha$ profiles are quite well reproduced by the model, which seems to differ from the previous studies by Kulas et al. (2012) and Chonis et al. (2013). These authors have had difficulty reproducing their Ly$\alpha$ profiles, especially the position and the flux of the blue bump. This might be due to model differences. These two studies have utilized the uniform expanding shell model constructed by Zheng & Miralda-Escudé (2002) and Kollmeier et al. (2010). There are three major differences between the models (see Chonis et al. 2013). First, in addition to the three common parameters, $V_{\text{exp}}, N_{\text{H}_1},$
and $b$, the model used in this study also includes an additional one for dust absorption. Second, the grid points and the physical range of parameters are different. The model by Zheng & Miralda-Escudé (2002) and Kollmeier et al. (2010) has four values for each parameter: $V_{\text{exp}} = 50, 100, 200, 300 \text{ km s}^{-1}$, $\log (N_{\text{HI}}) = 17, 18, 19, 20.3 \text{ cm}^{-2}$, and $b = 20, 40, 80, 120 \text{ km s}^{-1}$, whereas the model used in this study has $12 V_{\text{exp}}, 13 N_{\text{HI}},$ and $5 b$ values spanning wider physical ranges. Finally, the intrinsic spectrum of the previous models is a monochromatic Ly$\alpha$ line, while we model a Gaussian Ly$\alpha$ plus a continuum. As we show in Section 4.3.2 and later sections, we infer that the key to better reproducing the blue bump is to assume the Ly$\alpha$ profile to be a (broad) Gaussian.

4.3.2. Derived Parameters

The best-fit parameters are summarized in Table 5. We describe the mean values of the derived parameters and systematically compare them with those of LBGs modeled by the same code (Schaerer & Verhamme 2008; Verhamme et al. 2008; Dessauges-Zavadsky et al. 2010). For the parameter FWHM$_{\text{int}}$(Ly$\alpha$), we examine the mean values of two subsamples, objects with a blue bump and those without. We have checked that there is no significant difference between the two subsamples in the other parameters.

The mean $V_{\text{exp}}$ value of the LAEs is $148 \pm 14 \text{ km s}^{-1}$, which is comparable to that of LBGs, $131 \pm 25 \text{ km s}^{-1}$. This strongly
disfavors the hypothesis that the small $\Delta v_{\text{Ly}\alpha}$ of LAEs is due to their large outflow velocity.

The most interesting parameter, $N_{\text{HI}}$, ranges from $\log(N_{\text{HI}})$ = 16.0 to 19.7 cm$^{-2}$, with a mean value of 18.4 ± 0.4 cm$^{-2}$, which is more than one order of magnitude smaller than the typical log($N_{\text{HI}}$) value of LBGs, 19.8 ± 0.2 cm$^{-2}$.

The mean values of $\tau_{\alpha}$ and $b$ are 0.9 ± 0.2 km s$^{-1}$ and 37 ± 10 km s$^{-1}$, respectively, both of which are comparable to those of LBGs, 0.8 ± 0.1 km s$^{-1}$ and 28 ± 5 km s$^{-1}$.

FWHM$_{\text{int}}$($\text{Ly}\alpha$) values range from FWHM$_{\text{int}}$($\text{Ly}\alpha$) = 50 to 847 km s$^{-1}$. The mean values for the whole sample, the non-blue-bump sample, and the blue bump sample are 354, 169, and 602 km s$^{-1}$, respectively. This shows that the blue bump objects have significantly larger FWHM$_{\text{int}}$($\text{Ly}\alpha$) than that found in the non-blue-bump objects. This trend is similar to Verhamme et al. (2008); they have found that most LBGs with a single-peaked Ly$\alpha$ profile are best fitted with moderate values of FWHM$_{\text{int}}$($\text{Ly}\alpha$), ~200 km s$^{-1}$, whereas the best-fit FWHM$_{\text{int}}$($\text{Ly}\alpha$) values for two LBGs with a blue bump are greater than 500 km s$^{-1}$. These results support our claim that large FWHM$_{\text{int}}$($\text{Ly}\alpha$) helps in fitting the blue bump.

We investigate whether there are any observational trends for the blue bump objects and discuss possible mechanisms for the blue bump objects to have large FWHM$_{\text{int}}$($\text{Ly}\alpha$) in Section 5.1.

Since starburst activities that produce Ly$\alpha$ photons should be similar between LAEs and LBGs, we expect comparable EW$_{\text{int}}$($\text{Ly}\alpha$) values for these two galaxy populations. The result is that the mean EW$_{\text{int}}$($\text{Ly}\alpha$) value of LAEs, 65 ± 18 Å, is somewhat smaller than that of LBGs, 107 ± 25 Å.

In summary, the model parameter $N_{\text{HI}}$ derived in LAEs is more than one order of magnitude smaller than that of LBGs, whereas the remaining parameters are consistent within 1σ between LAEs and LBGs.

4.3.3. Influence of Spectral Resolution on the Fitting Procedure

To investigate the influence of spectral resolution on the fitting results, we compare the best-fit parameters of the two objects observed with the two spectrographs, COSMOS-13636 and COSMOS-43982. As can be seen in Table 5, the two fitting results of COSMOS-43982 are consistent with each other, whereas those of COSMOS-13636 are not, possibly owing to the large difference in the best-fit reduced $\chi^2$, 1.1 and 6.2.

Taking a closer look into these two fits, we see that the extremely small 1σ noise in the flux of LRIS-COSMOS-13636 could be a key reason for its high $\chi^2$ value. On the other hand, the modeled spectrum seems to be oversmoothed, leading us to infer that its Ly$\alpha$ line resolution is underestimated. Indeed, it is known that the spectral resolution for a given line can be higher than the canonical value. A combination of these factors would naturally cause the large resultant $\chi^2$ value and the discrepancy between the different best-fit parameters at two resolutions.

4.4. Degeneracy among Parameters

In this subsection, we investigate degeneracies among the model parameters to understand how they affect our determination of the best-fit parameters. First, we describe possible degeneracies, and then we statistically examine them using 2D $\chi^2$ values.
It is possible that parameters $\tau$ and $\text{EW}_{\text{int}}(\text{Ly}\alpha)$ are degenerate as an observed profile can be reproduced equivalently well assuming either a weak intrinsic line with low dust extinction or a strong intrinsic line with high dust extinction. There would also be a degeneracy between $b$ and $\text{FWHM}_{\text{int}}(\text{Ly}\alpha)$ in the sense that both broaden the line profile. Furthermore, when there is a blue bump in the profile, we need either a high $b$ or a low $V_{\text{exp}}$ to reproduce it.

Figures 12–14 in the appendix are 2D parameter grid maps for CDFS-3865, with the gray dots showing the entire grids. We use these maps and $\chi^2$ values to examine the actual degeneracies among the parameters. If there is a degeneracy between two parameters, the $\chi^2$ contour would be tilted and elongated. The blue grids in these figures show those satisfying $\Delta \chi^2 \leq 6.17$ above the raw minimum $\chi^2$ designated by the white dots, i.e., the $3\sigma$ uncertainty in the parameter set (Press et al. 1992). Thanks to the number of data points given by high spectral resolutions and the relatively coarse grids, even the $3\sigma$ uncertainty is converged into one grid. This indicates that there is no degeneracy that affects our determination of the best fit. We have checked that this is also true for the rest of the sample in this study. Thus, we conclude that the systematic uncertainties among the parameters due to the degeneracies are small and thus do not affect our discussions.

4.5. Comparison between Observation and Model

In order to examine whether the best-fit parameters are reasonable, we compare the derived parameters with the observables.

4.5.1. $|\Delta V_{\text{abs}}|$ versus $V_{\text{exp}}$

As stated in Section 3.5.1, several LIS absorption lines have been detected in individual spectra of COSMOS-12805, COSMOS-13636, and SXDS-10600 (Shibuya et al. 2014b) and in a stacked spectrum of four LAEs, CDFS-3865, CDFS-6482, COSMOS-13636, and COSMOS-30679 (Hashimoto et al. 2013). The measured blueshift of LIS absorption lines with respect to the systemic, $\Delta V_{\text{abs}}$, is listed in Table 4. Figure 6 shows a comparison between $|\Delta V_{\text{abs}}|$ and the best-fit expansion velocity, $V_{\text{exp}}$. For the stacked spectrum, we plot the mean $V_{\text{exp}}$ value of the four LAEs, $163 \pm 25$ km s$^{-1}$. While there are only four data points, $|\Delta V_{\text{abs}}|$ and $V_{\text{exp}}$ are in excellent agreement with each other.

4.5.2. $E(\text{B} - \text{V})_s$ versus $\tau_a$

The stellar dust extinction values, $E(\text{B} - \text{V})_s$, for the sample have been derived in previous studies (Hashimoto et al. 2013; Nakajima et al. 2013; Shibuya et al. 2014b; see Section 3.5.1). Figure 7 compares them with gas dust extinction, $E(\text{B} - \text{V})_{\text{gas}}$, derived assuming the relation

$$E(\text{B} - \text{V})_{\text{gas}} \approx 0.10\tau_a.$$  

(5)

Dotted and dashed lines correspond to empirical relations $E(\text{B} - \text{V})_s = E(\text{B} - \text{V})_{\text{gas}}$ (Erb et al. 2006a) and $E(\text{B} - \text{V})_s = 0.44 E(\text{B} - \text{V})_{\text{gas}}$ (Calzetti et al. 2000), respectively, for host galaxies. As Kashino et al. (2013) have shown, the difference between $E(\text{B} - \text{V})_s$ and $E(\text{B} - \text{V})_{\text{gas}}$ becomes smaller for higher-$z$ galaxies.

In this study, we expect that data points are located below these relations. This is because $E(\text{B} - \text{V})_{\text{gas}}$ obtained from Ly$\alpha$ modeling is gas dust extinction for outflowing shells, which should be smaller than that for host galaxies. The figure shows that half of the sample roughly lies between the two lines, while the rest of the sample shows low $E(\text{B} - \text{V})_{\text{gas}}$ values. A similar trend has been found in Figure 12 of Verhamme et al. (2008), who have compared $E(\text{B} - \text{V})_s$ and $E(\text{B} - \text{V})_{\text{gas}}$ for $z \sim 3$ LBGs. They have assumed two different star formation histories (SFHs) in deriving $E(\text{B} - \text{V})_s$: a constant SFH, indicated by red triangles, and
an exponentially decreasing SFH, indicated by blue open circles, the former of which is the same as that assumed in this study. Both our data and the red triangles in Verhamme et al. (2006) are similarly distributed in the sense that half of the sample has comparable extinction values and the rest has low \( E(B-V)_{\text{gas}} \) values.

### 4.5.3. FWHM(neb) versus FWHM(int(Lyα))

Figure 8 plots the observed FWHM of nebular emission lines, FWHM(neb), versus modeled FWHM of the intrinsic (i.e., before being affected by the radiative transfer effect) Lyα line, FWHM\(_{\text{int}}\)(Lyα). Assuming that both Lyα and nebular emission lines originate from H ii regions, the two FWHMs should be similar. However, FWHM\(_{\text{int}}\)(Lyα) is systematically larger than FWHM(neb). Additional scattering of Lyα photons in an H ii region due to residual H\(_2\) atoms in it may be at work. Assuming a static H ii region with a neutral hydrogen column density of \( \log(N_{\text{H}}) \lesssim 17.0 \text{ cm}^{-2} \), corresponding to a unity optical depth for ionizing photons, \( \tau_{\text{ion}} \lesssim 1 \) (see Verhamme et al. 2015), FWHM\(_{\text{int}}\)(Lyα) can be broadened by 200 km s\(^{-1}\) compared to FWHM(neb). As can be seen from Figure 8, while this additional broadening would help explain the discrepancy for the non-blue-bump objects, it is still not enough for the blue bump objects. We discuss some interpretations for the huge FWHM\(_{\text{int}}\)(Lyα) in the blue bump objects in Section 5.1.

We also perform Lyα profile fitting of the blue bump objects by fixing FWHM\(_{\text{int}}\)(Lyα) = FWHM(neb). As shown in Figure 9, the blue bumps are poorly reproduced compared to the fitting without fixing FWHM\(_{\text{int}}\)(Lyα) cases. We examine whether the derived best-fit model parameters differ between the free and fixed FWHM\(_{\text{int}}\)(Lyα) cases. There is no systematic difference for \( V_{\text{exp}} \) and \( N_{\text{H}} \), we find that \( b \) (\( \tau_{\text{a}} \)) becomes large (small) in the fixed FWHM\(_{\text{int}}\)(Lyα) case. This would be related to the intrinsic degeneracy between them discussed in Section 4.4.

### 4.5.4. EW(Lyα) versus EW\(_{\text{int}}\)(Lyα)

Figure 10 plots the observed EW(Lyα) against the best-fit intrinsic EW(Lyα) obtained from the Lyα fitting, EW\(_{\text{int}}\)(Lyα). Since we have modeled Lyα emission lines that fall in the slit, we use EW(Lyα) values measured from spectra as the observed EW(Lyα). All the data points are expected to lie above the one-to-one relation, \( \text{EW}_{\text{int}}(\text{Ly} \alpha) > \text{EW}(\text{Ly} \alpha) \). This is because we have used the uniform shell model, which does not boost EW(Lyα), unlike clumpy shell models (see Neufeld 1991; Laursen et al. 2013; Duval et al. 2014; Gronke & Dijkstra 2014). As can be seen, all the data points satisfy the expectation within the 1σ uncertainty.

## 5. DISCUSSION

### 5.1. Mystery of the Blue Bump Objects

As described in previous sections, FWHM\(_{\text{int}}\)(Lyα) > FWHM(neb) is required to well reproduce the Lyα profiles for the blue bump objects. As seen in Figure 9, the position and flux of the blue bump are poorly reproduced if we fix FWHM\(_{\text{int}}\)(Lyα) = FWHM(neb). In this section, we first examine whether there are any characteristic properties for the blue bump objects and discuss the origin of the large discrepancy between the two FWHMs.

#### 5.1.1. Any Difference in Properties between the Blue Bump and the Non-blue-bump Objects?

In Section 4.3.2, we have argued that, among the model parameters, only FWHM\(_{\text{int}}\)(Lyα) is significantly different between the blue bump objects and the non-blue-bump objects. Here we examine the difference in stellar mass, Lyα luminosity, morphological ellipticity, and the merger fraction between the two samples.

First, it is possible that the non-blue-bump objects have faint Lyα luminosities and/or small stellar masses so that the blue bump cannot be observed. The Lyα luminosity of the blue bump sample ranges from \( L(\text{Ly} \alpha) = 0.3 \) to \( 29.8 \times 10^{42} \text{ erg s}^{-1} \) with a mean value of \( (8.8 \pm 5.6) \times 10^{42} \text{ erg s}^{-1} \), whereas that of the non-blue-bump sample ranges from \( L(\text{Ly} \alpha) = 0.5 \) to \( 15.4 \times 10^{42} \text{ erg s}^{-1} \) with a mean value of \( 7.0 \pm 2.1 \times 10^{42} \text{ erg s}^{-1} \). This indicates that the two subsamples have similar Lyα luminosities. Likewise, the stellar mass of the blue bump sample ranges from \( \log(M_*/M_\odot) = 7.73 \) to 10.80, with a mean value of \( 9.4 \pm 0.5 \), whereas that of the non-blue-bump sample ranges from \( \log(M_*/M_\odot) = 7.84 \) to 10.06, with a mean value of \( 9.3 \pm 0.3 \). Thus, this possibility is unlikely.

Second, objects with a blue bump may be more likely to be seen edge-on than those without. Recent theoretical studies (Verhamme et al. 2012; Zheng & Wallace 2014) have investigated the inclination effects to the Lyα emissivity and profile. These studies have shown that the blue bump flux relative to the total Lyα flux is enhanced with an increasing ellipticity. Indeed, Lyα profiles seen edge-on in these simulations resemble those produced by the static case of the spherical shell model. This is because outflowing gas is more likely to be blown out perpendicular to the galaxy disk, reducing the relative outflow velocity in the plane of the disk. As seen in Table 4, there are three objects whose ellipticity has been measured. Owing to the small number of objects, we cannot determine whether there is any difference between the two subsamples.
Finally, as discussed in Kulas et al. (2012) and Chonis et al. (2013), galaxy merging can be the origin of the blue bump. In this case, the redder and bluer Ly$\alpha$ emission components correspond to the two objects, respectively (see also Cooke et al. 2010; Rauch et al. 2011). However, as described in Section 3.5.3 (Table 4), the merger fraction in our sample is quite low.

We note here the observational results of Erb et al. (2010) and Heckman et al. (2011). These studies have found that objects with a blue bump tend to have a low CF of the neutral gas measured by LIS absorption lines. Unfortunately, we cannot test this trend with our sample because of a too small number of objects with detection of LIS absorption lines.

We conclude that there is no significant difference in Ly$\alpha$ luminosity, stellar mass, morphological ellipticity, or the merger fraction between the two samples. A large sample, whose Ly$\alpha$ and absorption-line velocity properties and morphological and stellar population properties are simultaneously available, is needed to understand the origin of blue bumps.

5.1.2. A Possible Explanation for Large FWHM$_{\text{int}}$(Ly$\alpha$) in Blue Bump Objects

In this subsection, we explore a possible explanation of the large discrepancy between FWHM$_{\text{int}}$(Ly$\alpha$) and FWHM$_{\text{neb}}$(Ly$\alpha$) in the blue bump objects.

It is possible that observed Ly$\alpha$ photons are produced not only from recombination of hydrogen gas ionized in H II regions but also from, e.g., shock heating (Otí-Floranes et al. 2012), fluorescence (e.g., Cantalupo et al. 2012, 2014), and/or gravitational cooling (e.g., Dijkstra et al. 2006). If these are taken into account, the huge FWHM$_{\text{int}}$(Ly$\alpha$) in the blue bump objects could be explained as follows.

Fluorescence caused by a QSO would ionize the outer layer of the ISM of galaxies and produce a large FWHM$_{\text{int}}$(Ly$\alpha$). However, there are no QSOs around any of our objects.

Gravitational cooling is another mechanism that produces Ly$\alpha$ photons. When gas inflows into the gravitational potential well of a galaxy, the gravitational binding energy is converted into the thermal energy, which is in turn released as Ly$\alpha$ photons (e.g., Dijkstra 2014). Since it occurs in both the inner and outer regions of the galaxy, gravitational cooling can give a large FWHM$_{\text{int}}$(Ly$\alpha$). Furthermore, gravitational cooling can reproduce not only the observed enhanced Ly$\alpha$ blue bump flux (e.g., Dijkstra et al. 2006) but also the spatially extended Ly$\alpha$. 

Figure 9. Ly$\alpha$ fittings with fixed FWHM$_{\text{int}}$(Ly$\alpha$) = FWHM$_{\text{neb}}$(Ly$\alpha$) for the objects with a blue bump. The reproduced Ly$\alpha$ lines (blue) are overlaid on the observed ones (gray). For comparison, we also plot the reproduced profiles without fixing FWHM$_{\text{int}}$(Ly$\alpha$) (red).

Figure 10. EW$_{\text{int}}$(Ly$\alpha$) plotted against EW$_{\text{spec}}$(Ly$\alpha$) obtained from spectroscopy. The meaning of the symbols and colors is the same as in Figure 7. Since we have assumed a uniform shell model that does not cause an EW(Ly$\alpha$) boost, the data points are expected to lie above the one-to-one relation.
source (Rosdahl & Blaizot 2012), i.e., diffuse Ly$\alpha$ halos that are common features around galaxies (Steidel et al. 2011; Matsuda et al. 2012; Hayes et al. 2013; Momose et al. 2014). We note here that there exists a large uncertainty in modeling the Ly$\alpha$ emission from gravitational cooling owing to its difficulty and assumed observation sensitivity (see Faucher-Giguère et al. 2010; Goerdt et al. 2010; Rosdahl & Blaizot 2012; Yajima et al. 2012, 2015). Our results, as well as observational results quoted above, can be useful for future modeling.

We conclude that not only the large discrepancy between the observed FWHM(neb) and FWHM$_{\text{tot}}$(Ly$\alpha$) but also the presence of a blue bump can be simultaneously explained if we introduce additional Ly$\alpha$ photons produced by gravitational cooling.

5.2. Origin of Small $\Delta v_{\text{Ly}\alpha,r}$ in LAEs

As described in Section 3.4, the mean $\Delta v_{\text{Ly}\alpha,r}$ of LAEs, $\lesssim 200$ km s$^{-1}$, is significantly smaller than that of LBGs, $\Delta v_{\text{Ly}\alpha,r} \approx 400$ km s$^{-1}$ (LBGs: e.g., Steidel et al. 2010; Rakic et al. 2011; Kulasekara et al. 2012; Schenker et al. 2013; LAEs: e.g., McLinden et al. 2011; Chonis et al. 2013; Hashimoto et al. 2013; Erb et al. 2014; Shibuya et al. 2014b). We have also demonstrated that some LAEs have an extremely small $\Delta v_{\text{Ly}\alpha,r}$ of $\lesssim 100$ km s$^{-1}$. Hashimoto et al. (2013) and Shibuya et al. (2014b) have also found that $\Delta v_{\text{Ly}\alpha,r}$ correlates with velocity dispersion, stellar mass, specific SFR, and dust extinction. Erb et al. (2014) have also found that $\Delta v_{\text{Ly}\alpha,r}$ correlates with velocity dispersion. In addition, they find that objects with a small $\Delta v_{\text{Ly}\alpha,r}$ have a large fraction of emission blueward of the systemic velocity, while the red wing of the Ly$\alpha$ profile and the outflow velocity traced by absorption lines remain unchanged. Following these findings, Erb et al. (2014) have argued that the small $\Delta v_{\text{Ly}\alpha,r}$ in LAEs is consistent with a scenario where the opacity to Ly$\alpha$ photons is reduced by a bulk motion and/or CF of the gas near the systemic velocity (see also Steidel et al. 2010). These results suggest that $\Delta v_{\text{Ly}\alpha,r}$ is closely related to the physical size of the galaxy system. However, there are still no definitive conclusions why LAEs have small $\Delta v_{\text{Ly}\alpha,r}$.

In this subsection, we explore the origin of the small $\Delta v_{\text{Ly}\alpha,r}$ in LAEs using the largest sample of LAEs whose high-quality spectroscopy data and several properties have been obtained. There are several hypotheses that give $\Delta v_{\text{Ly}\alpha,r}$ as small as 0–200 km s$^{-1}$: a uniform shell ISM with a high-speed galactic outflow (e.g., Verhamme et al. 2006), a uniform shell ISM with a low neutral hydrogen column density (e.g., Verhamme et al. 2006, 2015), and other models such as a clumpy ISM with a low covering factor $f_c$ (Hansen & Oh 2006; Dijkstra & Kramer 2012; Laursen et al. 2013), or shell models with holes/cavities, i.e., CF $< 1$ (e.g., Behrens et al. 2014; Verhamme et al. 2015). We quantitatively discuss the first two hypotheses based on our detailed comparison of data with uniform shell models (Sections 5.2.1 and 5.2.2) and then qualitatively discuss other models (Section 5.2.3).

5.2.1. High Outflow Velocity

An outflow velocity larger than $V_{\text{exp}} \sim 300$ km s$^{-1}$ can reduce $\Delta v_{\text{Ly}\alpha,r}$ because Ly$\alpha$ photons would drop out of resonance with H$\text{I}$ atoms in the outflowing gas (e.g., Verhamme et al. 2006, 2015). However, our results of Ly$\alpha$ radiative transfer fitting in Section 4.3.2 show that all objects have small $V_{\text{exp}}$ of 100–200 km s$^{-1}$. Combined with the findings in Section 4.5.1 that these $V_{\text{exp}}$ are consistent with the observed outflow velocities, $\Delta v_{\text{obs}}$, we conclude that the high outflow velocity hypothesis is unlikely.

5.2.2. Low $N_{\text{H}_1}$

We examine the low $N_{\text{H}_1}$ hypothesis. Although it is difficult to directly measure $N_{\text{H}_1}$ in LAEs from observations, we have inferred it using the expanding shell model (Section 4.3.2). If we exclude the blue bump objects from the sample, modeled Ly$\alpha$ profiles and parameters are all consistent with the observed Ly$\alpha$ profiles and several fundamental observables. Thus, we consider the derived neutral hydrogen column density, $N_{\text{H}_1}$, to be reliable as well. Figure 11 is a plot of $\Delta v_{\text{Ly}\alpha,r}$ against log($N_{\text{H}_1}$) for the non-blue-bump objects. We add results from the literature: Verhamme et al. (2008), Schaerer & Verhamme (2008), Vanzella et al. (2010), and Dessauges-Zavadsky et al. (2010). These authors have also utilized the model used in this study for $z \sim 3$ LBGs with various EW(Ly$\alpha$) (Verhamme et al. 2008), a strongly lensed LBG with Ly$\alpha$ absorption at $z \sim 2.73$ (MS 1512-cB58) (Schaerer & Verhamme 2008), a peculiar $z = 5.56$ [N$\text{IV}$ emitter with EW(Ly$\alpha$) = 89 Å (Vanzella et al. 2010), and a lensed LBG with Ly$\alpha$ absorption, “the 8 o’clock arc” (Dessauges-Zavadsky et al. 2010). We also add the results of Kulasekara et al. (2012) and Chonis et al. (2013), although models used in these studies are different from the one used in this study. In the figure, objects with EW(Ly$\alpha$) $\gtrsim 30$ Å are colored in red and labeled as LAEs, while those with EW(Ly$\alpha$) $< 30$ Å are colored in blue and labeled as LBGs.

We caution readers that all the data points and error bars in Figure 11 are obtained assuming uniform expanding shell models (see Section 4.2 for how we have obtained the error bars of our data points). The results can be significantly changed once we consider other theoretical models such as clumpy or patchy models (see Section 5.2.3).

The figure shows a clear correlation between log($N_{\text{H}_1}$) and $\Delta v_{\text{Ly}\alpha,r}$. As described in Section 4.3.2, the mean log($N_{\text{H}_1}$) in $z \sim 2$ LBGs is log($N_{\text{H}_1}$) = 18.9 cm$^{-2}$, which is more than one order of magnitude lower than those of $z \gtrsim 3$ LBGs, $\sim 20.0$. We have excluded the five blue bump objects in our 12 LAEs in Figure 11 for a secure discussion. However, we note that they have comparable $N_{\text{H}_1}$ values to the non-blue-bump objects and are consistent with the correlation. We conclude that the small $\Delta v_{\text{Ly}\alpha,r}$ in the LAEs can be well explained by the low $N_{\text{H}_1}$ hypothesis.

5.2.3. Other Models

Throughout the paper, we have assumed uniform expanding shell models constructed by Verhamme et al. (2006) and Schaerer et al. (2011). In this section, we qualitatively discuss alternative models such as clumpy and patchy models. Hansen & Oh (2006) have analytically investigated the Ly$\alpha$ radiative transfer in multiphase media, especially the one through dusty optically thick gas clumps. They have shown that radiative transfer strongly depends on the covering factor, $f_c$ (see also Dijkstra & Kramer 2012; Laursen et al. 2013). As can be seen from Figure 20 of Hansen & Oh (2006), asymmetric Ly$\alpha$ profiles with small $\Delta v_{\text{Ly}\alpha,r}$ can be reproduced.
by clumpy models with low $f_\alpha$, i.e., a small average number of interaction for $Ly\alpha$ photons before escaping from the galaxy.

Recently, Behrens et al. (2014) and Verhamme et al. (2015) have investigated the $Ly\alpha$ radiative transfer in a shell with holes and/or cavities, i.e., CF $< 1$. These studies have shown that, if a shell has holes, the modeled $Ly\alpha$ line profile through a transparent line of sight has $\Delta v_{Ly\alpha,r} = 0 \text{ km s}^{-1}$ even if convolved with spectral resolutions used for the observations (see Figures 4 and 5 in Verhamme et al. 2015). We qualitatively test the hypothesis by comparing $Ly\alpha$ and nebular emission line profiles. In the case of a patchy ISM, if we observe the galaxy through a transparent line of sight, observed $Ly\alpha$ line profiles would be indistinguishable from nebular emission line profiles. This is because the main $Ly\alpha$ component is dominant and is not affected by the radiative transfer effect. As can be seen in Figure 1, COSMOS-08357 and COSMOS-43982 have indistinguishable $Ly\alpha$ and nebular line profiles. We conclude that at least two objects, COSMOS-08357 and COSMOS-43982, could be explained by patchy ISM models.

Thus, we have demonstrated that the small $\Delta v_{Ly\alpha,r}$ in LAEs can also be well reproduced by clumpy and/or patchy ISM. However, future detailed $Ly\alpha$ modeling assuming clumpy and patchy ISM are needed for a more definitive conclusion. Whichever hypothesis is the most relevant one, the key for the small $\Delta v_{Ly\alpha,r}$ in LAEs would be the reduced number of resonant scattering of $Ly\alpha$ photons.

Hereafter in this section, we focus on the results obtained from uniform expanding shell models with low $N_{H1}$.

5.3. Interpretation of Low $N_{H1}$ in LAEs

We have shown that, on the assumption of uniform shell models, the most likely situation for the smaller $\Delta v_{Ly\alpha,r}$ in the present sample is that LAEs have low $N_{H1}$. We can envisage three possible scenarios for LAEs having low $N_{H1}$.

First, it is possible that LAEs have a low $H1$ gas mass. Indeed, Pardy et al. (2014) have detected an $H1$ 21 cm line for 14 local galaxies with $Ly\alpha$ emission (Ly$\alpha$ Reference Sample; Østlin et al. 2014), to find that the derived $H1$ gas mass tentatively anticorrelates with EW($Ly\alpha$). This trend is also consistent with theoretical predictions (T. Garel & C. Lagos 2015, private communication).

Second, if a galaxy has a high gas ionization state, ionizing photons would efficiently ionize the neutral gas in the ISM. This would decrease the thickness of the $H1$ gas in the outflowing shell and lower their $N_{H1}$. This picture is consistent with the recent finding of Nakajima & Ouchi (2014) that LAEs have a significantly higher ionization state than that of LBGs at the same redshift. The high ionization state in LAEs would be due to their young stellar populations (e.g., Pirzkal et al. 2007; Ono et al. 2010b, 2010a). Young O- and B-type stars in LAEs would efficiently produce ionizing photons and reduce the $N_{H1}$ of the surrounding gas.

Figure 11. log($N_{H1}$) plotted against $\Delta v_{Ly\alpha,r}$. Red (blue) symbols correspond to objects with EW($Ly\alpha$)$_{photo}$ larger (smaller) than 30 Å. Filled circles and diamonds are the non-blue-bump LAEs obtained by MagE and LRIS, respectively. Filled squares show $z \sim 3$ objects given by Verhamme et al. (2008). A filled triangle denotes a $z = 5.56$ [N iv] emitter with EW($Ly\alpha$) = 89 Å (Vanzella et al. 2010). An open triangle is a lensed LBG with $Ly\alpha$ absorption, cB38 (Schaerer & Verhamme 2008), while an inverted triangle is a lensed LBG with $Ly\alpha$ absorption, “the 8 o’ clock arc” (Dessauges-Zavadsky et al. 2010). In addition, the objects studied in Kulas et al. (2012) and Chonis et al. (2013) are plotted as a circle and three squares with a cross inside, respectively. For the purpose of display, three LAEs given by Chonis et al. (2013), which have similar $\Delta v_{Ly\alpha,r}$ and log($N_{H1}$) values of 175 km s$^{-1}$ and 18 cm$^{-2}$, are shifted toward the $x$-axis. We stress that all the data points and error bars are obtained assuming uniform expanding shells. The positions and/or error bars of data points in the figure can be significantly changed if we consider other models. See the text (Section 5.2.2) for details.
Figure 12. Upper and lower five panels show 2D $\chi^2$ contours for $V_{\text{exp}}$ and log($N_{\text{HI}}$), respectively, for CDFS-3865. The grids colored with blue (red) denote those within the 3$\sigma$ (5$\sigma$) level from the minimum $\chi^2$ grid shown as a white dot.
Finally, in the case of a face-on galaxy, we would see a lower $N_{\text{HI}}$ because Ly\textsc{α} photons would experience a shorter path length out of the disk (e.g., Verhamme et al. 2012; Zheng & Wallace 2014). Indeed, Shibuya et al. (2014a) have statistically examined the ellipticity, an indicator of the inclination, for $z \sim 2$ LAEs using HST data. A weak trend has been found that high EW(Ly\textsc{α}) objects are less inclined.

A combination of these effects would reduce the number of resonant scatterings of Ly\textsc{α} photons. This would, in turn, decrease the Ly\textsc{α} velocity offset, $\Delta v_{\text{Ly\textsc{α}}}$ (e.g., McLinden...
et al. 2011; Hashimoto et al. 2013; Erb et al. 2014), and the Ly\textsubscript{\alpha} spatial offset, \(\delta_{\text{Ly}\alpha}\) (Jiang et al. 2013; Shibuya et al. 2014a).

**Figure 14.** Upper and lower five panels show 2D \(\chi^2\) contours for \(\text{EW}_{\text{int}}(\text{Ly}\alpha)\) and \(\text{FWHM}_{\text{int}}(\text{Ly}\alpha)\), respectively, for CDFS-3865. The meaning of the colors is the same as in Figure 12.

### 5.4. Implication of Small \(\Delta v_{\text{Ly}\alpha,r}\) and \(\Delta v_{\text{peak}}\) in LAEs

Recent theoretical studies (Behrens et al. 2014; Verhamme et al. 2015) have proposed that the Ly\textsubscript{\alpha} line profile can be used
as a probe of Lyman continuum (LyC; \( \lambda < 912 \) Å) leaking galaxies (LyC leakers). LyC leakers are thought to have contributed to cosmic reionization. Observationally, detections of LyC emission are claimed for LAEs and LBGs both spectroscopically (e.g., Shapley et al. 2006) and photometrically (e.g., Iwata et al. 2009; Nestor et al. 2013). However, the success rate is very low possibly because LyC leakers are extremely faint objects (e.g., Ouchi et al. 2008).

Verhamme et al. (2015) have investigated two scenarios for the ionizing photon escape: (1) the density-bounded \( \text{H} \text{I} \) regions with an extremely low \( N_{\text{HI}} \) value, log\((N_{\text{HI}})<17.0\) cm\(^{-2}\), corresponding to a unity optical depth for ionizing photons, or (2) a galaxy has a partial spatial covering fraction of the gas. They have shown that \( \Delta V_{\text{Ly} \alpha , r}(\Delta V_{\text{peak}}) \), if the blue bump exists, is extremely small in these cases, \( \Delta V_{\text{Ly} \alpha , r} \lesssim 100\) km s\(^{-1}\) \((\Delta V_{\text{peak}} \lesssim 150\) km s\(^{-1}\)) (see also Jaskot & Oey 2014; Martin et al. 2015).

Thus, we propose that selecting objects with EW(Ly\( \alpha \)) as large as 100 Å is a promising way to search for LyC leaking galaxies. The merit of this candidate selection technique is that it does not require spectroscopy.

6. SUMMARY AND CONCLUSION

We have presented the results of an Ly\( \alpha \) profile analysis of 12 LAEs at \( z \sim 2.2 \) for which high spectral resolution Ly\( \alpha \) lines are obtained in Hashimoto et al. (2013) and Shibuya et al. (2014b) with Magellan/MagE or Keck/LRIS. Two objects have been observed with both spectrographs. All 12 objects have detections of nebula emission lines, which are used not only to define the systemic redshift but also to infer the intrinsic FWHM of the Ly\( \alpha \) line. We have also derived the galactic outflow velocity from blueshifted LIS metal absorption lines with respect to the systemic redshift for three individual LRIS spectra, as well as for a stacked spectrum of four MagE spectra. In addition, we have obtained stellar dust extinction from the SED fit. The high spectral resolution Ly\( \alpha \) data in conjunction with these measurements have enabled us to perform detailed comparisons between observed and modeled Ly\( \alpha \) lines. Our main results are as follows.

1. We find that all 12 objects have Ly\( \alpha \) profiles with a main peak redward of the systemic redshift and five objects (six spectra) have a weak, secondary peak blueward of the systemic redshift (the blue bump). For a sample of 17 objects from our study and the literature with a resolved Ly\( \alpha \) line, we estimate the ratio of LAEs with a blue bump to be \( \sim 50\% \), which is slightly higher than that of LBGs. We have obtained \( \Delta V_{\text{Ly} \alpha , b} = 174 \pm 19\) km s\(^{-1}\) \((\Delta V_{\text{Ly} \alpha , b} = -316 \pm 45\) km s\(^{-1}\)\), which is smaller than (comparable to) that of LBGs, \( \Delta V_{\text{Ly} \alpha , b} \approx 400\) km s\(^{-1}\) \((\Delta V_{\text{Ly} \alpha , b} = -367 \pm 46\) km s\(^{-1}\)\).

2. The high spectral resolution and sensitivity of Subaru/FMOS have enabled us to detect two-component [\( \text{O} \text{II} \)] profiles in two LAEs for the first time. While its origin is not clear, we find that even the FWHM of the broad component is as small as 70–80 km s\(^{-1}\). This excludes the possibility of its origin being AGN activity or powerful hot outflows.

3. We have applied the uniform expanding shell model constructed by Verhamme et al. (2006) and Schaerer et al. (2011) to our sample. The model successfully reproduces not only Ly\( \alpha \) profiles but also the galactic outflow velocity measured from LIS absorption lines and the FWHM of nebular emission lines for the non-blue-bump objects. However, for the blue bump objects, the intrinsic FWHMs of Ly\( \alpha \) predicted by the model are significantly larger than the observed FWHMs of nebular emission lines.

4. For the blue bump objects, we have tried another fit fixing the intrinsic FWHM of Ly\( \alpha \) to the observed FWHM of nebular emission lines. The position and flux of the blue bump are poorly reproduced.

5. To understand the large discrepancy between FWHM\(_{\text{int}}\)(Ly\( \alpha \)) and FWHM\(_{\text{neb}}\) in the blue bump objects, we have examined whether objects with and without a blue bump have different properties such as the Ly\( \alpha \) luminosity, stellar mass, and the merger fraction. We find no significant difference between the two samples. We propose that taking into account Ly\( \alpha \) photons produced by gravitational cooling might simultaneously explain the large FWHM\(_{\text{int}}\)(Ly\( \alpha \)) and the existence of a blue bump.

6. We quantitatively demonstrate that the small \( \Delta V_{\text{Ly} \alpha , r} \) in LAEs can be well explained by uniform expanding shell models with neutral hydrogen column density as low as log\((N_{\text{HI}}) = 18.9\) cm\(^{-2}\). This value is more than one order of magnitude lower than that of LBGs and is consistent with the recent findings that LAEs have a high ionization parameter and a low HI gas mass. These results imply that low \( N_{\text{HI}} \) is the key for the small \( \Delta V_{\text{Ly} \alpha , r} \) and the Ly\( \alpha \) escape mechanism. However, we caution readers that our results are based only on uniform expanding shell models, and that future detailed modeling with clumpy and/or patchy ISM is needed for a definitive conclusion.

7. As an implication of the small \( \Delta V_{\text{Ly} \alpha , r} \) and low \( N_{\text{HI}} \) in high EW(Ly\( \alpha \)) objects, we propose that targeting high-EW(Ly\( \alpha \)) objects would be an efficient way to search for Lyman continuum leaking galaxies from photometry data alone.

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